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PROCEEDINGS

OF THE

INTERNATIONAL CONFERENCE ON THE

PEACEFUL USES OF ATOMIC ENERGY

Volume 6

GEOLOGY OF URANIUM AND THORIUM

Proceedings of the International Conference on the Peaceful Uses of Atomic Energy

Held in Geneva
8 August-20 August 1955

Volume 6

Geology of Uranium and Thorium

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PREFACE

The Proceedings of the International Conference on the Peaceful Uses of Atomic Energy are published in a series of 16 volumes, as follows:

Volume Number	Title	Sessions Included
1	The World's Requirements for Energy; The Role of Nuclear Power	2, 3.2, 4.1, 4.2, 5, 24.2.
2	Physics; Research Reactors	6A, 7A, 8A, 9A, 10A.1.
3	Power Reactors	10A.2, 3.1, 11A, 12A, 13A, 14A.
4	Cross Sections Important to Reactor Design	15A, 16A, 17A, 18A.
5	Physics of Reactor Design	19A, 20A, 21A, 22A, 23A.
6	Geology of Uranium and Thorium	6B, 7B.
7	Nuclear Chemistry and the Effects of Irradiation	8B, 9B, 10B, 11B, 12B, 13B.
8	Production Technology of the Materials Used for Nuclear Energy	14B, 15B, 16B, 17B.
9	Reactor Technology and Chemical Processing	7.3, 18B, 19B, 20B, 21B, 22B, 23B.
10	Radioactive Isotopes and Nuclear Radiations in Medicine	7.2 (Med.), 8C, 9C, 10C.
11	Biological Effects of Radiation	6.1, 11C, 12C, 13C.1.
12	Radioactive Isotopes and Ionizing Radiations in Agriculture, Physiology and Biochemistry	7.2 (Agric.), 13C.2, 14C, 15C, 16C.
13	Legal, Administrative, Health and Safety Aspects of Large-Scale Use of Nuclear Energy	4.3, 6.2, 17C, 18C.
14	General Aspects of the Use of Radioactive Isotopes; Dosimetry	7.1, 19C, 20C.
15	Applications of Radioactive Isotopes and Fission Products in Research and Industry	21C, 22C, 23C.
16	Record of the Conference	1, 24.1, 24.3.

These volumes include all the papers submitted to the Geneva Conference, as edited by the Scientific Secretaries. The efforts of the Scientific Secretaries have been directed primarily towards scientific accuracy. Editing for style has been minimal in the interests of early publication. This may be noted especially in the English translations of certain papers submitted in French, Russian and Spanish. In a few instances, the titles of papers have been edited to reflect more accurately the content of those papers.

The editors principally responsible for the preparation of these volumes were: Robert A. Charpie, Donald J. Dewar, André Finkelstein, John Gaunt, Jacob A. Goedkoop, Elwyn O. Hughes, Leonard F. Lamerton, Aleksandar Milojević, Clifford Mosbacher, César A. Sastre, and Brian E. Urquhart.

The verbatim records of the Conference are included in the pertinent volumes. These verbatim records contain the author's corrections and, where necessary for scientific accuracy, the editing changes of the Scientific Secretaries, who have also been responsible for inserting slides, diagrams and sketches at appropriate points. In the record of each session, slides are numbered in numerical order through all presentations. Where the slide duplicates an illustration in the submitted paper, appropriate reference is made and the illustration does not appear in the record of the session.

Volume 16, "The Record of the Conference," includes the complete programme of the Conference, a numerical index of papers and an author's index, the list of delegates, the records of the opening and closing sessions and the complete texts of the evening lectures.

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The Natural Occurrence of Uranium and Thorium

United Nations*

INTRODUCTION

Scope of Papers Presented

This paper on the natural occurrence of uranium and thorium is written to provide a summary for the non-geological members of the conference. Seventeen nations have submitted a total of 95 papers† on the natural occurrence of these two elements. Several comprehensive published papers have also been received. The total of conference papers, recent publications supplied, and current scientific literature, establish a striking pattern of geologic knowledge. It is also a pattern which is applicable to exploration and discovery of uranium and thorium as required for the peaceful uses of atomic energy.

In an attempt to summarize this knowledge for the conference, the subject of natural occurrence has been considered from three points of view: (1) original sources, (2) mechanisms of transport and deposition, and (3) types of deposits produced.

Conference papers concerned with original sources devote particular attention to the basic problem of distribution in the earth's crust, both horizontally and vertically. Subjects of special interest are the natural provinces of these two metals, the significance of widespread traces in original rock types, the time and duration of emplacement, and interpretations to be derived from an unusual chemical assortment of minerals.

The attention of those concerned with mechanisms of transport has been directed to the role of solutions under various temperatures and pressures, the precipitants involved, the influence of the host rock, and the part that many structures play in controlling forms of deposits. Mechanical transport has also received close scrutiny, particularly in the study of thorium deposits where the high hinterland areas have revealed data which account for accumulations on flood plains below.

One of the major contributions of the group of papers as a whole concerns the types of uranium and thorium deposits. Here one finds the immediate application of geological principles to discovery. The geological problems of discovery include the extension of known deposits, the discovery of new deposits, the projection of exploration into new areas, in addition to finding uranium or thorium in new materials, different rock types and in new formations.

Grade of Natural Materials

Seldom has the progress of mineral discovery for any metal equalled the rate at which new uranium deposits have been found and brought into production in recent years. The major commercial discoveries of the last decade as made public are outlined in Table I.

New commercial deposits, deposits long known which have been expanded, hundreds of small deposits, and deposits which are probably known although unreported, if combined indicate major supplies of raw material for peaceful uses of atomic energy.

Deposits from which commercial production has been mainly reported to date include uranium and thorium veins of numerous types, accumulations in ancient sediments, uranium replacements in younger permeable sediments, replacements in limestone, uraniferous lignite, and dissemination of uranium and thorium in crystalline rocks.

The major deposits of thorium differ materially from those of uranium although in many instances the two elements are found together. Thorium occurs mainly in detrital deposits, but it is found less abundantly in veins, disseminations in crystalline rocks and in ancient sediments. The principal sources reported are India, Ceylon, Brazil and the United States.

Commercial uranium ore is largely based on the lower limit that will be purchased in terms of

Table I. A Decade of Commercial Uranium Discovery

1945	By-product uranium, South Africa
1947	White Canyon, Utah
1948	Beaverlodge Lake area, Canada
1949	Todilto limestone deposits, New Mexico
1949	Marysvale, Utah
1949	Rum Jungle, Australia
1950	Jackpile deposit, Laguna, New Mexico
1950	Monument No. 2 Mine, Arizona
1950	Poison Canyon, Grants, New Mexico
1951	Black Hills, South Dakota
1952	Gunnar Deposit, Saskatchewan, Canada
1952	Lisbon Valley, Moab, Utah
1952	Delta deposit, San Rafael Swell, Utah
1953	Blind River area, Canada
1954	Commercial lignite, South Dakota

* A summary prepared for the United Nations by Paul F. Kerr, Department of Geology, Columbia University, New York.

† After the preparation of this Summary, papers P/1073, P/1101, P/1105, P/1118, P/1121 were submitted by Austria, Greece, Belgium, Korea and Spain, respectively. The total number of papers submitted for this Session was 100.

Table II. Sub-commercial Sources of Uranium

Source	*Per cent U_3O_8*	*Pounds U_3O_8 per ton*	*Tons of rock yielding 2 pounds U_3O_8*
Commercial ore (published lower limit, USA–AEC)	0.1	2.0	1
Phosphate rock 0.012% U (P/292)	0.014	0.28	7
Bituminous shale 0.005–0.008% U (P/53)	0.0077 Avg.	0.15	13
Normal granite 4 ppm U; 12 ppm Th(P/850†)	0.00047 0.00137 (ThO_2)	0.037‡	54‡

* In this Summary references to papers submitted to this Conference are designated P/292, etc. Unless otherwise stated, the papers themselves are published in this volume of the Proceedings of the Conference.

† See Volume 8, Session 14B, These Proceedings.

‡ Combined.

metal content. This limit in the USA has been published as 0.1 per cent U_3O_8 or 2 pounds per ton of containing rock.

In addition to commercial sources of the type listed in Table I, several sub-commercial sources have been suggested (Table II). These include sea water, normal granite, bituminous shale, and by-product phosphate rock. None as yet appears competitive with commercial ores.

The largest single natural body known to contain uranium is the ocean. Figures for the total amount of water in such a source would be astronomical, but the uranium content is only 1.2×10^{-6} gm/l at the surface of the ocean as measured[49] by the Swedish "Albatross" expedition, 1947–48.

Brown (P/850 Session 14B, Volume 8 of these Proceedings) suggests granite as a potential source. Normal granite is much more limited than sea water in distribution, but it is still widespread. It is reported to contain about 4 ppm uranium and 12 ppm thorium. Yet, to obtain 2 pounds of combined uranium and thorium oxides from normal granite, neglecting loss in recovery, would require about 54 tons of rock.

Bituminous shales in the eastern United States have been proposed as potential sources of uranium. The Gassaway shale of the Chattanooga formation in Tennessee averages about 0.0077 per cent U_3O_8 or some 65 ppm uranium (P/53). To obtain 2 pounds of uranium oxide from such shale would require about 13 tons of rock.

Phosphate rock has been proposed as a by-product source of uranium. The uranium content is said to be about 0.012 per cent or 100 ppm (P/292). To recover 2 pounds of uranium oxide from phosphate rock would require about 7 tons of material.

In addition to the above, a considerable group of deposits exists where the grade reported is close to the lower limit of commercial ore, but factors such as size and accessibility indicate that the deposits may be workable. In process of development or in operation are uranium deposits in ancient sediments such as the Witwatersrand, South Africa, and the deposits near Blind River, Canada. The Canadian deposits are reported[37] to contain on the order of 0.10 per cent U_3O_8. In such areas where exploration has established large deposits, it is claimed that commercial recovery from such low grade ore is feasible.

Favorable Host Rocks

Uranium and thorium are found in a variety of rocks and in widely different formations. However, three broad source types stand out as the most productive: (1) belts of ancient pre-Cambrian rocks, (2) widespread areas of permeable sediments, and (3) accumulations of detrital sands. The great belts of ancient (pre-Cambrian) crystalline rocks exposed on each continent are distinctive either as existing or potential sources of uranium and thorium (Fig. 1). Uranium deposits in such rocks include the occurrences of Czechoslovakia, the Canadian Shield, the Belgian Congo, South Africa and Australia. Thorium deposits would include the peninsula of India, the hinterland behind the coastal areas of Brazil and the piedmont of the Carolinas in the United States.

Major occurrences of uranium are found in permeable sediments. In this form of occurrence, the area of greatest productivity reported would be the great region of plateau sediments and intermountain basins of the western United States. As indicated in the older literature, a similar district may exist in the Ferghana area, USSR.

Major occurrences of thorium are found in detrital sands of comparatively recent geological age. Such deposits are well-known along the coastal belt of India, along the northeast shore of Brazil, as well as in the Carolinas and Idaho in the United States.

ORIGINAL SOURCES OF URANIUM AND THORIUM

Crystal Units

The science of geology provides few more challenging problems than the interpretation of the various steps by which elements such as uranium and thorium accumulate within the earth, find their way into the crust, form deposits, suffer erosion and disintegration and ultimately come to rest in the ocean. Much thought and study have been devoted to the

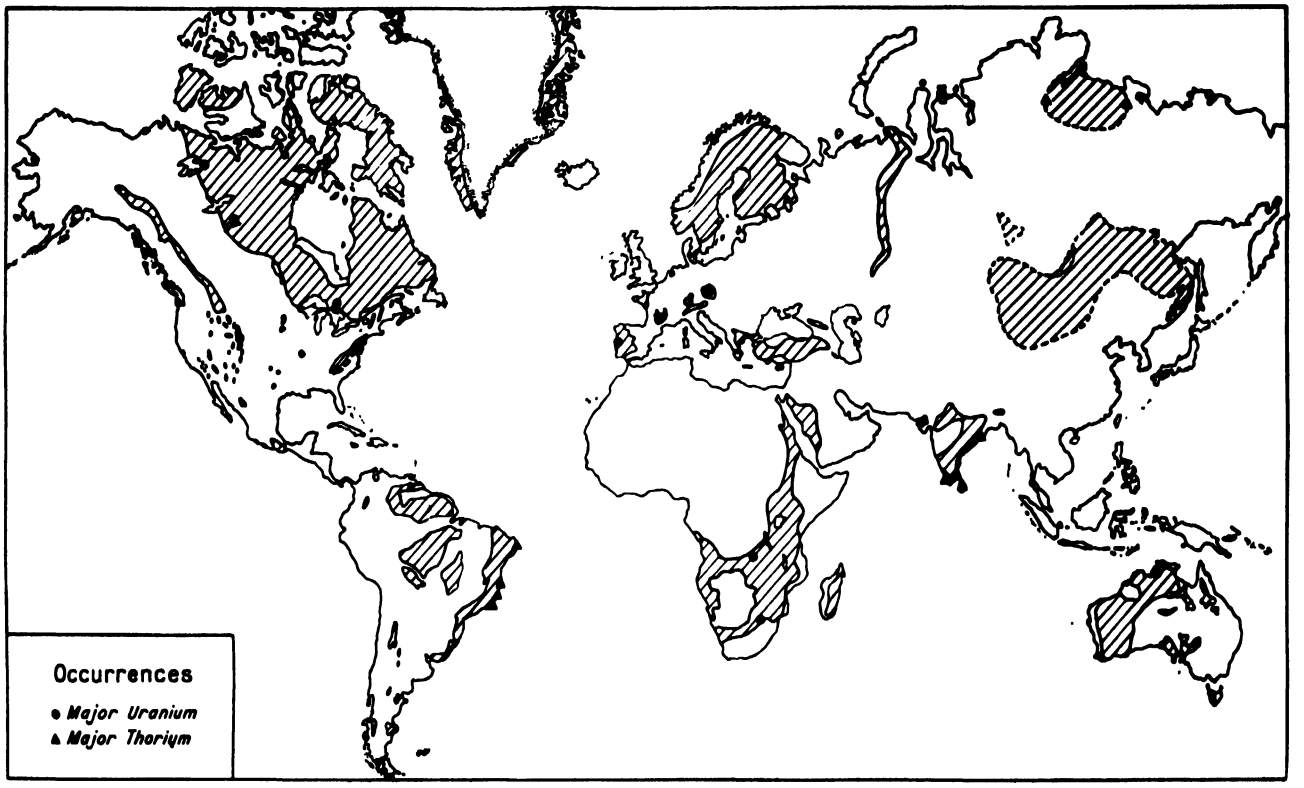


Figure 1. Ancient rock areas. Major Pre-Cambrian areas

several phases of these problems, yet in truth it must be admitted that important gaps in a complete picture remain to be filled.

Fragments of information concerning the probable nature of the earth's core are derived indirectly from a variety of sources. Such sources include seismic disturbances originating in earthquakes or explosions, gravity measurements on the earth's surface, density computations for the earth as a celestial body, chemical and physical data of the earth's crust, minerals, and studies of meteorites. The earth, as recently illustrated (Fig. 2) in a review of modern concepts by Walton,[90] consists essentially of four parts each with a fairly well measured radius; an inner core (1300 km), outer core (3473 km), mantle (2898 km) and a crust (35 km ± beneath the continents).

The mean density of the earth was long ago computed by Cavendish in 1798 as 5.48 gm/cm^3 and has been found only moderately greater in modern measurements. The figure represents a possible average between the outer portion and the core. Worzel and Shurbet[92] on the basis of gravity measurements have recently concluded that the standard continental crust has a mean density of 2.84 while the mantle beneath has a density of 3.27.

The core materials of the earth may or may not correspond to the fragmental materials from outer space found on the earth as meteorites. Nevertheless, the mean earth density of 5.48 and the resemblance between meteorites and materials which could conceivably exist in the earth's core have led to an extended study of meteorites in an attempt to fill the great vacuum which exists in definite information concerning the earth's interior.

Meteorites may be completely crystalline-like terrestrial rocks, masses of metallic iron alloyed with nickel or other elements, and mixtures of iron and rock.[26] These have been extensively and carefully examined.[71] Traces of uranium and thorium have been detected[3] but the amounts noted are less than contained in the average igneous rock.

On the basis of Bullen's calculations[10] and observations concerning earth magnetism, Urey[89] favors a metallic core.

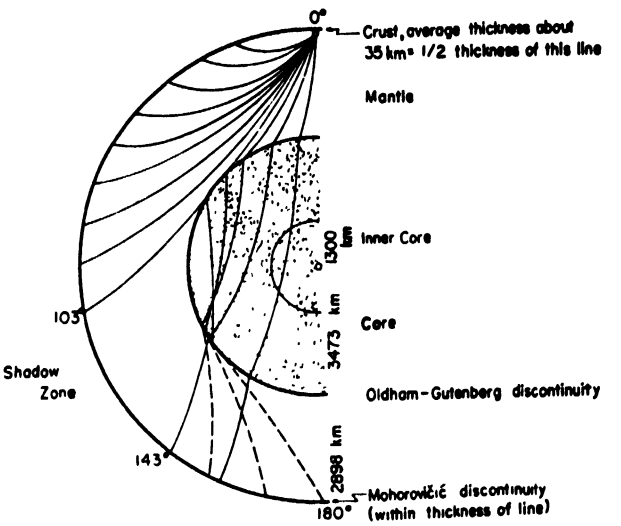


Figure 2. The earth's interior. The crust is a thin shell compared with the interior (after Walton)[90]

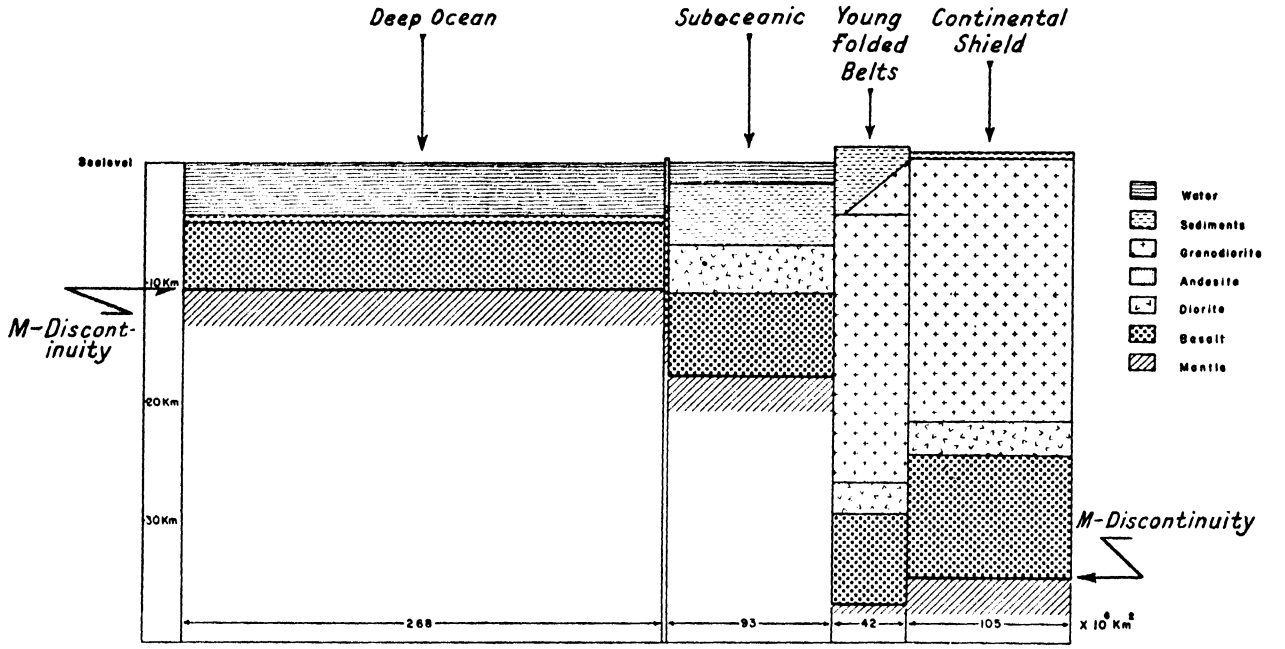


Figure 3. Major segments of the crust. Schematic sections of major areas of the earth's crust (after Poldervaart).[72] Boundaries between segments mark areas of crustal disturbance

The inner core, he postulates, could be nearly pure iron, some iron-nickel alloy or nearly pure nickel.

The pattern of uranium and thorium distribution of immediate concern is in the crust. Although the crust is some 35 km thick beneath the continents and 10.5 km thick beneath the deeper part of the ocean, it is essentially a thin veneer separated from the much thicker mantle beneath by the great Mohorovičić discontinuity. The distribution of the major crustal elements as reviewed by Poldervaart[72] is set forth in Fig. 3.

Accumulation in Provinces

Certain fairly wide areas of the earth's crust show concentrations of particular mineral deposits. Many deposits of tungsten are concentrated in one portion of China. Tin is found throughout a wide area in Bolivia and northern Argentina. A belt of silver deposits occurs in Mexico. Lead-zinc deposits favor the central part of the Mississippi Valley. Such areas are frequently referred to as metallogenic provinces.

The boundaries of a province may be ill-defined, but, in general, the salient features are recognized by most authorities. It may cover a large part of a continent or it may be restricted to a few hundred square miles. Many complexities of mineralization are included beyond the geographic localization of a metallic element.

The concept of metallogenic provinces aids in establishing regional features which govern deposits of a particular metal. It also establishes boundaries within which the likelihood of added mineral discovery is greater. Likewise, the concept facilitates the accumulation of knowledge of individual deposits and the application of local experience generally.

Several important metallogenic provinces of uranium and thorium exist in different parts of the world (Fig. 4). One such province would be the belt which involves at least eight states in the western United States and extends from southern Arizona and New Mexico northward to the Dakotas and Montana. Other uranium provinces would be the western Canadian Shield and the shield area of southern Africa. Two thorium provinces would be the coastal region of eastern Brazil and the peninsula of India. Joachimsthal in Czechoslovakia is a center in a small uranium province, and it seems likely that the Ferghana region of the USSR lies in another province. Lang[52,53] discusses the main Canadian province and possible sub-provinces.

Uranium-rich provinces are believed to persist through long periods of geologic time. Regions result in which considerably different types of deposits form—but all of the same metal. It has been suggested by Klepper and Wyant (P/14) that uranium provinces may be related to original inhomogeneities in the earth's crust. The vertical boundaries between areas shown in Fig. 3 would lead to widespread inhomogeneities. In such places from geologic age to geologic age the interplay of mineral forming and mountain making processes tends to undergo repetition.

The processes of generation, internal adjustment, emplacement and crystallization of a molten magma during mountain forming may accentuate crustal inhomogeneities. Since the final fractions of a magma to crystallize are apt to be higher in uranium, mountain forming processes may cause the concentration of uranium in certain rock types. A magma rich in uranium may hold the metal in coarsely crystalline pegmatite dikes and various granular

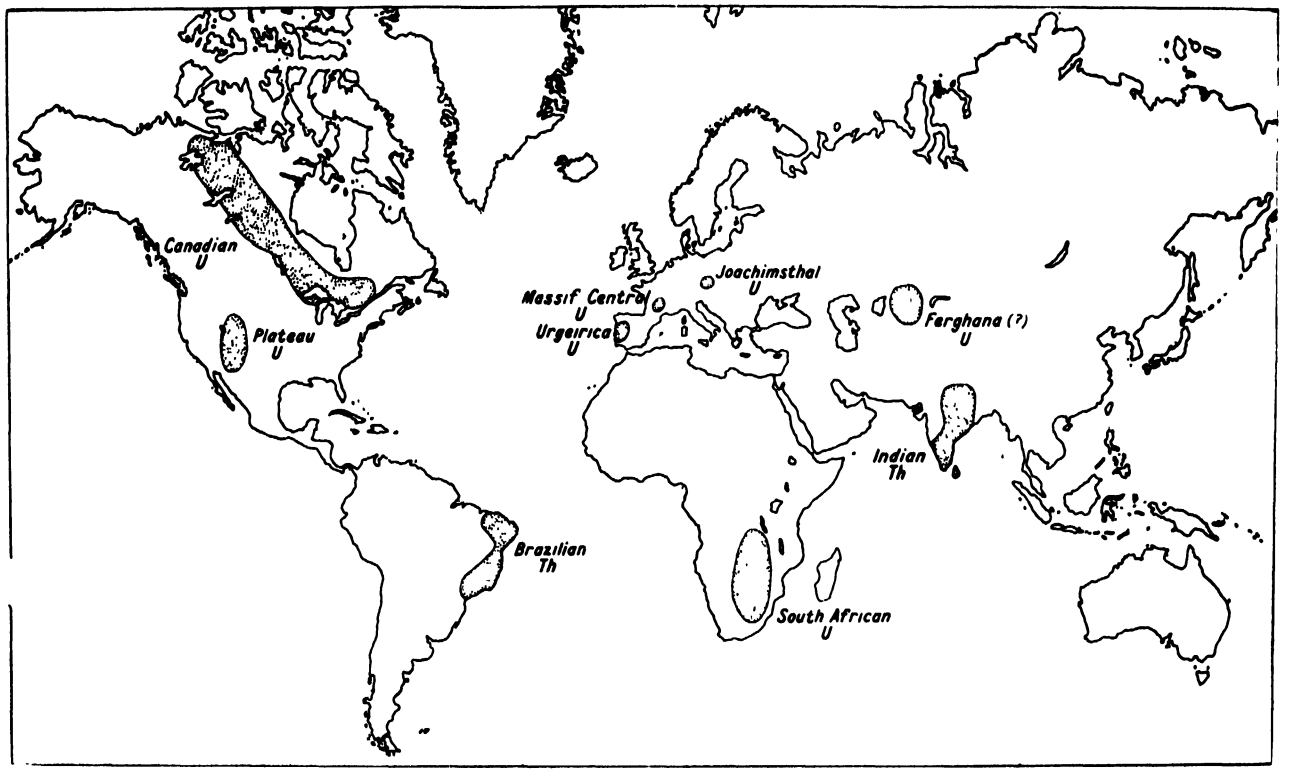


Figure 4. Principal metallogenic provinces. Major uranium and thorium provinces (compiled from published data). Limited areas of the earth contain groups of deposits

plutonic masses or allow it to escape in hot aqueous solutions to form vein-type deposits.

The rhyolitic or somewhat similar volcanic rock types from the Cordillera of the western United States represent a distribution which may imply a broad scale igneous relationship in nature and origin or perhaps a magmatic province. Rock types attributed to such a widely distributed magma have been subject of detailed analysis by Coats (P/18).

Samples of more or less glassy volcanic rocks, rhyolitic or dacitic in character, have been examined from ten western states, 116 samples being analyzed. All samples were examined fluorimetrically for uranium, chemically for fluorine, and spectrographically for B, Be, La, Li, Nb, Sn, Pb, and Zr.

The content of uranium appears to correlate with fluorine, lithium, niobium, tin and beryllium. Where lanthanum is present uranium is absent. Elements Pb, B, Zr or Mn showed no significant correlation.

The analytical data suggest that uranium and associated elements may have been concentrated in somewhat residual rhyolitic magmas in a broad province following removal of other elements during earlier crystallization.

Traces in Igneous Rocks

Information concerning the accumulation of uranium or thorium within the earth's interior and migration to surface deposits must be largely inferred. Observational data are limited to the study of rocks which were once molten masses within the crust, the distribution of uranium in natural provinces at the earth's surface, the nature of uranium minerals together with the deposits in which they are found, and the analysis of physical measurements‡ which furnish indirect information on the earth's interior.

Quantitative data on the elements found in igneous rocks of the earth's crust are uncertain and estimates of amounts vary. Rankama and Sahama[73] place uranium in abundance slightly above the lower third of the list of elements with thorium in a somewhat higher position. Uranium (4 gm/ton) is considered to be about as widespread as Hf, As (5 gm/ton) and Be (6 gm/ton), while thorium (11.5 gm/ton) is less widespread than Co (23 gm/ton), Pb (16 gm/ton), and Ga (15 gm/ton). The abundance or uranium in the earth's crust is estimated by Fleischer[25] to be 0.0002 per cent, or about equal to tungsten or tantalum. Urey[89] indicates that uranium is the least common element in the earth, having an atomic abundance of 0.0002 (Si = 10,000).

Considerable attention has been devoted to the traces of uranium and thorium in igneous rocks. Study of the amount and distribution serves two functions (P/16). It gives information on material which some consider a potential low grade uranium source; it furnishes data on igneous activity which is indirectly related to many uranium deposits.

Uranium is an ubiquitous and small component of all igneous rocks, but, as Neuerburg (P/16) points out, it is emplaced in a variety of ways. The element may be distributed through the structure of rock

‡ Much information relevant to this subject will be found in the volume "The Crust of the Earth," Memoir 61, Geol. Soc. Amer., 1955, 750 p.

forming minerals, held in cation exchange positions, absorbed on the surfaces of crystals, dissolved in fluid inclusions within crystals, or dissolved in intergranular fluids. The complexity of events involved in the distribution indicates that the total uranium content of any rock is an average of the interplay of several sources.

Nearly all of the uranium, except that held structurally in rock materials, is soluble in dilute mineral acids. The part that is structurally held is significant of the final crystallization of the rock minerals. The acid soluble uranium represents the portion most likely to have been changed after final consolidation. Likewise it may be the aureole around an ore deposit (P/16).

Large numbers of sensitive fluorimetric analyses have been made to determine the variation of uranium content in rocks derived from molten magma (P/17). The rocks analyzed include such plutonic masses as the southern California batholith (Fig. 5), intrusives of the Colorado Front Range, volcanics of the San Juan Mountains in Colorado and a goodly number of other well-known plutonic rock types. It appears that rocks high in magnesium, aluminum and iron (mafic type) are low in uranium, containing about 0.3 ppm. In contrast, rocks at the alkali end of the normal igneous rock series such as granite contain about 5.0 ppm uranium.

The tendency of uranium to favor alkali-type magmas is further emphasized by analyses of Colorado Front Range rocks impoverished in calcium, but rich in alkalies. These contain as much as 100 ppm uranium above the average for a calcium-alkalic granite.

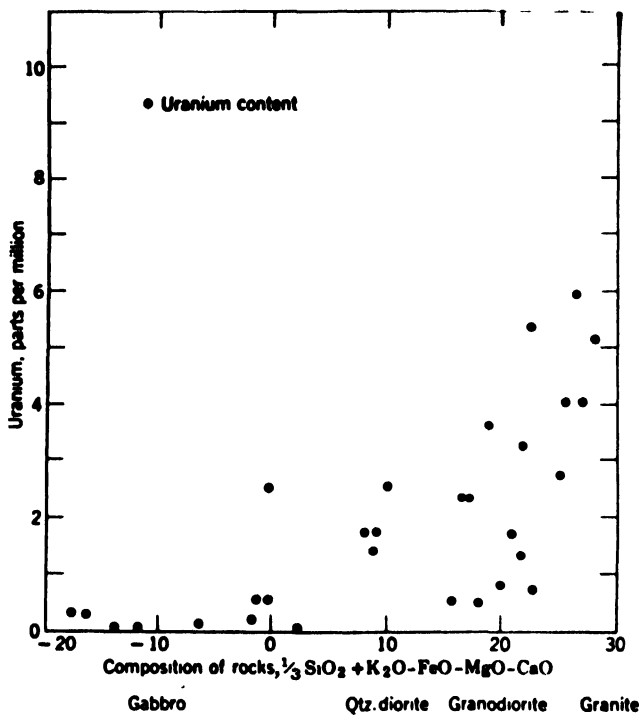


Figure 5. Uranium in rocks of the Southern California batholith (after Larsen, Phair, Gottfried and Smith, Paper P/17, Session 6B, this Volume)

Larsen and Phair[57] have indicated that not only end stage granitic rock, but end stage Ca–Mg rich rocks as well may show an increase in uranium. Since the original amount in the latter is low, presumably the total increment would be less.

An illustration of end stage concentration may be an unusual alkali-rich granite mentioned by Davidson (P/761) in northern Nigeria with 0.33% Nb_2O_5, 0.012% U_3O_8 and 0.03% ThO_2. The productive mineral is pyrochlore with 41.1% (Nb,

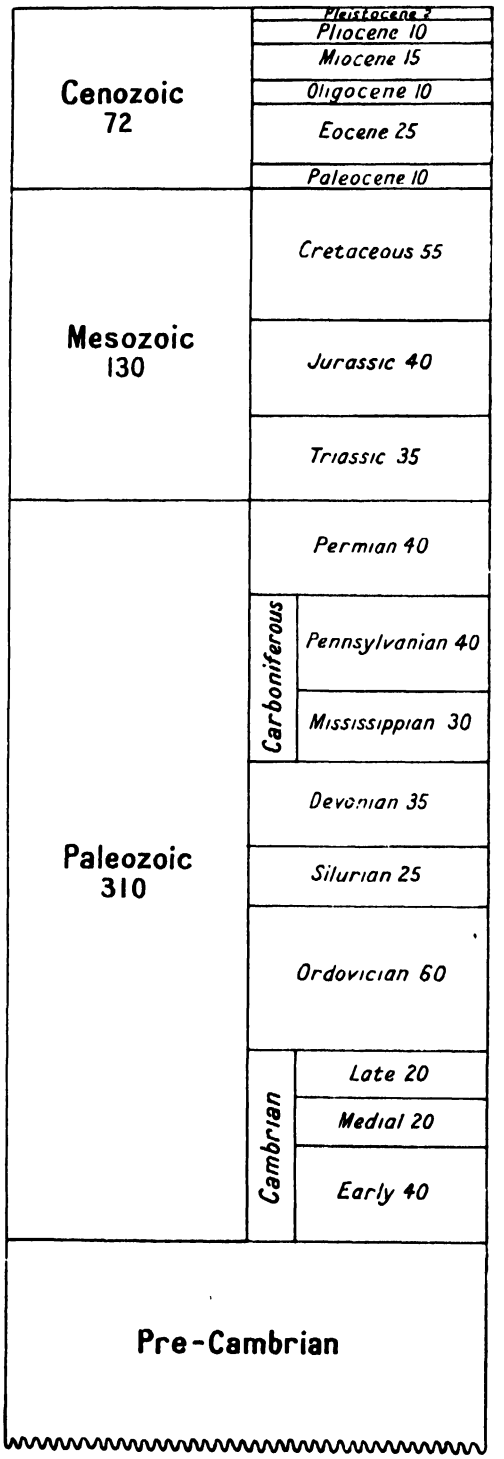


Figure 6. Geological time-scale in millions of years (after Kay[58] and Holmes[33])

$Ta)_2O_5$, 3.1% U_3O_8 and 3.3% ThO_2. The operation of the deposit depends upon the ability to successfully produce niobium.

Age of Deposition

Broadly considered, age data of two general types apply in geological interpretation. On one hand, there is a tremendous accumulation of information based primarily upon fossil evidence, but combined with stratigraphic correlation[38] which has been built up by painstaking programs of field and laboratory study (Fig. 6). On the other hand, there is the determination of absolute age which is based upon the laboratory application of various aspects of radioactive disintegration applied to specimens collected in the field. The first provides a relative sequence; the second more definitely supplies years.

The Colorado Plateau has long been an area in which the conventional program of matching fossils with strata has served to established the basis for establishing the age of stratigraphic units. The discovery of uranium in certain formations in greater abundance than in others has furthered an elaborate program of stratigraphic study to learn more about the nature or the ore-bearing formations in contrast to those formations which appeared to be barren or less extensively mineralized. As a result of these studies, much has been learned about the formational units of the plateau, the conditions under which they were deposited and the relative ages of the different formations.

As the ages of the various strata became better known and formations were more extensively compared throughout the plateau, knowledge of the distribution of uranium ore with respect to formational units advanced. Originally, ores were thought to be limited to one or two formations, but now the ores are known to occur in a number of units. Recently, Mitcham, Isachsen and Wood[35] indicated 15 formations of the Colorado Plateau (Table III) which have shown a uranium production of more than 1000 tons of ore. These formations range in age from Pennsylvanian to Tertiary and the widespread vertical occurrence is considered strong evidence for the emplacement of uranium from sources external to the strata involved.

The recent rapid evolution of laboratory techniques has made possible the determination of absolute age in a number of ways. Among the methods usually mentioned, the determinations of the lead-uranium ratios for specimens of uraninite or pitchblende from various well-known uranium deposits furnish age information of considerable interest. The entire subject is reviewed and many determinations are given in a text edited by Faul.[22] With a few exceptions, the absolute ages shown for a few significant deposits outlined in Table IV are from this text.

Notwithstanding the excellent progress which has been made in absolute age determinations, possible errors constitute a major factor in current study. One particular basic difficulty may also exist which requires clarification. Stieff and Stern (P/298) conclude that two types of lead are recognized in studies of uranium ores from the Colorado Plateau. One is lead derived since the uranium mineral was deposited and the other represents original radiogenic lead present at the time of deposition.

Many absolute ages determined on uraninite or pitchblende samples appear to be consistent with each other and also with established mineralogical and geological observations. For example, 10 age determinations of Shinkolobwe uraninite from the Belgian Congo by Nier[64] show a range of 582 to 676 million years with an average of 631 million years. Collins, Farquhar and Russell[13] give five determinations on similar samples from the same locality with a range of 612 to 655 million years and an average of 629 million years. Thus an age of some 630 million years would seem reasonable for Shinkolobwe uraninite.

On the other hand, Nier[64] records in addition to the above, determinations on two specimens, one containing an unnamed secondary mineral, the other curite, both of which at Shinkolobwe are commonly derived from uraninite. Ages given are in excess of 900 million years. Since it must be assumed that these specimens would be younger than the uraninite from which they were derived, and not older as given, the determinations were omitted from the average.

Robinson[76] has published a series of age determinations based up an extended study of specimens from the general region in the vicinity of the Beaverlodge development in Saskatchewan, Canada. Determinations reported include a considerable number of specimens collected on various levels of the Ace mine and represent different portions of the deposit.

As a result of this study, it would appear that the period over which mineralization must have taken place in the region is remarkably long, representing an interval on the order of 1300 million years. Age differences are found in the same deposit. Within the Ace mine on the basis of age determinations a pitchblende zone rich in chalcopyrite east of the mine shaft is considerably younger than another pitchblende-bearing zone west of the shaft.

Significant Mineralogical Features

Studies of uranium and thorium minerals emphasize several features important in the interpretation of natural occurrence. Major differences in regional distribution may be attributed to the character of the minerals formed by the two elements. Minerals resulting from the replacement of uranium-vanadium ores in the sedimentary strata of the Colorado Plateau are a measure of the degree of oxidation of deposits. The urano-organic association furnishes important data on the mechanism of emplacement of uranium in certain sediments. Rare earth complexes, containing uranium and thorium long thought to be mineralogical oddities, have emerged as important source materials. Uraninite, the leading uranium

Table III. Uranium-Bearing Rock Units of the Colorado Plateau

Period	Formation or Unit*	Total uranium production from unit	Depositional environment of host
TERTIARY	Monzonite Porphyry		Igneous Stock
	Browns Park fm.		Fluvial
	Bidahochi fm.	■	Lacustrine
	Uinta fm	■	Fluvial
	Wasatch fm	■	Fluvial
CRETACEOUS	Pictured Cliffs ss		Fluvial
	Mesaverde gr	■	Fluvial
	Dakota ss	■	Fluvial & Lagoonal
	Burro Canyon fm.		Fluvial
JURASSIC	Brushy Basin sh	■	Fluvial
	Westwater ss	■	Fluvial
	Recapture sh.	■	Fluvial
	Salt Wash ss	■	Fluvial
	Bluff ss		Eolian
	Summerville fm	■	Lacustrine
	Curtis fm.		Marine
	Todilto ls.	■	Lacustrine
	Entrada ss	■	Eolian
	Carmel fm.		Marginal marine
	Navajo ss.		Eolian
JRASSIC ?	Kayenta fm	■	Fluvial
TRIASSIC	Wingate ss		Eolian
	Chinle fm	■	Fluvial
	Shinarump cgl.	■	Fluvial
	Moenkopi fm	■	Fluvial
PERMIAN	Cutler (Big Buck) fm	■	Fluvial
	Kaibab ls		Marine
	DeChelly ss	■	Eolian
	Coconino ss		Eolian
	Hermit sh.	■	Fluvial
	Supai fm.		Fluvial
	Rico fm.		Fluvial
PENNSYLVANIAN	Hermosa fm.	■	Marine

Mineralized

Production under 1,000 tons

Production over 1,000 tons

* Rock units are shown in approximate time sequence

(After Isachsen, Mitcham and Wood, 1955)

Table IV. Absolute Age Determinations from Commercial Deposits on Selected Uraninite

Locality	*Age (years × 10^6)*	*Host rock*
Colorado Plateau		
Temple Mountain, Utah[22a]		
Camp Bird mine		
Urano-organic ore	80 ± 8	Triassic
White Canyon, Utah[22a]		
Happy Jack mine	42 ± 4; 65 ± 6	Triassic
Monument Valley, Arizona[22a]		
Monument No. 2 mine	70 ± 7; 85 ± 8; 100 ± 10	Triassic
Czechoslovakia[22b]		
Joachimsthal	220; 145	Paleozoic
Belgian Congo [22c]		
Shinkolobwe	630	pre-Cambrian
Canada		
Great Bear Lake[13]		
Eldorado mine	1400	pre-Cambrian
Beaverlodge area[13, 76]		
Ace mine	1820	pre-Cambrian
Martin Lake mine	1110–1670	
Eagle mine	1430–1700	

Table V. Selected Minerals of Uranium and Thorium

Oxides			
Uraninite (var. pitchblende)	UO_2	Thorianite	ThO_2
Hydrous Oxides			
Gummite	$UO_3 \cdot nH_2O$		
Becquerelite	$2UO_3 \cdot 3H_2O$		
Multiple Oxides			
Brannerite	$(U, Ca, Fe, Th, Y)_3Ti_5O_{16}$	Yttrocrasite	$(Y, Th, U, Ca)_2(Ti, Fe, W)_4O_{11}$
Davidite	$(Fe, Ce, U)(Ti, Fe, V, Cr)_3(O, OH)_7$	Zirkelite	$(Fe, Th, U, Ca)_2(Ti, Zr)O_5$
Silicates			
Coffinite	$U(SiO_4)_{1-x}(OH)_{4x}$	Thorite	$Th(SiO_4)$
Hydrous Silicates			
Uranophane	$CaO \cdot 2UO_3 \cdot 2SiO_2 \cdot 6H_2O$	Thorogummite	$Th(SiO_4)(OH)_{4x}$
Beta-uranotile	$CaO \cdot 2UO_3 \cdot 2SiO_2 \cdot 6H_2O$		
Sklodowskite	$MgO \cdot 2UO_3 \cdot 2SiO_2 \cdot 6H_2O$		
Hydrous Phosphates		**Anhydrous Phosphates**	
Autunite	$CaO \cdot 2UO_3 \cdot P_2O_5 \cdot 8H_2O$	Monazite	$(Ce, Y, La, Th)PO_4$
Torbernite	$CuO \cdot 2UO_3 \cdot P_2O_5 \cdot 8H_2O$	Xenotime	$Y(PO_4)+Th$
Hydrous Arsenates			
Zeunerite	$CuO \cdot 2UO_3 \cdot As_2O_5 \cdot 8H_2O$		
Carnotite	$K_2O \cdot 2UO_3 \cdot V_2O_5 \cdot 3H_2O$		
Tyuyamunite	$CaO \cdot 2UO_3 \cdot V_2O_5 \cdot 8H_2O$		
Hydrous Sulphates			
Zippeite	$2UO_3 \cdot SO_3 \cdot nH_2O$		
Uranopilite	$6UO_3 \cdot SO_3 \cdot nH_2O$		
Johannite	$CuO \cdot 2UO_3 \cdot 2SO_3 \cdot 7H_2O$		
Carbonates			
Schroeckingerite	$3CaO \cdot Na_2O \cdot UO_3 \cdot CO_2 \cdot SO_3F \cdot 10H_2O$		
Organic Compounds			
Urano-organic complexes— Thucholite (Carburan)	Mixture of hydrocarbon with U, Th, and rare earths.		

mineral found in multitudinous localities, provides a unique story of time relations and mineral genesis.

Extended reports on the minerals of uranium and thorium have been made by George,[30] Weeks and Thompson,[91] Gruner,[31] Frondel (P/302), Robinson,[76] and Weeks (P/295). A selected group of the more significant or common minerals of the two elements is shown in Table V.

Although thorium is more abundant as a rock constituent than uranium, there are only six distinct minerals known with thorium as an essential component (P/302). The common ore minerals monazite and xenotime are highly variable in thorium content. In contrast, about 70 minerals are significant for uranium. However, many minerals not listed as thorium compounds according to chemical formula, at times contain thorium as a vicarious constituent.

In the list shown in Table V, oxides and silicates are shown for both elements, but here the parallelism between the minerals of the two elements ends. Uranium is found in a wide variety of chemical compounds, whereas thorium shows a distinct affinity for rare earth oxides or phosphates and an antipathy to occurrence in the hydrous minerals. Even the parallelism in the case of uraninite and thorianite is only one of classification, since uraninite is an abundant uranium mineral, while thorianite as a source of thorium is either uncommon or rare.

Uraninite and Pitchblende

Although uraninite has been found in nature in solid masses of oxide reported to measure 10 feet across and to weigh 20 tons,[11] such occurrences are rare and specimens only inches across may be considered collector's items. Uraninite is the most widely reported of the uranium minerals. The mineral is ordinarily massive, although remarkable rounded (botryoidal) surfaces are occasionally found in openings along veins. The curved patterns due to this structure may persist even to microscopic dimensions and have been observed in pitchblende synthesized in the laboratory. The aggregates of crystallites may exhibit curved and rounded structures observable under the microscope although the crystallite dimensions themselves may be less than a micron.[76]

Pitchblende is considered in the seventh edition of Dana's "System of Mineralogy" as a finely crystalline variety of uraninite. It is suggested by Cohen,[12] on the basis of X-ray study, that the term be applied to aggregates of crystallites less than 10^{-3} cm in size. Robinson[76] points out that crystallite dimensions below 10^{-3} cm prevail in much of the vein material in the Canadian Northwest where the term pitchblende is generally applied.

Hoekstra and Katz (P/299) have studied the isotope ratios for various specimens of uraninite and pitchblende in an effort directed toward ascertaining the original temperatures of crystallization which prevailed in the veins at the time of origin. While various factors have as yet precluded reliable interpretations of original temperatures, several determinations have been obtained for calcite associated with pitchblende as a vein mineral.[76]

The evidence of fluid inclusions has also been applied in an effort to ascertain the temperatures of formation of Canadian pitchblende veins. The method[81] depends upon heating a specimen of vein mineral, usually either quartz or calcite, and noting instrumentally the decrepitation of the inclusions. Robinson[76] reports determinations on 10 calcite and 9 quartz samples by Haycock. These indicate a range in temperature of formation from 234°C to 371°C. After a review of the data available, Robinson suggests that the early temperatures of deposition for pitchblende in the veins may have been as high as 500°C, but apparently the bulk of the uranium deposition occurred between 250°C and 350°C. Some later pitchblende may have formed at 200°C.

Multiple Oxides—Brannerite and Davidite

As found in nature both of these minerals are believed to have suffered from auto-destruction. Distinct crystals with well-formed outlines of crystal faces, as illustrated by Bannister and Horne,[5] are internally devoid of regular atomic arrangement and fail to yield the usual X-ray diffraction patterns of crystalline material. Such minerals, which constitute a considerable group, are described as metamict. Brannerite and davidite are the only two metamict uranium minerals found in abundance.

The widespread distribution of brannerite through the Mississagi quartzite in the Blind River region of Ontario, Canada, and the occurrence of davidite as an ore mineral at Radium Hill in South Australia, have attracted attention to these two minerals.

The crystal structure of brannerite may be restored by heating.[67] This also applies to davidite and to other metamict minerals. The oxides of the major elements in brannerite as given by Trail[88] vary as follows:

Chemical Variations in Brannerite

TiO_2	32.4–39.0	Rare earth oxides including yttrium	1.1–6.5
U_3O_8	33.8 51.8	CaO	2.7–2.9
ThO_2	0.3– 5.0	FeO	2.4–5.4

Oxidized Uranium Minerals

Ellsworth[20] describes a specimen of uraninite from Villeneuve, Canada, in which the percentages of Pb, UO_3, Th, Ca, SiO_2, and H_2O increase with alteration, and U, UO_2 and rare earths decrease. Kidd and Haycock[48] noted a somewhat similar progressive oxidation in the pitchblende of Great Bear Lake. It is possible that the variation in the lattice constants of uraninite which are found by Kerr[39] to vary between 5.49 and 5.3857Å may be attributed in part to the influence of UO_3 on the UO_2 lattice. This may occur as a replacement effect.

A more obvious effect is the colorful replacement of black pitchblende by bright orange curite, green

torbernite, yellow autunite or other minerals as observed in uranium ores. The minerals produced by this change are generally considered to be formed in the zone of oxidation above the water table and are referred to as the oxidized uranium minerals.

As pointed out by Gruner,[31] secondary uranium minerals occur as relatively insoluble chemical combinations, particularly in arid regions. The acid sulfate radical, released by the solution of pyrite, profoundly influences its environment. Uraninite is easily oxidized to form uranyl (UO^{2+}) minerals which in protected places may become somewhat water-soluble basic sulfates such as yellow uranopilite, yellow zippeite and apple green johannite. These minerals, for example, form on the walls of drifts in the Happy Jack mine, Utah, where just enough moisture condenses to supply the necessary H_2O, but not enough to carry the uranium away as the highly soluble uranyl sulfate.

In the Happy Jack mine, if vanadium had been present in the unoxidized ores, it is likely that the more insoluble carnotite and tyuyamunite would have formed rather than the sulfates. In the majority of the Plateau deposits, vanadium is common, hence the basic sulfates are relatively rare in spite of the abundance of pyrite and its easy oxidation.

If no vanadium is present in the unoxidized ores, no oxidized uranium-vanadium minerals will be found. Under these conditions, the hydrous phosphates (autunite and torbernite) and the corresponding hydrous arsenates will form and probably will appear on or near the outcrops.

Schroeckingerite, the complex uranium carbonate, is precipitated as an efflorescent salt only near the surface at Lost Creek, Sweetwater County, Wyoming.[68] In a trench filled with water, Wyant[94] notes a concentration of the yellow mineral just above the water line.

In the Rum Jungle area of northern Australia, radioactivity has been found associated with a fluctuating water table which varies from the grass roots during the wet monsoon season to a depth of 200 feet[23] at the end of the dry season. Laterite formed by the tropical weathering of rocks containing aluminum and iron appears susceptible to the accumulation of radioactivity under such conditions. The hydrous iron oxide of the laterite is believed to adsorb uranium. Laterite areas have been observed to yield high radioactivity in contrast to other rocks in airborne surveys. Presumably, uranium previously dissolved from underlying rocks by the ground water is taken up by the laterite. While commercial deposits are not so formed, the mechanism is of interest.

Until 1952 the Salt Wash sandstone member of the Morrison formation had been considered to yield only carnotite and other oxidized minerals. At that time a mass composed largely of uraninite amounting to 1,000 lb. and assaying about 64% U_3O_8 was described by Rasor[74] from the Grey Dawn mine on the southeast flank of the La Sal Mountains near the Colorado line, Utah. A primary vanadium mineral was found associated with the uraninite, and both occurred in the Salt Wash sandstone. Ores in which the uranium is fixed in uraninite, and the uranium mineral coffinite associated with a vanadium mineral, are now found extensively in the Salt Wash sandstone (P/295). In such ores, the vanadium-uranium ratio varies from 15:1 to 1:1. The ore is almost without exception associated with coalified wood or other carbonaceous material.

The primary ores are stable in reducing environments and generally remain without change as long as they are below the water table (P/295). However, on the Colorado Plateau deformation of strata since the deposits were formed has frequently resulted in changes of position of individual deposits with respect to the water table. As a result, many deposits have been elevated above the water for a long time, and the processes of oxidation have changed the original uraninite, coffinite and associated vanadium minerals to carnotite. Study has shown that intermediate stages also exist in which other minerals form. In fact, the mineral assemblage of the ores in the Salt Wash sandstone has been found to furnish an index to the degree of oxidation.

Thorium Silicates

Frondel (P/302) has submitted a review of the mineralogy of thorium. While thorite ($ThSiO_4$) as a pure compound is readily synthesized, the composition of the natural mineral is greatly modified by the entrance of other elements into solid solution, notably U, Fe, Ca, rare earths and P. The mineral is also subject to secondary alteration which may result from loss of regular crystalline structure due to internal emission and absorption of alpha particles. This structural disintegration is accompanied by chemical alteration which includes hydration and some leaching of Si. No less than 14 different minerals described as distinct species are now known or suspected to be identical with thorite or its variant, thorogummite.

Uranium differs from thorium as it may occur in large amounts in hydrothermal deposits which form at relatively low temperatures. Large amounts of uranium can be lost during oxidation by solution in meteoric circulation, particularly in acid waters, whereas the primary compounds of thorium, being chemically stable and quite insoluble during the weathering cycle, tend to accumulate in detrital residues. Soluble salts of thorium hydrolyze readily to insoluble hydrous oxides.

Anhydrous $USiO_4$ does not occur in nature (P/302) and has not been synthesized in spite of repeated attempts, but the solid solution $(Th, U)SiO_4$ extends from $ThSiO_4$ toward $USiO_4$ up to at least Th:U = 1:1. However, the uranium mineral coffinite, although it presumably yields water on dehydration, may be closely related.[84]

Thorium Phosphates

There is a considerable contrast between the hydrous phosphates of uranium, autunite and tor-

bernite and the anhydrous phosphates of thorium, monazite and xenotime, which contain thorium as a variable constituent. The first occur as weathering products comparatively close to the surface and are destroyed by the processes of erosion. The second may occur in veins in igneous rocks from which they may be eroded, transported for many miles, and redeposited in placers. Small angular crystals which are found frequently in the placers indicate the resistant qualities of the thorium minerals. Both monazite and xenotime are characterized by high specific gravity, hardness, and general stability.

Urano-organic Mineralization

A subject of considerable interest is the association of uranium with lignite as in northwestern South Dakota; with petroliferous material as found on the

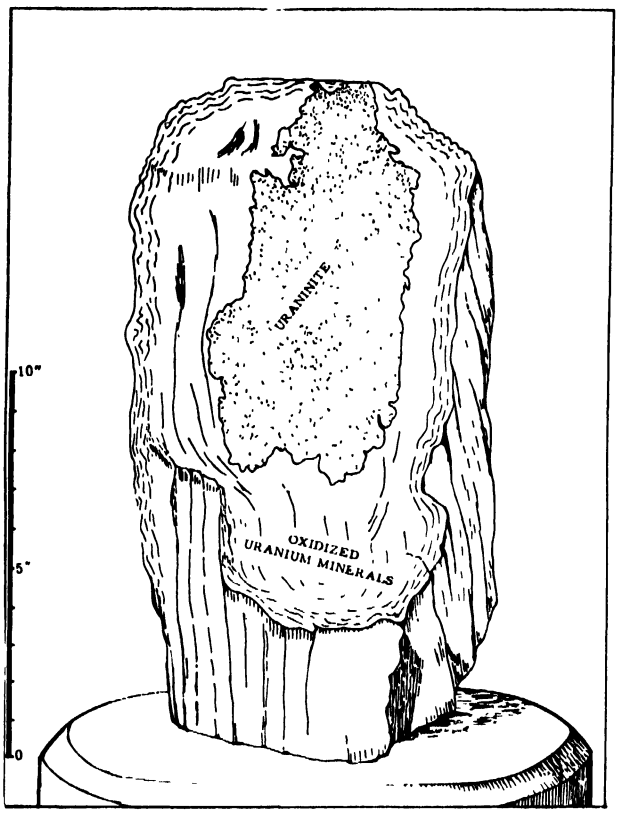


Figure 7. Uranium minerals in the form of a log. Originally a tree in Chinle time about 180,000,000 years ago, the wood was completely replaced by uraninite (UO_2). Much later, oxidized minerals were formed from uraninite still preserving the outlines of the log. An irregular core of uraninite remains in the center. Specimen data: length, 19 in.; weight, 103 lb; Delta mine, San Rafael Swell, Utah. Presented by Mr. Vernon Pick, sketch from a photograph supplied through the courtesy of the American Museum of Natural History

San Rafael Swell; with carbonaceous shale as in Tennessee; in coal as in Wyoming; together with the long established existence of the urano-organic mineral thucholite. Inorganic uranium minerals are also frequently found associated with plant debris in the strata of the Colorado Plateau. Remarkable replacements of fossil wood by uraninite (Fig. 7) and other uranium minerals are occasionally found.

Breger and Deul (P/49) conclude that uranium is not genetically associated with carbonaceous substances, but it is collected by these substances during its migration. It is essential for an organo-uranium association to have an external source of uranium, a transporting medium and organic matter. In areas of the Colorado Plateau, two masses of coalified wood in close proximity may be either uraniferous or non-uraniferous depending upon the course of uranium-bearing solutions. Aside from minute traces, uranium in petroleum is believed to be due to the ability of certain petroleum constituents to pick up and carry the element. Where large amounts of uranium are present in organic association, the relationship is abnormal and probably indicates addition from outside sources.

Thucholite

Thucholite, a synthesized mineral name proposed by Ellsworth[19] indicating the chemical constituents *th* (thorium), *u* (uranium), *c* (carbon), and *ho* (water) combined with *lite* as a mineral termination, was first recognized in the vicinity of Parry Sound, Ontario, Canada. It has since been reported in the hypogene vein deposits at Boliden, Sweden; Moonta Mines, South Australia; Isle of Man; near Deerfield, Saskatchewan, Canada; and near Placerville, Colorado. It is also found in gold-bearing conglomerates of the Witwatersrand, South Africa, and in similar strata near Blind River, Ontario, Canada.

Uranium-bearing hydrocarbons of the thucholite type occur as lenses and fracture fillings in a fault zone at Placerville, Colorado, and replace sedimentary rocks adjacent to the fault zone. The uranium of the veins is limited to masses of hydrocarbons and minor amounts of autunite and uranophane. Coffinite and pitchblende have been detected by X-ray study of hydrocarbon.

Chemical analyses of the ash of the hydrocarbon show a range in uranium content from 0.034 to 9.8 per cent. The elements chromium, cobalt, copper, molybdenum, nickel, lead, vanadium and yttrium which are consistently present suggest a relationship to oil rather than coal.

The association of the uranium-bearing hydrocarbon with base metal sulphide minerals (chalcopyrite, bornite, sphalerite, tetrahedrite-tennantite and galena) and with minor molybdenum and cobalt sulphides strongly supports the hypothesis that hydrothermal solutions were active in the genesis of the deposit.

MECHANISMS OF TRANSPORT AND DEPOSITION

The Role of Fluids

Earth temperatures and pressures become extreme with depth and experimental techniques are inadequate to furnish data to any considerable degree which apply below the crust. Classic studies of the effects of pressure on natural materials demonstrate that forces within the mantle, and even more so within the core, are adequate to make the hardest

rocks plastic. At the same time, the thermal gradient makes it possible to predict temperatures in the mantle and below that exceed the critical temperatures of liquids observable on the surface.

Knowledge of the fluids upon which one must depend to provide a conveying mechanism for uranium and thorium in the earth may be derived in several ways. Thermal springs, geysers, volcanic emanations, rocks ejected from volcanos, lava flows, and masses of plutonic rocks each provide a small quota of information which in the aggregate yields a total of considerable significance.

Molten magma poured out on the earth's surface in the form of lava or scattered as rock ash by volcanic explosions contains little more than traces of uranium or thorium. Even the normal granite masses exposed by erosion, although containing the most uranium and thorium of igneous rocks (P/17), yield only a general total of 16 ppm combined uranium and thorium (P/850, Session 14B, Volume 8 these Proceedings).

Within the earth's crust, the evolution of fluids from molten rock provides a mechanism of transport whereby metallic ions of various types may be removed from widely disseminated distribution and placed in a position for accumulation in deposits. As observed around vents yielding escaping gases and solutions, surface incrustations contain elements ordinarily associated with metallic ore deposits. This has been well illustrated by the studies of Allen, Zies and their associates of the Geophysical Laboratory made in the Valley of Ten Thousand Smokes after the Katmai eruption in Alaska.[1] The presence of uranium in the waters of a number of the geysers of Yellowstone Park was demonstrated by Schundt and Moore[80] in studies of the US Geological Survey.

One of the most significant uranium deposits from the standpoint of interpretation of fluid origin is located at Marysvale, Utah. Here, volcanic rocks in great profusion flowed out upon sediments along the western border of the Colorado Plateau in late Tertiary time. Both the flows and the sediments were invaded by intrusive masses, some several miles across. The area was partially eroded. Still later, outpourings of siliceous lava penetrated the earlier rocks. These lava eruptions were accompanied by an outpouring of thermal solutions some of which deposited uranium. Concentrations of pitchblende, along veins (Fig. 8) believed to be derived from these solutions, furnish deposits of uranium at Marysvale which have been mined since their discovery in the winter of 1948-1949.[40]

Veins at Marysvale are bordered by halos of clay minerals which formed by the interaction of the solutions with the wall rock. The solutions rose along fractures first reacting with the wall rock to form clay minerals and later depositing uraninite toward the more central portion of the conduit. Where vein conduits in their upward course encountered a barrier, in the form of a blanket-like siliceous flow which covers part of the area, the solutions spread out forming large areas of decomposed rock at the bottom of the blanket and in places penetrating fractures above. The deposits formed are among the most youthful of uranium deposits known; the absolute age as determined by Kulp, Bate and Giletti[50] is on the order of 10×10^6 years. The absolute age is in reasonable agreement with geological observations which would indicate that the wall rocks are late Tertiary and therefore the ore could be Pliocene.

Hot springs at the base of mountains to the north and northeast of Marysvale are radioactive in places. The erosional history of the region also indicates that at one time the lavas formed a cover several thousand feet above the terrain of the present surface at Marysvale. The Marysvale veins probably represent the roots of a pre-existing hot springs area the top of which has been removed by erosion.

Solutions rising from the earth's depths are generally believed to have temperatures of at least several hundred degrees centigrade. Allen and Zies[1] reported that fumarole temperatures in the Katmai region in 1919 ranged from less than 100°C to 650°C. Zies in 1929 reported mineral crusts formed at 500°C. Temperatures in deep oil wells, even in sedimentary basins remote from igneous activity, are frequently reported to be 175°C or above. The literature is replete with illustrations of mineral precipitation from heated solutions.

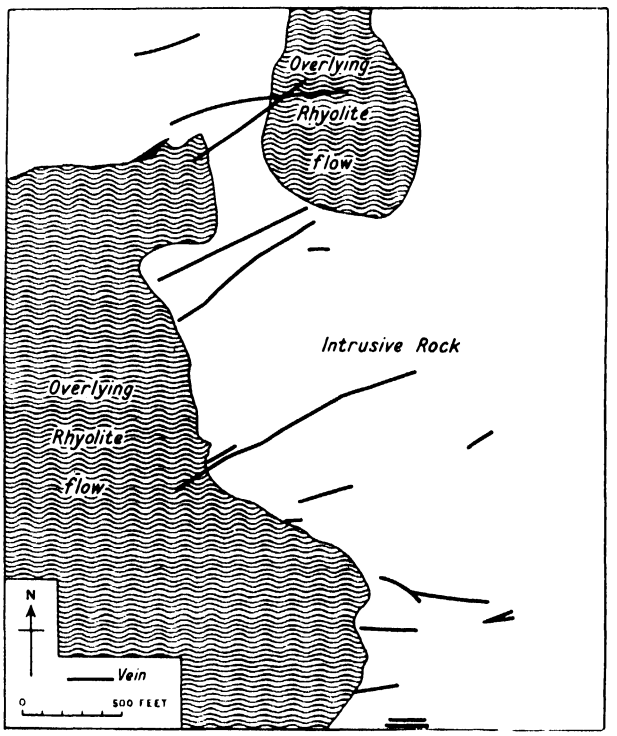


Figure 8. Vein pattern at Marysvale, Utah, USA (after Kerr, Braphy, Dahl, Green and Woolard).[40] Tertiary veins emplaced from solution

In contrast to precipitation from hot solution, many minerals may form by precipitation from cold meteoric waters. Several uranium minerals are particularly susceptible to this form of precipitation. In the Red Desert region of Wyoming, Wyant[94] has

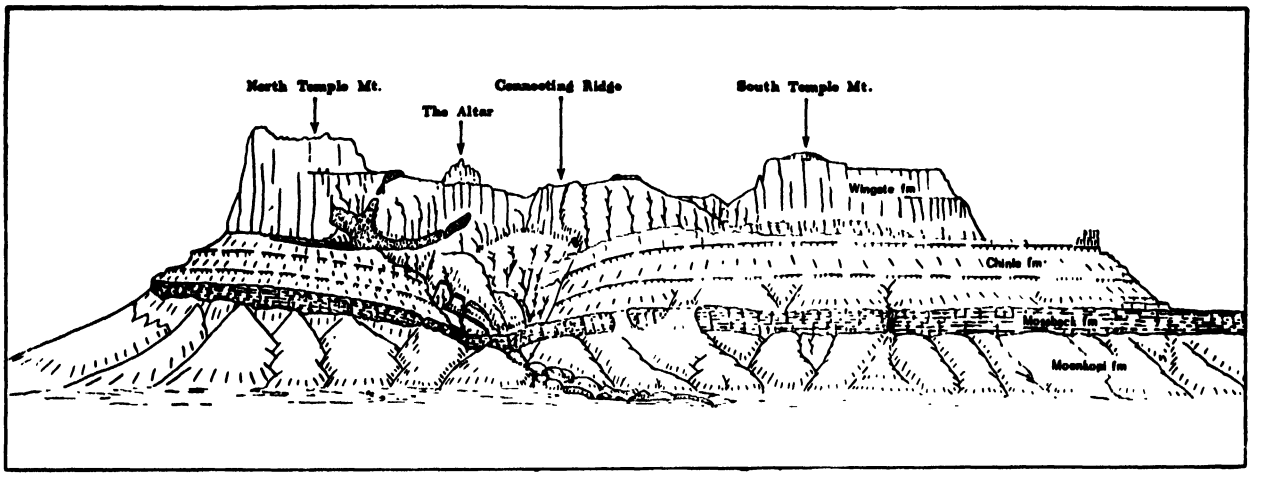


Figure 9. Solution effects at Temple Mountain, Utah, USA. The sag in the strata is attributed to collapse due to removal of calcium carbonate from below (Kerr, Kelley, Keys and Bodine)[41]

reported the formation of the uranium carbonate schroeckeringerite as a crust around the rim of a pond. Uranium-bearing pendants have also been observed hanging from the roofs of mine workings, contaminated by uranium-bearing solutions as the dripping and precipitating action forming the stalactites proceeded. In the zone above the water table, as shown in mines, uranium minerals are frequently dissolved from earlier formed deposits and reprecipitated. In fact, uranium minerals such as carnotite, tyuyamunite, autunite, torbernite and uranophane are generally considered by their presence to signify the action of ordinary surface solutions.

As fluids of magmatic origin rise, they may meet with ordinary ground water in varying degrees depending upon local conditions. In some areas where the magmatic activity is intense, the flow of heated solutions from below may dominate. In areas where magmatic activity is weak, or the center is remote, the effects due to rising solutions may be obscured by the prevalence of groundwater. This influences interpretation of the origin of urainum deposits.

The widespread distribution of magmas in the earth's crust constitutes a likely general source for uranium and thorium ions. If one overlooks the extent to which groundwater may have diluted magmatic fluids, the most readily available original source of uranium or thorium ions appears to lie in the final consolidation of magmas.

Solution Effects

Collapse Features

Near Temple Mountain in Utah, heated waters from below appear to have ascended through Triassic formations taking into solution along the way carbonate portions of otherwise siliceous strata. The solution of the carbonate strata appears to have created caverns into which large masses of overlying beds have collapsed.

The collapse features produced (Fig. 9) have been accompanied by a number of solution effects. In these it is believed that the solutions moved upward and that they were heated. One of the most convincing indications of upward transfer is the extensive leaching of calcium, magnesium and iron from the rocks of the Chinle formation below, and removal upward to be precipitated as a Ca–Mg–Fe dolomite and the iron carbonate siderite in sandstone of the Wingate formation above. In one instance, a great mass of highly siliceous Wingate sandstone is almost completely replaced by dolomite for a thickness of 200 feet. In fact, the replacement has been so complete in many places that silica of the Wingate sandstone has been almost entirely removed.[43]

The thermal character of the solutions may be inferred from the nature of the minerals and bleaching effects associated with the collapse feature. One of the most striking is the effect on petroliferous material found in the porous strata of the sandstones and conglomerates in the Temple Mountain area.

The Temple Mountain area lies on the east slope of a great anticlinal upwarp where permeable strata may contain a thin dried infiltration of petroliferous matter referred to in the field as "dead" oil sand.

As shown by analytical data, the dead oil sand does not appear to contain uranium in significant quantities. In the collapse area, however, and in horizontal strata for some distance away on either side, impregnation with uranium has taken place accompanied by the introduction of metallic elements which include sulphur, iron, arsenic, vanadium, lead, copper, selenium and zinc. Among the metallic minerals formed is native arsenic,[42] and other significant arsenic minerals are known to exist although they have not as yet been fully identified. Polymerization of the petroliferous matter has also occurred with the formation of hard brittle urano-organic material in contrast to viscous non-uraniferous tar found away from the ore. The brittle urano-organic material frequently replaces sand grains of the porous sediment in which deposits have accumulated.

Another feature noted in connection with the mineralization has been the effect of solutions on the clays and other silicate minerals in the strata invaded. Original clay minerals (kaolinite and illite) have been shown by microscopic study to have been

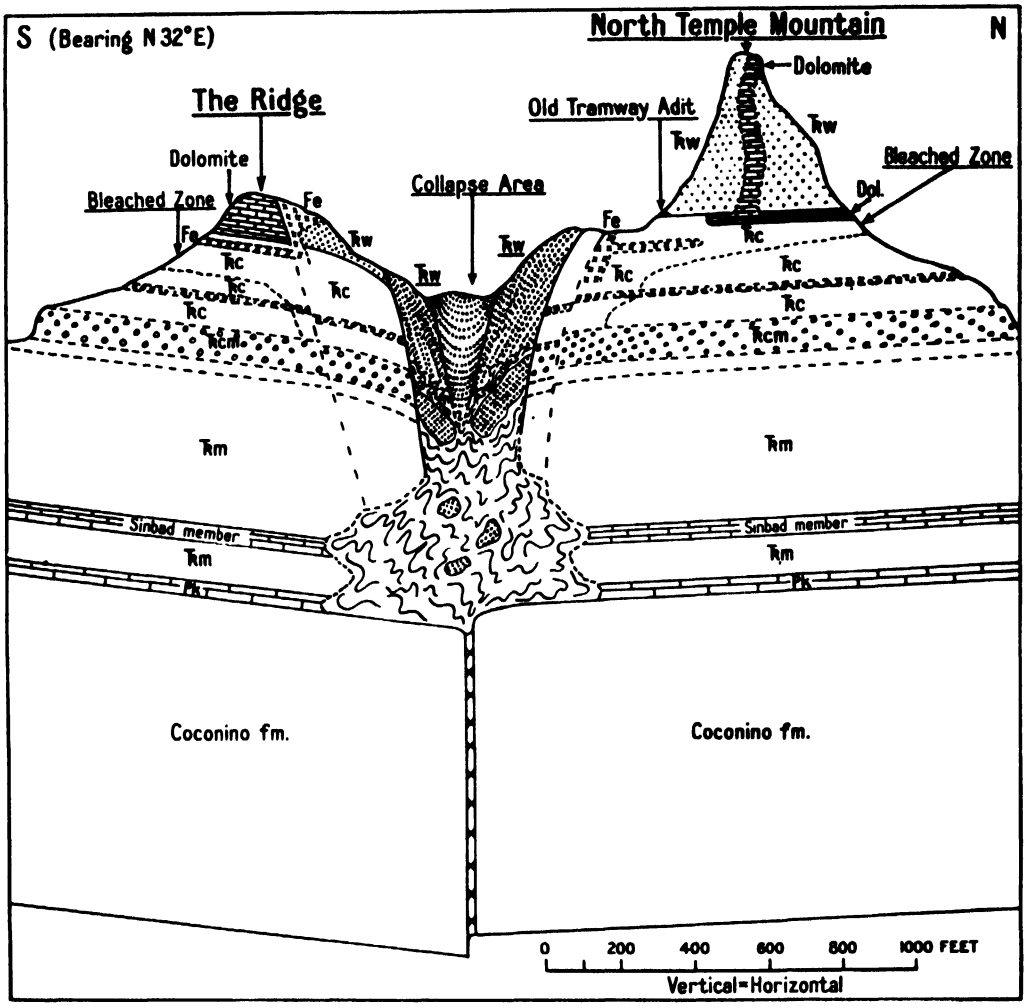


Figure 10. Section of Temple Mountain Collapse, Utah, USA. Heated solutions appear to have dissolved carbonate in rocks above the Coconino sandstone and caused the collapse of overlying strata (Kerr, Kelley, Keys and Bodine)[45]

dissolved and redeposited. Associated silicates have been altered and replaced by clay minerals. The activity may be noted in the field by a change in the color of the strata in the vicinity of faults along which solutions have had an opportunity to circulate and to spread out into permeable beds on either side.

Study of the collapse feature at Temple Mountain and others nearby has led to a drilling program the results of which have been described by Keys (P/41). Since the field study of the collapse features has led to the discovery of considerable dead oil sand in the Coconino sandstone known to underlie Temple Mountain, Keys, in planning his drilling program, undertook to test the top of the Coconino formation in its position beneath the mountain. This led to his discovery of ore at the top of the Coconino formation (P/41) apparently in the fragmental remnants of carbonate strata (Kaibab formation) immediately above the Coconino.

The general relationships in the area drilled are set forth in a cross section through a collapse feature showing strata from the base of the Coconino formation to the top of the Wingate sandstone (Trw) (Fig. 10). The formations above the Coconino in order are Kaibab (Pk), Moenkopi (Trm) and Chinle (Trc). Two members are also indicated: the Sinbad, a limestone in the Moenkopi, and the Mossback, a conglomerate in the Chinle. While ore distribution is not shown in the section, ore bodies have been reported at the Kaibab horizon, in the collapse, in the Mossback, at the Chinle—Wingate contact and in the Wingate. The diagram also shows zones of alteration or bleaching in the sediments, iron carbonate areas (Fe) and dolomite zones.

Discoveries to date demonstrate the presence of urano-organic ore at Temple Mountain in strata which represent stratigraphic differences of approximately 1500 feet. Such a vertical spread in deposition, the mineralogical evidence as outlined, and observation of the various alteration effects on the wall rock, indicate the emplacement of the uranium by rising heated solutions.

Solutions in Volcanic Vents (Diatremes)

Although the Colorado Plateau is generally looked upon as a large area of stratified sediments, it contains significant examples of igneous activity. The most noteworthy are igneous intrusives of the Henry

Mountains, the La Sal Mountains, the Abajo Mountains and other somewhat similar scattered intrusive masses. Also, in some areas, as on the southwest slope of the San Rafael Swell, numerous small dikes and sills are found. In northern Arizona and adjacent parts of New Mexico and Utah some 250 volcanic vents have been observed. These vents exhibit a somewhat restricted form of volcanism in which much of the broken and ejected volcanic material has fallen back into the crater where the eruption took place. They are known as diatremes.

Shoemaker (P/48) reports that diatremes are funnel-shaped and flare to a width of a mile or more where erupted on a surface of Pliocene age. At depths of 1000 to 2000 feet below they measure from a few hundreds of feet to half a mile in diameter. Diagrammatic sections and plans of eroding diatremes have been shown by Shoemaker (Fig. 11).

Shoemaker states that several uranium deposits occur in diatremes in a number of widely separated localities. The minerals thus far encountered are small pod-like concentrations of uranyl-vanadates and copper carbonates. The rocks of the diatremes, because of the eruptive forces involved, the number of diatremes to be studied, and the complexity of the deposition, present complex problems of interpretation. In one portion of the diatreme area, however, Shoemaker (P/48) points to the role of uranium-bearing solutions originating at depth.

Erosion, Transportation and Deposition

Once a deposit of uranium or thorium becomes part of the surface of the ground it becomes subject to the processes of chemical disintegration and mechanical transport. In general, uranium and thorium respond differently at this stage.

Thorium, as ordinarily found in nature, is less soluble, and, as pointed out by Lovering,[58] less subject to disintegration. Thus the processes by

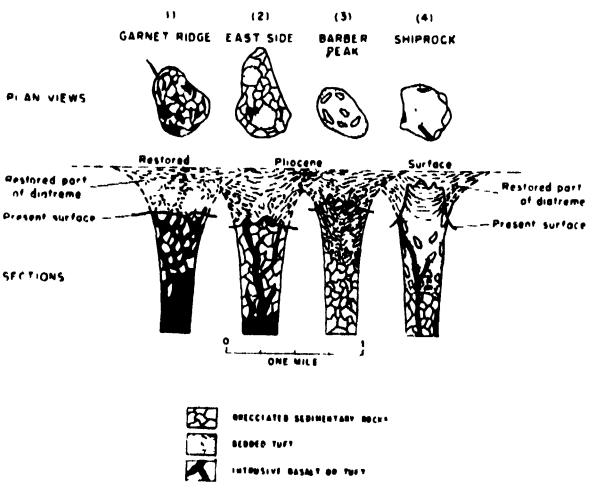


Figure 11. Volcanic vents on the Colorado Plateau, USA. Diagrammatic plan views and sections of four diatremes from the Navajo Reservation illustrating successive stages of subsidence (after Shoemaker, Paper P/48, Session 6B, this Volume). Eruptions have produced funnel-shaped forms which have been eroded to different levels

which thorium is transported and redeposited are essentially mechanical transfer and gravity accumulation. In Idaho, Mackin and Schmidt (P/305) have indicated how small crystals of heavy thorium minerals disseminated through parts of the mountainous Idaho batholith have been transferred by stream erosion and concentrated in detrital deposits at lower levels. The same principle of accumulation may apply to many of the deposits in India and Brazil.

In contrast, uranium, unless retained as a minor constituent of an unusually resistant mineral, is dissolved directly or broken into fine particles and dissolved. The products of solution, unless entrapped and precipitated, ultimately find their way through stream courses to the ocean. Thus the lack of records of detrital uranium deposits in recent sediments may be attributed to the chemical nature of the minerals formed rather than to lack of observation.

An exception, if it does exist, would be the uranium of the ancient sediments of the Blind River area in Canada and the Witwatersrand in South Africa. Considerable evidence exists, however, to indicate that even these are not exceptions and that the deposits have originated by precipitation rather than by detrital action.

Davidson[15] has investigated gold placers from various parts of the world in order to ascertain the effect of mechanical destruction during placer accumulation on the relative amount of uranium and thorium retained. The study has included gold placer concentrates from New Zealand, the Gold Coast, Sierra Leone, the Belgian Congo, Northern Rhodesia, Canada, Alaska, California, Idaho, Mexico, Colombia and the USSR. In the concentrates the mean radioactivity is low. The radioactive minerals identified are mainly monazite, xenotime, thorite, zircon or complex rare earth oxides. Uraninite was not reported and the uranium detected would be the small amount apt to be found in traces along with thorium. The radioactivity was found to be due essentially to thorium. On the basis of such a study, it is concluded that uraninite lacks the capacity of resistance to abrasion which would make it a placer mineral. Thus the presence of uraninite in ancient pebble accumulations such as the conglomerates of Blind River or the Witwatersrand is in itself evidence of precipitation from solution rather than deposition after mechanical transport.

TYPES OF URANIUM AND THORIUM DEPOSITS

Deposits Due to Heated Fluids

A large group of deposits is believed to have originated from heated fluids which probably vary from highly compressed vapors to ordinary hot solutions. Uranium and thorium ions taken into solution within the earth's crust terminate their ascent by precipitation in some favorable environment. Often the site of precipitation is a veinlet in a rock mass where uranium or thorium minerals fill fractures. In rare cases, a segregation of productive minerals in large masses may be found.

Occasionally, small crystals and fine particles may occur disseminated through wall rock.

The type of deposition may be influenced considerably by the depth within the earth's crust that precipitation takes place. Ancient rocks are apt to have been deeply buried during their penetration by solutions. Hence, deposits in such rocks show the effects of precipitation under pressure and at considerable temperature. Younger rocks are more apt to be permeable and to contain openings, but the pressures are less and the temperatures may be lower.

Deposits formed by heated solutions include the effects caused by residual crystallization of extracts from molten magma (pegmatites), disseminations in mixed crystalline rocks, and veins of various types. In the first two types, extreme pressure is a dominant factor, as indicated by phenomenal crystallization in pegmatites and by rock flowage accompanying mineralization as shown in mixed rock disseminations. The fractures and broken zones of veins, resulting from rock deformation, lack the solidity of a mass subjected to flowage under extreme pressure of the coarse crystallization of a pegmatite.

Residual Igneous Crystallization (Pegmatites, Migmatites, etc.)

Pegmatites represent remarkably coarse crystallization that follows the solidification of large plutonic rock masses. They are found in greatest abundance in the pre-Cambrian areas of the world. The fluids of the magma that remain after the main mass has solidified force their way along fracture planes into surrounding rocks and into portions of the main pluton already solid. In these natural traps, the physical and chemical conditions are ideal for crystal products. At the same time pegmatites are apt to be erratic in shape and distribution and are chiefly considered as sources of feldspar, lithium, beryllium, tantalum and columbium rather than uranium and thorium.

Pegmatite dikes yield attractive specimens of uranium and thorium minerals. Among the many hundreds of dikes known, only a few have offered the possibility of commercial development for uranium or thorium minerals. Exceptional pegmatites, suggesting possible commercial development, have been described at Charlebois Lake, Saskatchewan,[52,53] and Bancroft, Ontario, Canada.[70]

Pegmatite districts in the USA that show uranium and rare earth minerals are generally rich in potash feldspar. However, Page[69] reported that no pegmatites had been found rich enough to support an economic operation for uranium and thorium alone.

Recent developments in the Bancroft region[56] indicate uranium ore of possible commercial grade. A general description of the area has recently been furnished by Bateman[8] with geological features as outlined in Fig. 12. Satterly and Hewitt[79] have particularly described the rock types of the district with the mineral occurrences. Table VI gives a summary of radioactive minerals most commonly found.

At times residual fluids corresponding in many respects to the fluids which form pegmatites force their way along with portions of the unconsolidated magma into border rocks. The process occurs where pressures are great—well toward the bottom of the earth's crust. Later, after consolidation and the long process of erosion, such rocks ultimately become exposed at the surface. Many examples of so-called injected rocks (mixed rocks or migmatites) may be observed particularly in pre-Cambrian area.[7] Occasionally, mineral deposits are created in such areas. Uranium and thorium deposition found under such circumstances may have many of the characteristics of a pegmatitic occurrence, but it offers the possibility of more widespread distribution.

An unusual columbium-uranium deposit has been described by Rowe[78] which underlies the Manitou Islands and intervening spaces under Lake Nipissing, Ontario, Canada. Columbium and uranium occur in pyrochlore, a complex mineral which contains also Na, Ca, Fe, Mg, Zr, Sn, Th, Ti and Ta oxides, silica, fluorine and water. The deposits may represent bodies of considerable size from which columbium is recoverable with uranium as a by-product. Deposits appear as disseminations in a mixed assortment of metamorphic rocks which are high in carbonate as well as in alkali and calcic types. These rocks are presumably recrystallized old sediments. On the map of the district they encircle a diorite mass.

Large masses and crystals of a complex uranium oxide which is related to davidite have been described by Bannister and Horne[5] from Mozambique. These crystals may measure as much as a foot across. The deposits are complex in their geological relations, but, according to Davidson and Bennett,[16] are unlike pegmatites which are found in the same region. Lenses of ore occur along a shear zone in anorthosite, an unusually calcic host rock for a uranium occurrence. Davidite occurs in scattered crystals in a lens of calcite and more abundantly in a band of scapolite, a complex calcium silicate.

Radium Hill

The uranium mineral of the orebody at Radium Hill in Australia resembles the davidite of Tete, Mozambique and the brannerite of the Blind River area, Canada, since in each uranium is found in a metamict mineral of a type foreign to pitchblende veins. Such metamict minerals would be expected in pegmatites, yet the more recent field descriptions indicate that the ores are not found in pegmatites in any of the three localities. The two davidite occurrences, however, as described may represent a phase not far removed in terms of temperature and fluidity from the pegmatitic stage in the same way that quartz veins may frequently grade into pegmatites. For this reason, the Radium Hill occurrence is considered as being formed under higher pressure and temperature than that of a pitchblende vein; it formed toward the end, and probably below, the pressure-temperature conditions of a pegmatite or migmatite.

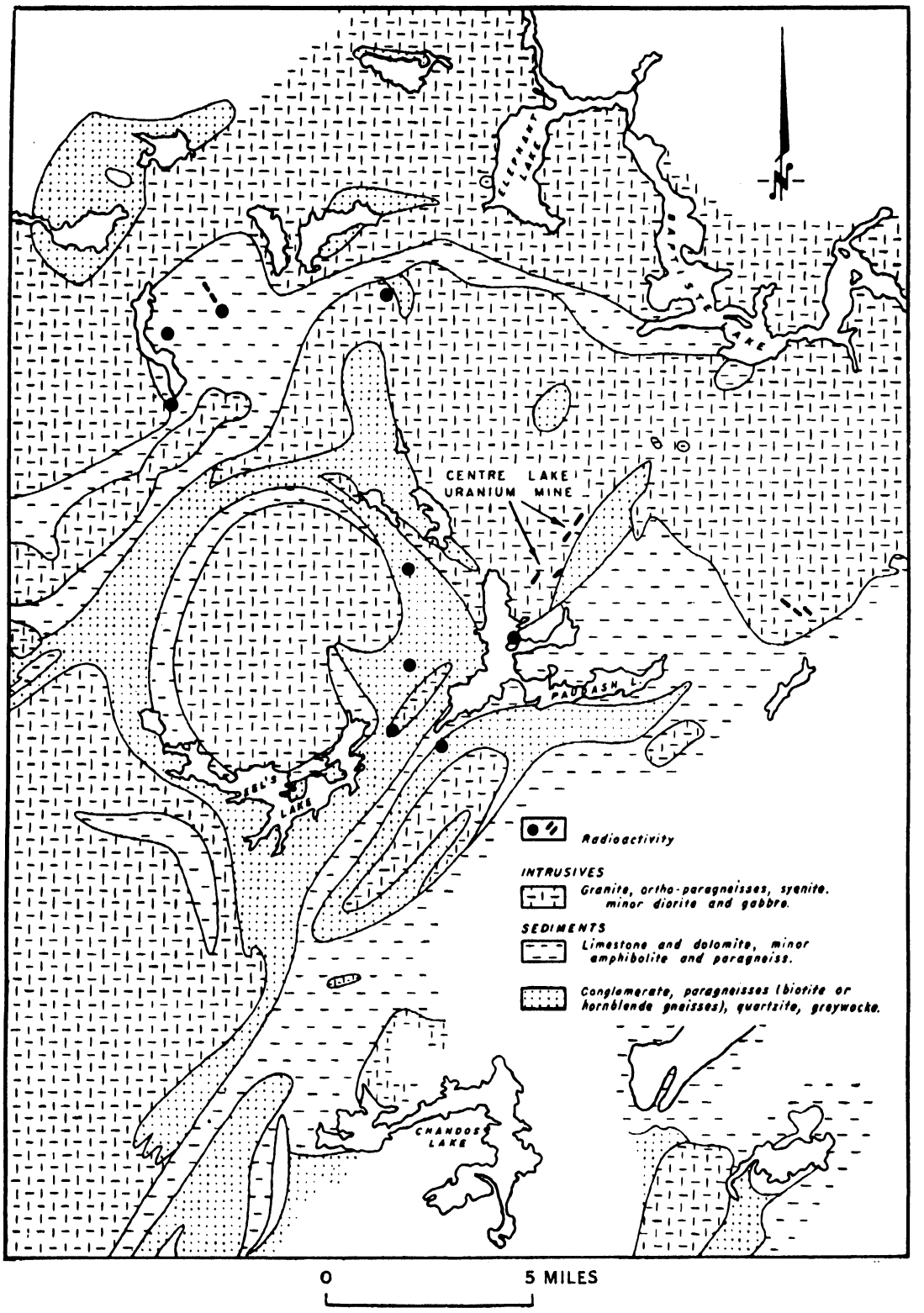


Figure 12. Pegmatite area, Bancroft, Ontario, Canada. Geological sketch map of the Bancroft area showing radioactive zones (after Batemam).[8] One of the pegmatite areas which is considered as a possible source of uranium

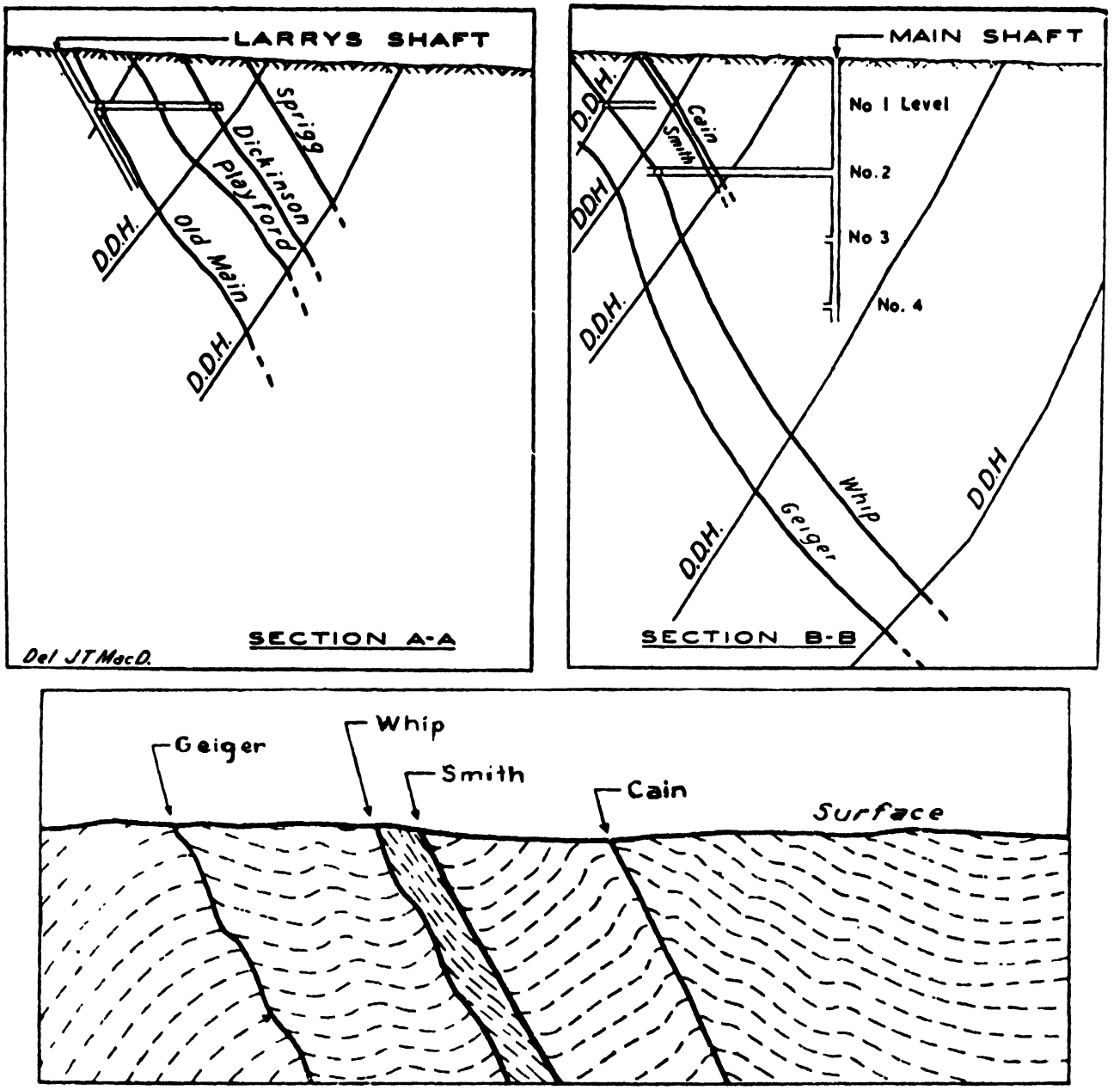


Figure 13. Sections at Radium Hill, South Australia. Above, the relationship of mine workings to uranium lodes. Below, structural relationship between lodes and anticlinal crests in the wall rock (after Parkin and Glasson).[70] Diagrammatic cross section looking north showing relationship of shears to folding

The mineralization at Radium Hill, as indicated by Parkin and Glasson,[70] occurs in fracture plane structures in pre-Cambrian sedimentary gneisses and igneous intrusions (Fig. 13). The structures are steeply inclined along somewhat curved planes and lie almost parallel with each other in an *en echelon* pattern. The bodies are described as lodes rather than veins, although they have the geometrical characteristics of nearly parallel veins. The lodes are distributed along shear planes which slice the crests of tightly compressed anticlinal structures which occur in the wall rock.

The orebodies consist of an intergrowth of bronze mica (biotite), titanium oxide (rutile), iron titanium oxide (ilmenite), iron oxide (hematite), silica in the form of quartz together with the uranium-bearing complex oxide, davidite. The main elements to be introduced are uranium, iron, titanium and magnesium. It has been suggested that the fluids responsible for this mineralization may have been related to the introduction of certain sodic dike rocks (aplites) which are prevalent in the area. These fluids appear to have followed the shear structures along the broken anticlinal crests where precipitation occurred.

Veins

Uranium veins represent fracture planes along which uraninite or pitchblende have been precipitated. The fractures are believed to form most frequently

Table VI. Common Radioactive Minerals of the Bancroft Area, Canada

Mineral	Main constituents	Maximum per cent U_3O_8	Maximum per cent ThO_2
Oxides and Silicates			
Uraninite	$UO_2 \cdot UO_3$	95	15
Thorite	$ThO_2 \cdot SiO_2$	–	82
Uranothorite	$(U, Th)O_2 \cdot SiO_2$	30	50
Columbates—Tantalates—Titanates			
Euxenite	$(Y, Ce)(Ti, Cb, Ta)_2O_6$	15	17
Polycrase	$(Y, Ce)(Cb, Ti, Ta)_2O_6$		
Pyrochlore	$NaCaCb_2O_6F$	20	5
Microlite	$(Na, Ca)_2Ta_2O_6(O, OH, F)$		
Yellow Secondary Alteration Products			
Uranophane	$CaO \cdot 2UO_3 \cdot 2SiO_2 \cdot 6H_2O$	60	3
Radioactive Accessory Minerals			
Allanite	$4(Ca, Fe)0.3(Fe, Al, Ce)_2O_3 \cdot 6SiO_2 \cdot H_2O$	2	6
Cyrtolite	$ZrO_2 \cdot SiO_2$	4	5

where rocks have been subjected to tensional stress. Sizes vary from veinlets of paper thickness to massive veins several feet across. As mined, veins are ordinarily groups of fracture fillings which in the aggregate constitute an economic unit.

Veins are found in a variety of rock types which include normal igneous rocks, recrystallized igneous or sedimentary rocks, and porous sediments. In age of emplacement the uranium mineral in veins may be as young as the uraninite from Marysvale, Utah (ca 10×10^6 years) or as old as pitchblende from the Ace mine north of Lake Athabasca, Canada (1820×10^6 years).

At least three general epochs of uranium mineralization have been recognized.[21]

1. Pre-Cambrian; Examples: Great Bear Lake, Lake Athabasca area, Montreal River (Canada), and Shinkolobwe (Belgian Congo).
2. Paleozoic; Examples: Joachimsthal and Johanngeorgenstadt (Czechoslovakia), Wolsendorf (W. Germany), Cornwall (United Kingdom), and Urgeirica (Portugal).
3. Tertiary; Mesozoic; Examples: Coeur d'Alene, Colorado Front Range, Marysvale (USA), and Carrizal-Alto (Chile).

A selected group of vein deposits in North America is shown in Fig. 14 based upon data by Everhart (P/20) and Lang.[52]

Silica in the form of quartz is seldom absent in uranium veins and is frequently a major constituent. Iron and sulphur are abundant as pyrite. Iron, however, may form ferric oxide which frequently causes a red stain along veins and in bordering rocks. Calcium fluoride as fluorite is an important constituent of some veins and represents a reaction product between fluorine in the vein forming fluid and calcium in wall rock along the vein conduit. Calcium carbonate may be present as calcite.

Several veins and groups of veins have furnished remarkable uranium deposits. A few of the more important examples will be mentioned briefly in an attempt to outline the salient features of uranium-bearing veins. Thorium-bearing veins will be briefly mentioned although thorium as a vein element has attracted less attention than uranium.

Older Uranium Mineralization (Veins)

Great Bear Lake

The most historic uranium-bearing veins in North America are located about 20 miles south of the Arctic circle on the east shore of Great Bear Lake in Northwest Territories, Canada. In the years which have elapsed since the deposits were first noted in an airborne reconnaissance by Gilbert LaBine and E. C. St. Paul in 1930, several excellent descriptions have been furnished by Canadian geologists. Among these may be mentioned an account of the early pitchblende and silver mineralization by Spence,[82] a geological study with an elaborate description of the ores by Kidd and Haycock,[48] a general account by James, Lang, Murphy and Keston[36] and a more recent summary by Lang.[52,53]

A series of nearly east-west veins cuts a pre-Cambrian complex known as the Echo Bay group (Fig. 15), The rocks of the Echo Bay group have been so altered by igneous invasion and hydrothermal processes since their formation that their exact original character has been largely obscured. In general, the group is considered to consist of materials originally fragmental volcanics, stratified sediments and igneous intrusives.

The veins are vertical or steeply inclined and are ore-bearing at least to a depth of 1800 feet as established by underground workings. Although small amounts of oxidized uranium minerals have been noted in thin films or coatings on fractures near the surface, the uranium has been found almost entirely in pitchblende.

Pitchblende occurs in forms characteristic of deposition in a colloidal state. The rounded botryoidal (grape-like) masses originally gelatinous typify sub-microscopic crystals which have formed con-

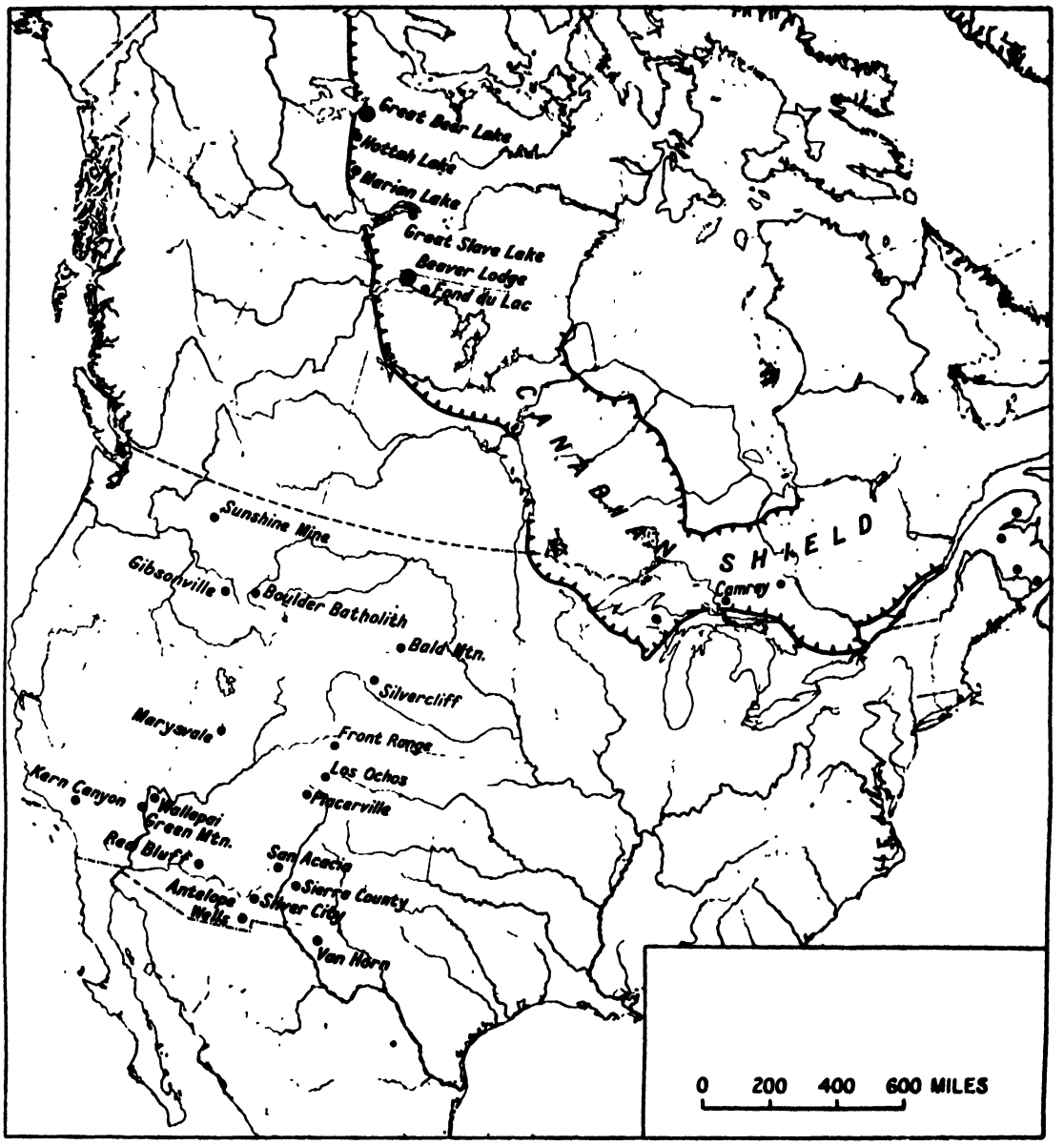


Figure 14. Major vein areas. Uranium-bearing veins, Canada and United States

centric aggregates. Several textures have been described signifying emplacement of the more or less colloidal pitchblende in fractures and as vein fillings. The openings in which the uranium mineral has been deposited resulted from rock shearing along minor fault planes. These pitchblende-bearing shear zones form the veins now mined and vary from a few feet to stockworks 40 feet thick.

Pitchblende was probably the first metallic mineral to be deposited, and it is said to occur in two types with different ratios of UO_2 to UO_3. These may indicate different surges of the uranium-bearing solutions with lapses of time between. Age determinations[13] indicate an age of 1400×10^6 years as the younger limit for the age of the enclosing rock.

At least 40 metallic minerals have been recognized in the pitchblende-bearing veins. These include various sulphides, oxides, arsenides and sulpharsenides as well as the native elements silver and bismuth. The metallic elements represented include Fe, Co, Ni, Mo, Cu, Zn, Pb, Mn, Ag, Bi, As and Sb. Studies of the decrepitation of quartz, a common vein constituent, indicate that the temperatures in the vicinity of the orebodies at the time of vein formation were probably greater than elsewhere along the veins.

A red iron oxide coloration of the bordering rocks occurs along the veins. Murphy[62] has attributed the color to the effect of silica and ferric oxide-precipitating solutions which existed early in the history of vein formation. These solutions were apparently most concentrated in the vicinity of the uranium-bearing zones. The coloration along the veins is useful in exploration as a guide to ore, but the vagaries of natural deposition are such that the color is not always indicative.

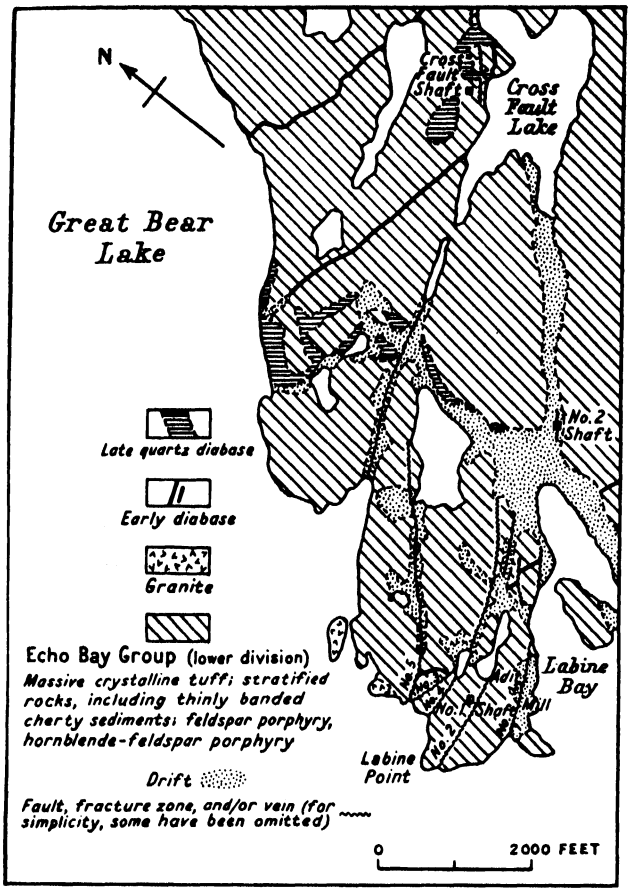


Figure 15. Veins at Great Bear Lake, Canada. Eldorado mine and vicinity, Great Bear Lake, Northwest Territories, Canada (after map by Jolliffe and Bateman, 1944, Lang).[52,53] Mining has followed the several veins shown on the map

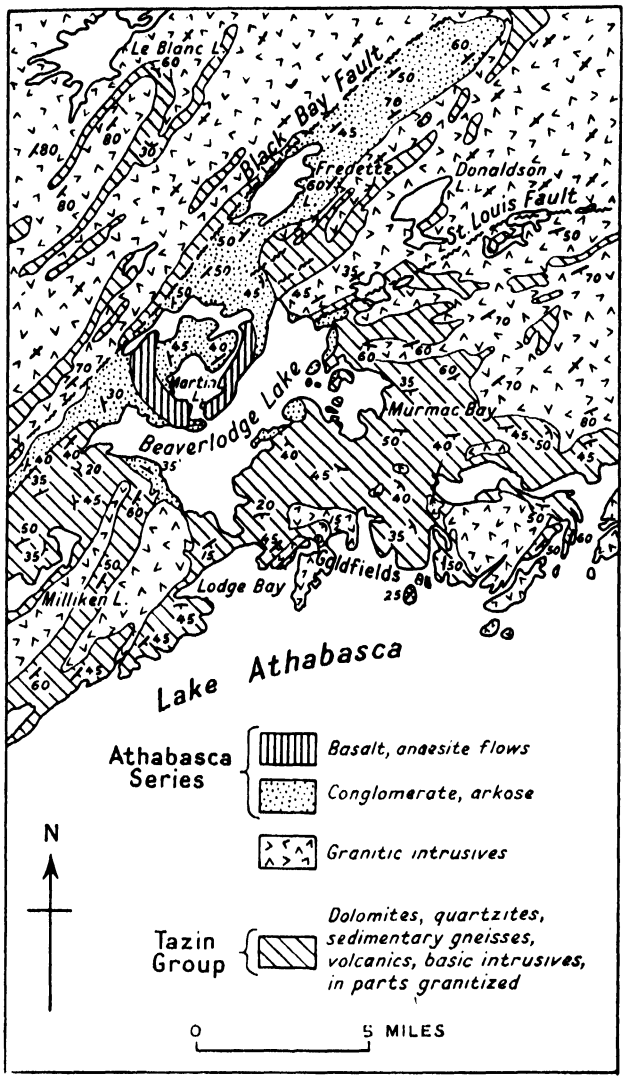


Figure 16. Beaverlodge Lake Area, Canada. Geologic map Beaverlodge region, Saskatchewan, Canada (after A. M. Christie-Lang).[52] Major mine development has occurred along the St. Louis fault

Ace Mine, Lake Athabasca

Within the last few years, an extensive uranium-producing district has been developed in the vicinity of Beaverlodge Lake just north of Lake Athabasca, Saskatchewan, Canada. Extending northeasterly from Beaverlodge Lake for a distance of at least 10 miles is the St. Louis fault. The fault may be traced across Ace Lake to Raggs Lake (Fig. 16) and is well marked along the surface by a broad trough which cuts an almost straight line across the rocks of the pre-Cambrian shield.

The St. Louis fault is inclined at about 50° to the south (Fig. 17) and marks a break between the Athabasca series of rocks which lies above the fault plane and the Tazin Group below. The uranium ore occurs as pitchblende in a network of small stringers which underlie and form a band within 200 feet of the fault plane.

The main surface showings were discovered by radioactivity surveys and cut with trenches. They were small and unimpressive as uranium prospects. The decision to institute a drilling program was based upon geological considerations, the most important reason being the proximity of the showing found to a regional fault and the fact that the rocks nearby were poorly exposed. The belt along the fault was explored to a depth of 300 feet by drilling amounting to 12,097 feet. The presence of two fairly large orebodies was suggested. These have since been placed in production (Fig. 18).

The original compositions of the ore-bearing rocks have been obscured by the processes of mineralization. Silica has been extensively distributed through the ore zone and an extensive zone of red coloration, presumably consisting of hematitic alteration, has been developed.

Within a radius of 15 to 20 miles encircling the Ace mine, some 48 uranium concessions have been explored by underground operations and diamond drilling. For the most part, the occurrences consist of pitchblende-bearing fracture zones. In a number of instances, workable deposits have been found.[52-56]

Robinson[76] has furnished a comprehensive discussion of the emplacement of uranium in the veins north of Lake Athabasca. The main precipitation of vein minerals is believed to have taken place between 250°C and 350°C. On the basis of the prevalence

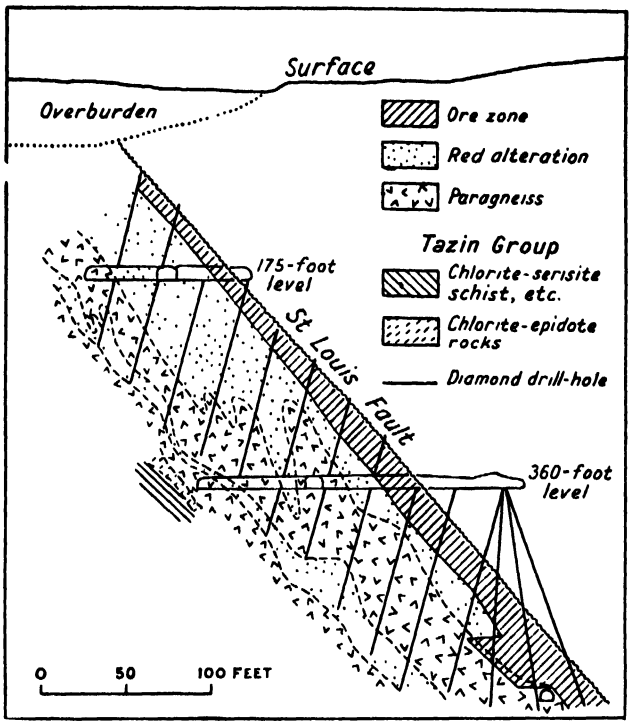


Figure 17. Vertical section of Ace Mine, Saskatchewan, Canada (after R. B. Allen, Eldorado Mining and Refining (1944) Limited, Lang).[52] The ore body occurs in a zone of veinlets on the under side of the St. Louis fault

of calcium carbonate in the viens and solubility experiments in which pitchblende was dissolved at 200°C and 180 psi with CO_2 and steam, it is suggested that carbonate solutions were active in the formation of the deposits. Spectrographic determinations and chemical analyses indicate the presence of 20 elements in addition to uranium in the veins.

Among the elements in the veins Si and Al are derived largely from the wall rock and crushed wall rock fragments in the veins. Iron is largely present as Fe_2O_3 (hematite) although minor amounts of pyrite and other iron-bearing minerals are found. Calcium is preponderately present as a carbonate and Mg, Fe, Mn, Sr, Ba and V are found in carbonates as well. Rare-earth elements are present, but in minor amounts. Copper is a major constituent as $CuFeS_2$ (chalcopyrite) although native copper and a number of other copper minerals are reported. Vanadium is fairly abundant and in the Ace mine appears to increase in quantity with depth. Lead is believed to be essentially due to the auto-disintegration of pitchblende and not to introduction in the vein-forming solutions. Selenium is present in addition to sulphur as indicated by the presence of PbSe (clausthalite).

As a result of careful collecting and numerous absolute age determinations, Robinson[76] suggests that there may have been three well-defined periods of uranium mineralization in the Athabasca region.

1. 1400–1600 $\times$ 10^6 years. This introduction followed sparse uranium and thorium distribution in pegmatites and other deposits of the region in which the deposition of the radioactive elements coincided wth the formation of the enclosing rock (epigenetic).
2. 850–950 $\times$ 10^6 years. Pitchblende of this generation as found in the veins is predominately found in rounded or concentric forms (colloform).
3. 230–350 $\times$ 10^6 years. The pitchblende of this age group is entirely massive.

Gunnar Uranium Deposit

The Gunnar uranium deposit on the Crackinghouse Peninsula of the north shore of Lake Athabasca, Canada was discovered in the summer of 1952. The

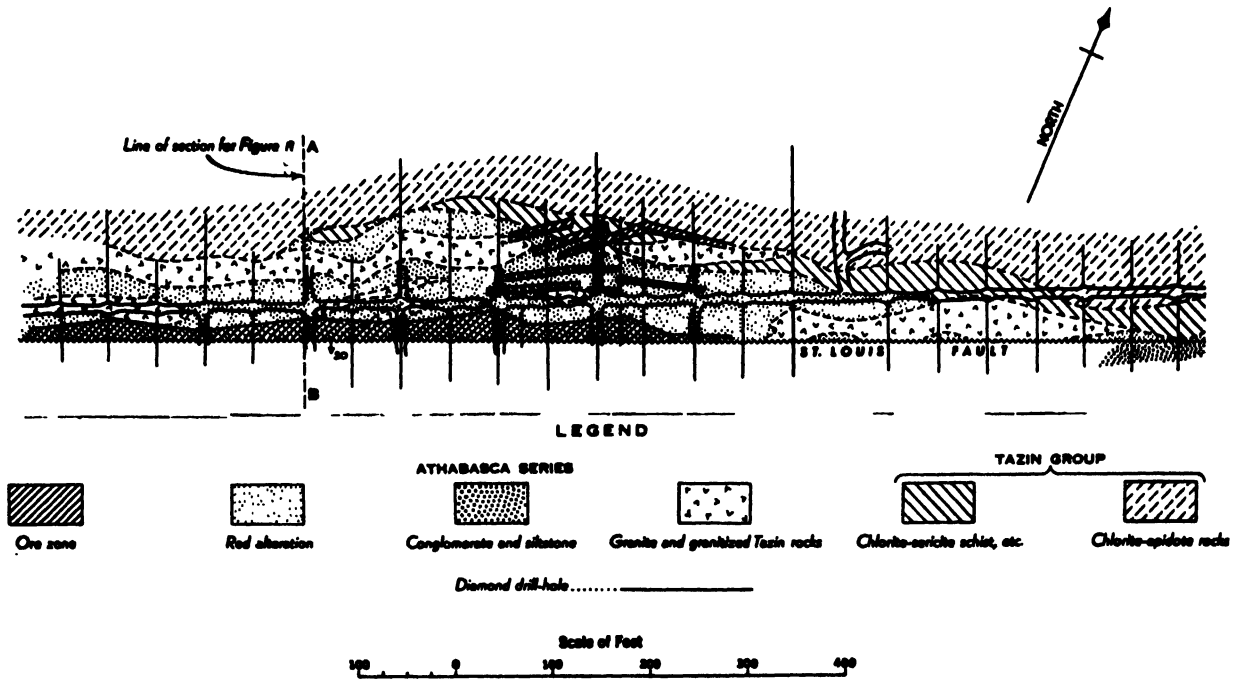


Figure 18. Part of one level in the Ace Mine. The section (Fig 17) cuts across the ore body shown on the mine level (after Lang)[52,53]

deposit lies in an area of pink granite-gneiss considered by Fraser[27] to be among the oldest rocks of the Canadian Shield (Archean or Proterozoic).

The rocks in which the uranium ores occur (Fig. 19) have been subjected to an involved sequence of genetic events. The prevailing formation in the district has been mapped as granite-gneiss, a recognizable field unit.[27] The ore, however, occurs in a somewhat different rock type described by Fraser and Robinson[28] as an albite monzonite. Both rock types retain banded structures and textures suggestive of old sediments. In fact, it is stated that the reworking of old sediments by magmatic melting and subsequent recrystallization may have been involved in their original formation.

The ore occurs in an irregular more or less rounded zone 200 to 600 feet wide and 1100 feet long. Uraninite and uranophane yield uranium and are disseminated through somewhat porous zones in the monzonite. Local high-grade ore zones are related to highly broken areas or zones of brecciation in the monzonite. Rare stringers also carry high grade pitchblende and iron oxide.

Uranophane (hydrous calcium uranium silicate) is developed as a secondary mineral because of the effect of weathering on the primary uraninite. At a depth of 400 feet uranophane accounts for about one-third of the value of the ore. On the other hand, the lower limit of surface oxidation is irregular. This may be attributed largely to the effect of the muskeg which covered a large part of the surface of the deposit when it was discovered.

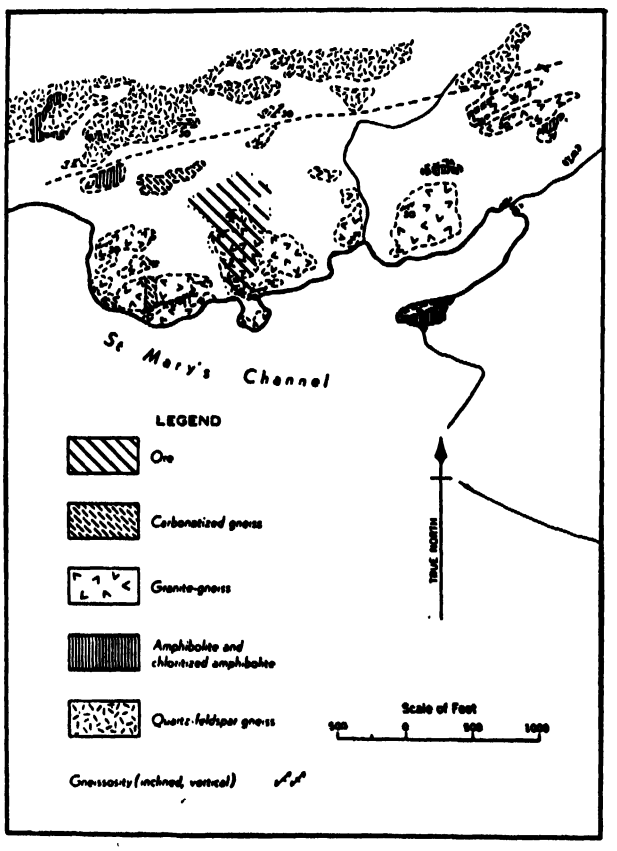


Figure 19. The Gunnar uranium deposit, Canada. The deposit lies in an area of finely fractured granite-gneiss (Fraser and Robinson)[28]

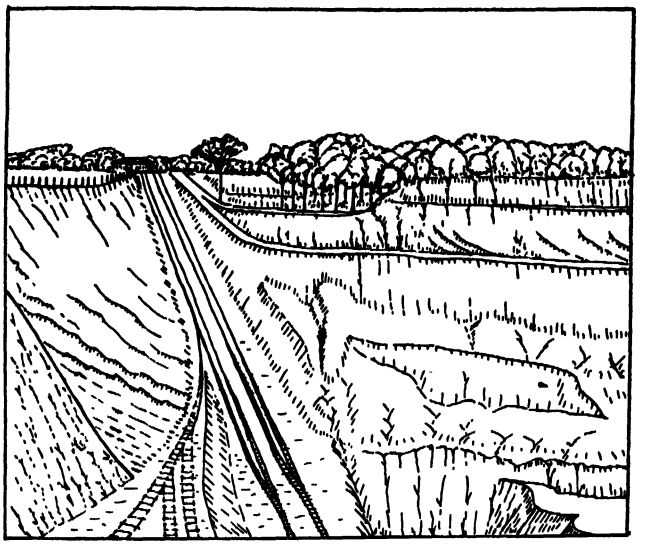


Figure 20. Open pit at Shinkolobwe, Belgian Congo. The rocks in the background belong to the pre-Cambrian Kundelungu System. In the immediate foreground strata are also pre-Cambrian but belong to the Mines series (after Nininger)[65]

Porosity of the wall rock at Gunnar may have been increased by the solution of previously introduced carbonate minerals. Pore spaces and an intricate system of fractures appear to have provided channelways through which heated uranium-bearing solutions migrated and deposited pitchblende.

The suite of minerals developed by the rising uranium-bearing solutions is comparatively simple. In addition to pitchblende, it includes the carbonate minerals calcite and dolomite, the iron-magnesium silicate chlorite, iron oxide as hematite, and traces of the iron, copper and lead sulphides pyrite, chalcopyrite and galena.

On the basis of information available, it would appear that the Gunnar deposit might properly be considered as a disseminated pitchblende deposit in an igneous rock. The essential difference between Gunnar and the other deposits in the region north of Lake Athabasca appears to lie in the local distribution of the ore rather than in the mechanism of emplacement. At the Ace mine, and in other deposits to the east, the distribution is in veins although even at the Ace the veins may consist of a network of veinlets where many small fractures have been filled in a zone. The term "concentrated shear zone" may be utilized to distinguish this more or less elliptical assemblage of veinlets from the more usual elongate pattern of other deposits in the general region.

Shinkolobwe

The uranium deposit at Shinkolobwe is located in the Belgian Congo 11° south of the equator and about equidistant between the two sides of the African continent. Uranium minerals were first discovered at the locality in 1915. Operations for radium began in 1921 and continued for a 15 year period during which time some 100,000 tons of radioactive

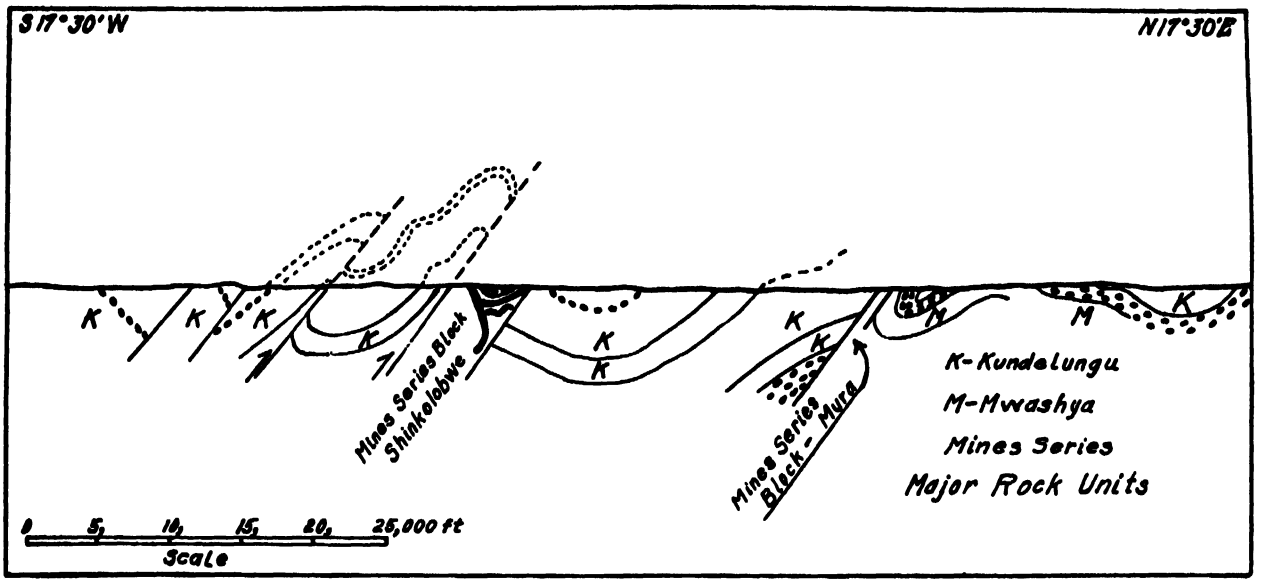


Figure 21. Regional structure at Shinkolobwe, Belgian Congo. The section extends for 22 km along a line N 17° 30′ E which cuts the heart of the Shinkolobwe mine area (after Derriks and Vaes)[18]

ores were extracted before the mine was closed in 1936. Selected high-grade ore was shipped to the radium refinery at Oolen, Belgium.

Operations were resumed in the open pit (Fig. 20) with the objective of mining uranium in 1944, and the following year mining was continued underground. During the decade of active operation which has ensued, the geological staff of the Union Minière du Haut Katanga has made a careful study of this most remarkable mineral occurrence as set forth in a comprehensive report by Derriks and Vaes (P/1105) submitted to this Conference. This report forms an excellent supplement to the earlier comprehensive study of the Shinkolobwe deposit by Thoreau and Terdonck.[85]

Shinkolobwe is situated along the western margin of a broad northwesterly trending arc of folded and faulted pre-Cambrian sediments known as the Katanga synclinorium. The arc is some 200 miles long and in the center 65 miles across. In addition to uranium, several significant copper deposits together with other metals, the most important of which are cobalt and zinc, occur in this belt.

The ancient rocks of the region have been subdivided into a large number of detailed units found important in the guidance of mining operations. In general, and particularly in the vicinity of Shinkolobwe, two broad divisions are recognized. A younger system, the Kundelungu, consists of brown and yellowish old sediments, once consisting largely of clays, sands and some pebble beds, but since then recrystallized to argillites, various quartzitic and micaceous schists and conglomerate. The older, the Mines series, consists of a sequence of carbonate rocks which exhibits an unusual sequence of recrystallized rock types resulting from the action of heated solutions.

A section showing the regional structure in the vicinity of Shinkolobwe (Fig. 21) exhibits faults and overturned folds, all cut by a comparatively horizontal line of surface erosion. At Shinkolobwe several important factors were involved in creating a major deposit. The coincidence of faulting brought the older rocks of the Mines series to the surface. Rock fracturing provided conduits for the migration of mineralizing solutions. Favorable host rock appears to have accelerated precipitation. Above all, the presence of heated solutions rising from below and carrying an abundance of metallic ions provided the uranium and associated metals.

A mineralized band of the Mines series is exposed at the surface between two broad masses of the non-ore-bearing Kundelungu system. A schematic diagram indicating the mechanism of emplacement has been shown by Derriks and Vaes (Fig. 22). The overlaying Kundelungu system is shown in section on either side, the rocks of the Mines series being in the center. Solutions responsible for depositing uranium ores have ascended along broken zones, accumulating particularly in a moderately inclined zone of concentrated deformation referred to as the *nappe*.

Mining at Shinkolobwe has proceeded from the surface to below the 350 meter level. During the first period of mining, as described by Thoreau and Terdonck,[85] the minerals were largely of the oxidized type. In the lower levels, however, and particularly below the water table, the minerals found have been mainly pitchblende and associated metallic sulphides.

The mineral associations of Shinkolobwe are remarkable. Some 30 mineral species have been recognized here for the first time. Including the new species, 67 minerals are considered significant in the description of the deposit. Uranium minerals found include 4 oxides, 9 uranates, 4 urano-silicates, 7 urano-phosphates, 4 urano-carbonates and a urano-

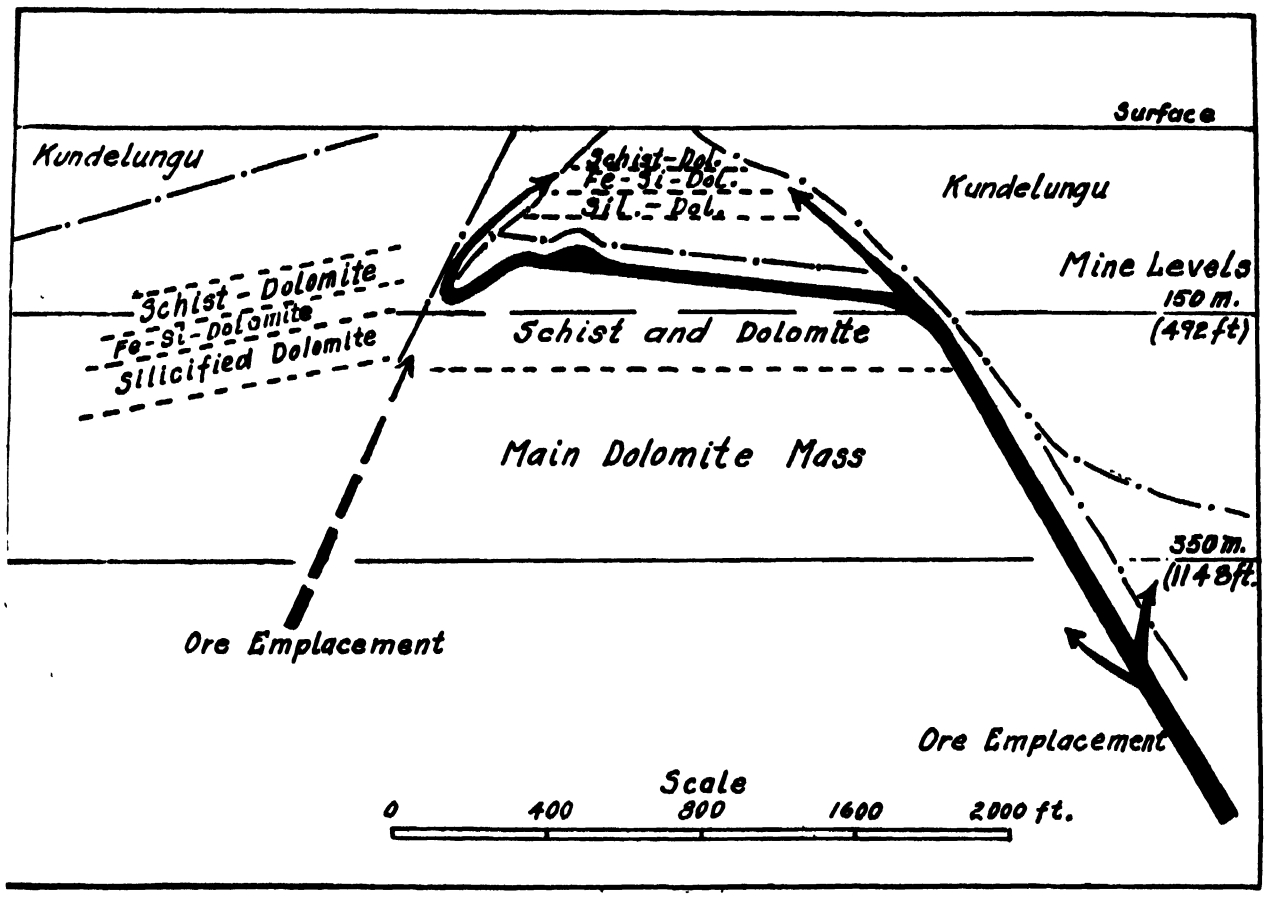


Figure 22. Diagram of ore emplacement at Shinkolobwe. The rise of ore-bearing solutions is indicated in a longitudinal section with concentration along faults and in an irregular layer or nappe (after Derriks and Vaes, Paper P/1105, Session 6B, this Volume)

molybdate. At least 11 of the oxidized minerals contain substantial amounts of lead presumably derived from the auto-disintegration of uraninite.

In the lower workings, unusual sulphide associations have been encountered. The common occurrence of CoS_2 and NiS_2, each with the crystal structure of pyrite FeS_2, and both minerals associated with uraninite is unique. The cobalt mineral, cattierite, and the nickel mineral, vaesite, have also been found with selenium substituting for sulphur.

The minerals of uranium are distributed in masses, along veins and veinlets in fractures, in seams and along planes of stratification, and at times are even disseminated in strata of the lower part of the Mines series. At depth, the deposits are composed in part of massive uraninite and in part of uraninite mixed with cobalt and nickel sulphides. The uraninite is crystalline and frequently occurs in cubes, a distinct contrast to the botryoidal form frequently observed in pitchblende at Great Bear Lake and Joachimsthal. Exceptional cubes have been found at Shinkolobwe that measure 4 cm along an edge.

Near the surface, uraninite is replaced by the numerous oxidized uranium minerals. In many cases, the uraninite may be observed to have been replaced *in situ*, the entire mass of a vein consisting of oxidized minerals. Elsewhere, the migration of solutions along fractures has distributed the oxidized uranium minerals as colorful brown, yellow or green veinlets.

Monazite is found in small crystals along veins and also in masses. As shown in microscopic study, veinlets of monazite may be observed that penetrate uraninite and hence are believed to have crystallized later.

The magnesium carbonate, magnesite, is abundant in the deposit. On the 255 meter level, it is veinlike in form and constitutes a white mass 50 to 60 meters across. It replaces the dolomite and is believed to have crystallized before the sulphide veins.

The solutions responsible for the deposition of the ores at Shinkolobwe are believed by Derriks and Vaes to have originated at depth and to be related to igneous activity. The principal metals deposited in order of importance are uranium, cobalt and nickel. Nickel in particular shows an affinity for uranium in the deposit. The sequence of events involved in the mineralization has been summarized in five phases. It would appear that the first phase in mineralization was the formation of the magnesite vein and the crystallization of magnesite in the dolomite. The second main phase was the crystallization of the uraninite. In a third phase, selenium and molybdenum were introduced, monazite was crystallized and parts of the Mines series were replaced by Mg-Fe mica (chlorite). A fourth phase was the formation of cobalt and nickel sulphides and a fifth, the introduc-

tion of copper. As described, the entire deposit furnishes a striking example of the emplacement of uraninite in carbonate rocks.

Joachimsthal (Jachymov), Czechoslovakia

The historic veins of Joachimsthal and nearby localities have been mined intermittently for centuries. During the period 1527–1533, Georgius Agricola served as city physician at Joachimsthal. In his book "De Re Metallica," translated by Herbert Hoover and Lou Henry Hoover, is a sketch of a stamp mill used to crush the ore from the mines and introduced a few years previously.

The uranium in the veins provided an early source of radium, but through the years the veins have been mined for lead, silver, nickel, cobalt and bismuth. The Erzgebirge, as the region has long been known, contains localities which lie along two zones which intersect at Joachimsthal.[4] One zone extends along a N-S line from Freiberg through Marienberg, Annaberg, Niederschlag, Joachimsthal, Schlaggenwald, St. Viti and Hagendorf to Wolsendorf. The other zone extends along a northwesterly line from Schneeberg through Johanngeorgenstadt to Joachimsthal and beyond.

Veins are formed along fractures and appear to vary considerably in thickness while also exhibiting changes in mineralization. Uraninite is the principal uranium mineral. Associated minerals in the veins include native silver, bismuth, cobalt-nickel minerals and sulphides of zinc, copper and lead.[21] Large portions of veins are suitably thick or grouped for mining.

At Joachimsthal, the wall rock which appears associated with the highest grade mineralization is schistose pre-Cambrian sediment. In some of the mines, as the veins cut granite at depth, it has been inferred that uranium values diminish. The granite is said to be late Paleozoic in age (Fig. 23).

The Erzgebirge area is a region of considerable size with many mines and a number of individual deposits. The veins appear to have been formed by precipitation from rising heated solutions. Red coloration is associated with the uraninite in places as in the Canadian deposits although hematite is not a common mineral in the veins.

Zükert[95] made a microscopic study of 200 samples of bismuth, silver, cobalt-nickel and pitchblende ore. Two mineralization periods were distinguished.

The first mineralization includes traces of hematite, native silver, native bismuth, pitchblende, niccolite, galena, sphalerite, arsenic and white cobalt-nickel arsenides. The second period of mineralization consists of replacement of the cobalt-nickel arsenides, native bismuth, native silver, and niccolite by a group which includes bismuth and silver minerals, carbonates, quartz and copper minerals. Several different generations of pitchblende are recognized.

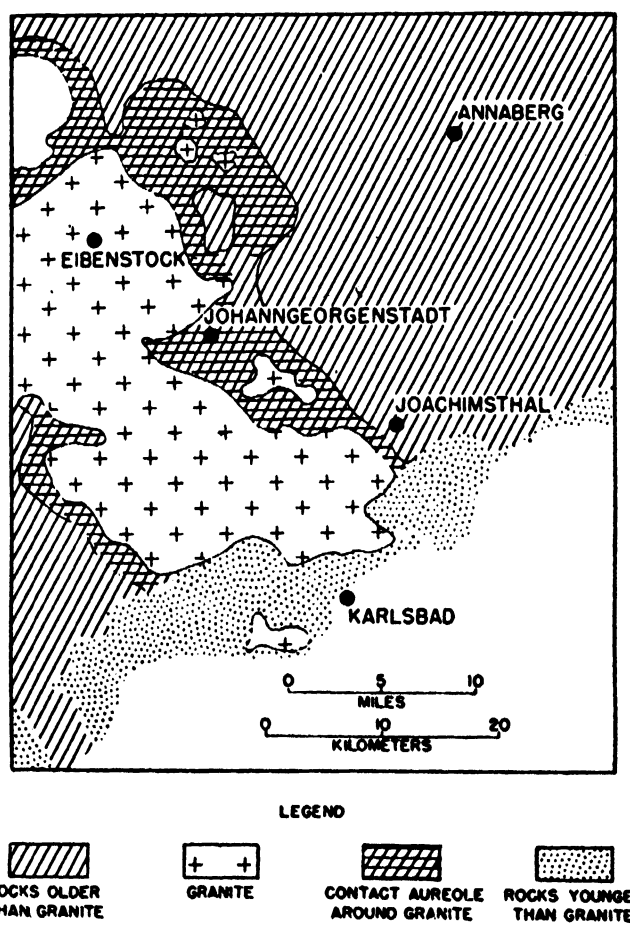


Figure 23. Uranium district, Joachimsthal, Czechoslovakia. Various deposits occur in or near the Eibenstock granite (Everhart and Wright)[21]

Younger Uranium Mineralization (Veins)

At least 23 veins are known in the USA in which uraninite or pitchblende emplacement occurred during, or slightly before, the Tertiary (P/20). At the Los Ochos mine, Saguache Co., Colorado, Derzay (P/285) has described a vein occurrence of pitchblende along the Los Ochos fault (Fig. 24). The fault cuts the Salt Wash member of the Morrison formation (Jurassic) and the younger Cretaceous formations, Dakota and Mancos, as well. The vein is comparatively narrow in underlying pre-Cambrian granite, but considerably wider in the porous Salt Wash sandstone. The mineralization is at least later than the Salt Wash.

McKelvey, Everhart and Garrels (P/300) refer to a mean age of 60.5×10^6 years for pitchblende found in veins of the Front Range deposits in Colorado. The pitchblende-bearing veins at Marysvale, Utah, as indicated by Kulp, Bate and Giletti[50] appear to be considerably younger ($10 \pm 2 \times 10^6$ years).

The Cordilleran region of the western USA is a region in which Tertiary and somewhat older mineral deposition has long been recognized for metallic elements other than uranium. It is also a region in which correspondingly youthful forces of deformation have been active. Thus in many places in the region in Tertiary time, fracture systems have been provided which probably extend to considerable

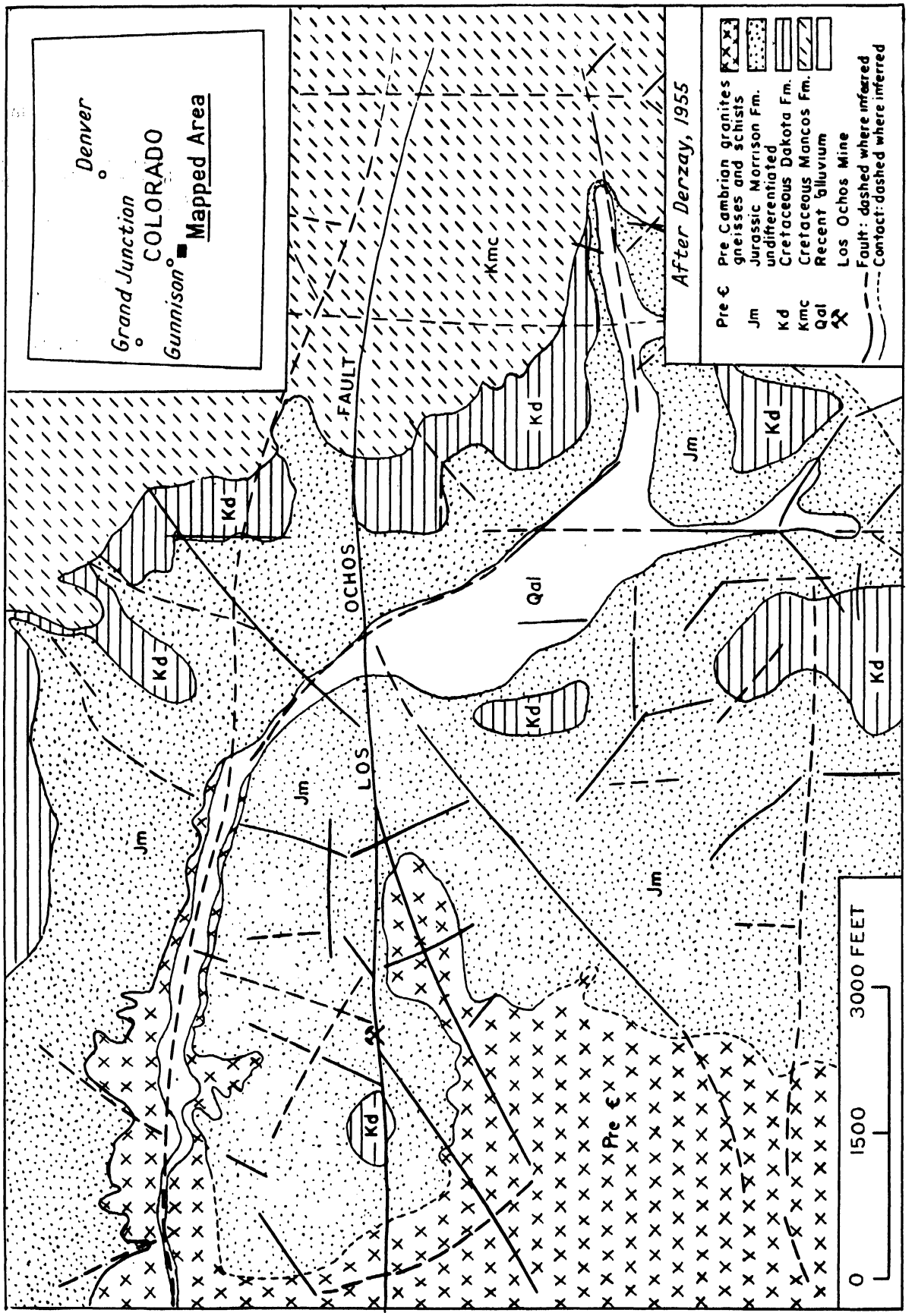
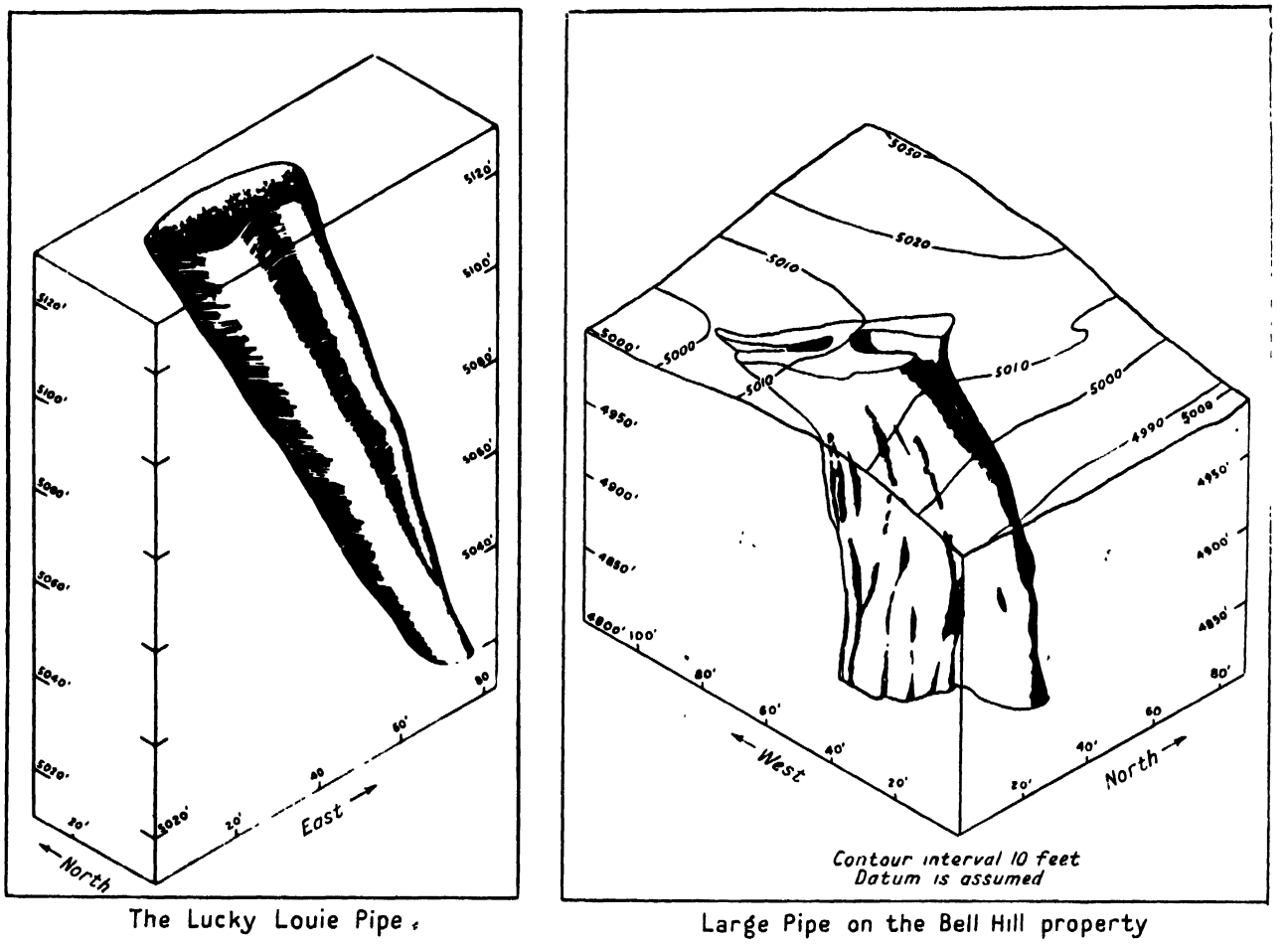


Figure 24. Vein along a post-Cretaceous fault. At the Los Ochos mine, Colorado, USA, pitchblende is found along a fault which cuts both Jurassic-Cretaceous strata and pre-Cambrian granite (after Derzay, Paper P/285, Session 68, this Volume)



The Lucky Louie Pipe

Large Pipe on the Bell Hill property

Figure 25. Uranium-fluorite deposit, Thomas Range, Utah, USA. Uranium-fluorspar pipes (after Staatz and Osterwald, Paper P/23, Session 6B, this Volume). Vein intersections in dolomite produce a pipe-like deposit in which uranium occurs in intimate mixture with fluorite

depths, and, at the same time, heated solutions carrying uranium have been available to form deposits.

The veins formed exhibit distinct differences from the older vein types of the Canadian Shield and elsewhere. Clay minerals and sericite are common in veins and along vein walls. Oxidation with the development of secondary minerals is on the whole more abundant. Vein zones and their environs show less evidence of consolidation since mineralization took place.

Veins bearing pitchblende and base-metal sulphides are found in Golden Gate Canyon, Colorado. The uranium occurs in a carbonate matrix in veins which cut metamorphic rocks of pre-Cambrian age. The veins, however, fill extensive faults of Laramide (earliest Tertiary) age. The precipitation of pitchblende has depended upon favorable wall rock and occurred only in places where the veins cut hornblende gneiss (P/24).

The hornblende gneiss is high in ferrous iron while biotite gneiss nearby contains much less iron. It is thought that alteration of the hornblende released ferric oxide and contemporaneously uranium was deposited as pitchblende. Base metal sulphides and the bulk of the carbonate vein filling were deposited after the pitchblende (P/24).

The Sunshine mine in the Coeur d'Alene contains silver-bearing carbonate veins and earlier silicified portions which contain pitchblende.[45] But an age determination by Kulp of 750 $\times$ 10^6 years suggests that Sunshine pitchblende may be pre-Cambrian[44] and represent an earlier phase of mineralization.

Contact Deposits

Two deposits are described by Thurlow (P/27) in which mineralization appears to be concentrated in small fractures in border rock along an intrusive contact. Although confirmatory age data are lacking, it would seem likely that the emplacement of these deposits would agree with the younger vein group.

Uranium occurs in an argillite series in contact with granite on the Spokane Indian Reservation in northeastern Washington in the USA. Diamond drill cores show the presence of uraninite and pyrite at depth (P/27). Autunite and meta-torbernite were mined at the contact. Mineralization extends 40 feet into the argillite series and 25 feet into the granite. Although the original mineralization appears to have occurred in the argillite, it may be related to the granite magma.

A contact deposit is reported from Lander County, Nevada, where uranium minerals occur in fractures

along a contact between a quartz monzonite intrusive and bordering metamorphosed sediments consisting of hornfels, quartzites and phyllites. Autunite and meta-torbernite are associated with fine grained siliceous dikes, vein quartz and iron oxides in an area of intense silicification.

Uranium-bearing Fluorite Deposits

Radioactive fluorite deposits occur on Spors Mountain in the western part of the Thomas Range, Juab County, Utah (P/23). The amount of uranium in 155 fluorite samples was found to range from 0.003 to 0.33 per cent.

The deposits are found in dolomite of middle Silurian age. Structurally the deposits form oval to irregular pipes (Fig. 25), veins and disseminations. The major deposits are the pipes which vary considerably in size. The pipes are adjacent to faults or to intrusive breccia bodies. In many instances, the pipes become smaller and lower grade with depth. Uranium is secondarily enriched near the surface due to leaching from upper parts of the deposits and redeposition below (P/23).

The formation of the fluorite is attributed to fluorine-rich fluids containing minor amounts of uranium which rose along faults and shattered zones. It is suggested that uranium was originally dispersed throughout the fluorite, perhaps within the crystal structure. Fluorite-forming fluids were probably derived from the same source which yielded abundant topaz in the rhyolites of the eastern half of the Thomas Range (P/23).

Uranium in Ancient Sediments

Blind River Area, Canada

Uranium occurs in ancient ore-bearing sediments in the vicinity of Blind River, north of Lake Huron, Ontario, Canada. The sediments lie at the base of the Mississagi quartzite which in turn rests upon an eroded basement of granite and gneiss. Both sediments and basement are pre-Cambrian, sediments being classed as Huronian and basement as pre-Huronian.[37]

The ore is found in a firmly cemented conglomerate consisting largely of quartz pebbles. Surrounding the pebbles is a matrix consisting, for the most part, of iron sulphide but containing disseminated grains of radioactive minerals. The conglomerate is distributed along the base of the Mississagi quartzite which in this region is from 1500 to 3500 feet thick.

The conglomerate forms a line of outcrops which may be traced with occasional gaps for 80 or more miles. Two major structural features extend east-west more or less parallel to the north shore of Lake Huron. On the north is a synclinal trough filled with quartzite some 25 miles long (Fig. 26). On the south is an eroded anticlinal arch of about the same length exposing the unwarped basement rock. A rim of conglomerate outcrops forms an inverted S-shaped curve encircling the syncline on the north, east and south sides and the anticline on the north, west and south. The west end of the syncline and the east end of the anticline remain open.

The distribution of radioactive anomalies in the Blind River region as shown by the airborne scintillometer follows the line of conglomerate outcrops. Drilling in the various areas in which exploration has been undertaken for mining has disclosed large bodies with a uranium content of 2.0 to 2.5 lb U_3O_8 per ton.

Trail[88] notes the resemblance between specimens of pyritized conglomerate from the gold ores of the Witwatersrand, South Africa, and the conglomerate in the Mississagi formation near Blind River. The geological occurrence in the two areas is also similar, both conglomerates resting upon a basement of ancient rocks.

Uranium in the Blind River ores is distributed through a somewhat unique mixture of the minerals brannerite, pitchblende and thucholite which are finely disseminated through the matrix of the ore. Until found at Blind River, brannerite was considered an uncommon mineral. At this widespread locality, however, it is the principal uranium mineral.

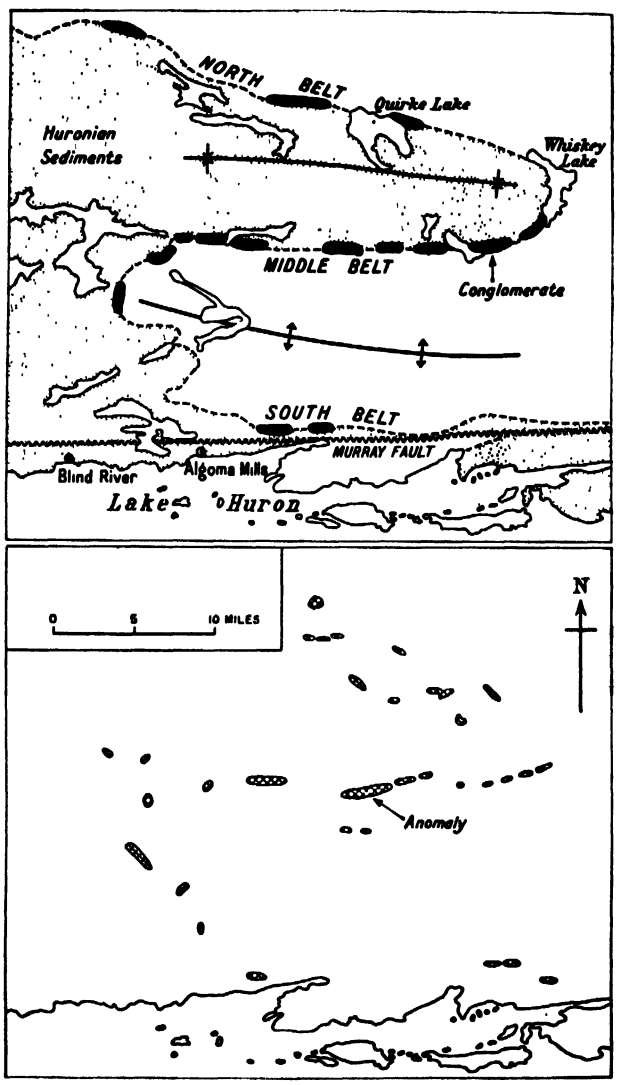


Figure 26. Blind River Area, Ontario, Canada. Low-grade uranium deposits occur in widespread ancient sediments. Above, conglomerate outcrop areas (after Joubin, 1954). Below, radioactive anomalies (after Brownell and Schaller-Joubin)[37]

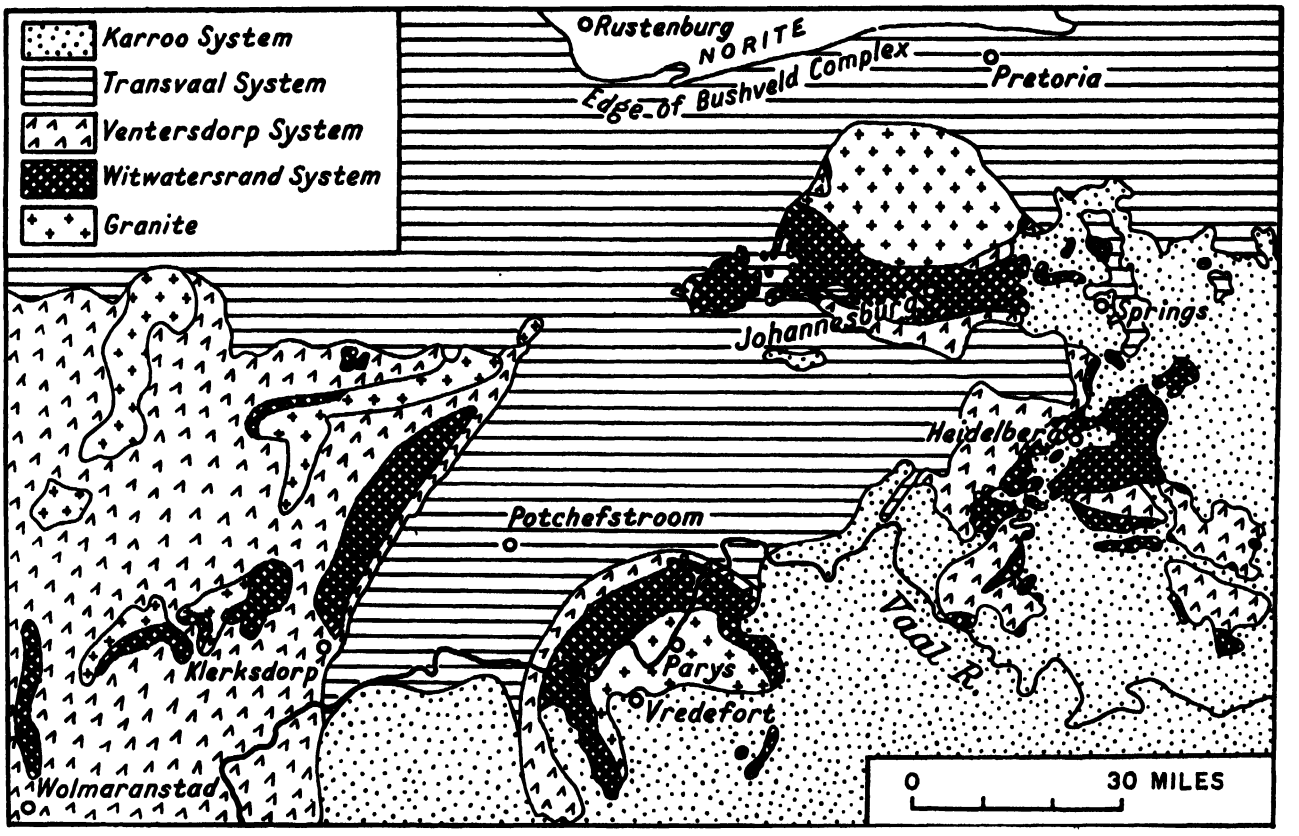


Figure 27. Witwatersrand system, South Africa. Geologic map showing distribution of Witwatersrand system (after Reinecke).[75] Gold-bearing reefs of the Witwatersrand carry uranium

Trail[88] has called the uranium oxide mineral uraninite rather than pitchblende because it contains more than 1 per cent thorium oxide. This is contrary to the generally accepted usage of Dana (7th ed.) in which uraninite is the normal form for uranium oxide found in nature, while pitchblende is the microcrystalline variety. Analyses given by Dana indicate that either the mineral or its varietal form may contain thorium oxide. Since the crystallites of the uranium oxide at Blind River are minute, it would appear that the name pitchblende would be justified notwithstanding the presence of a small amount of thorium.

The occurrence of the uranium-bearing organic material thucholite at Blind River is of considerable interest in view of the occurrence of the same material in the gold ores of the Witwatersrand, South Africa, as described by Davidson and Bowie.[17]

Witwatersrand, South Africa

Some 40 years ago, Rogers reported radioactive substances in South African gold ores. Later, Cooper[14] described the occurrence of uraninite. In 1945, Bain, along with Davidson, investigated the possibility of uranium recovery in connection with gold mining operations. The last decade has witnessed the active development of extensive mill facilities to recover uranium along with gold from the Witwatersrand goldfield of the Transvaal and Orange Free State.

Uraninite, with or without thucholite, is reported by Davidson and Bowie[17] to occur in all the workable gold-bearing conglomerate strata of the Rand (Fig. 27). It occurs from the Dominion Reefs at the base of the Witwatersrand System to the top in the Elsburg Reefs and Vetersdorp Contact Reef, a thickness in excess of 25,000 feet. Many reefs that are uneconomic for gold contain a significant amount of uranium. Data are inadequate to compute the uranium content of the Witwatersrand basin as a whole, but it has been estimated to be greater in total amount than that of any similiar volume of rock known anywhere in the world.[17]

The origin of the Rand gold ore has long been the subject of a major difference of opinion. One group, composed mostly of those engaged in active mining, has considered the gold to be contemporaneous in origin with the conglomerate in which it is found. Another group favors precipitation from heated gold-bearing solutions rising from below and depositing the metal in the porous conglomerate strata.

Davidson and Bowie[17] conclude that the gold and uranium were deposited at the same time, and also that any explanation of origin applicable to one would also apply to the other. This conclusion is based largely upon the observation that the gold and uranium as shown by many analyses have been found to vary sympathetically.

It is pointed out by Davidson and Bowie[17] that the uraninite-bearing hydrocarbon of the Rand is

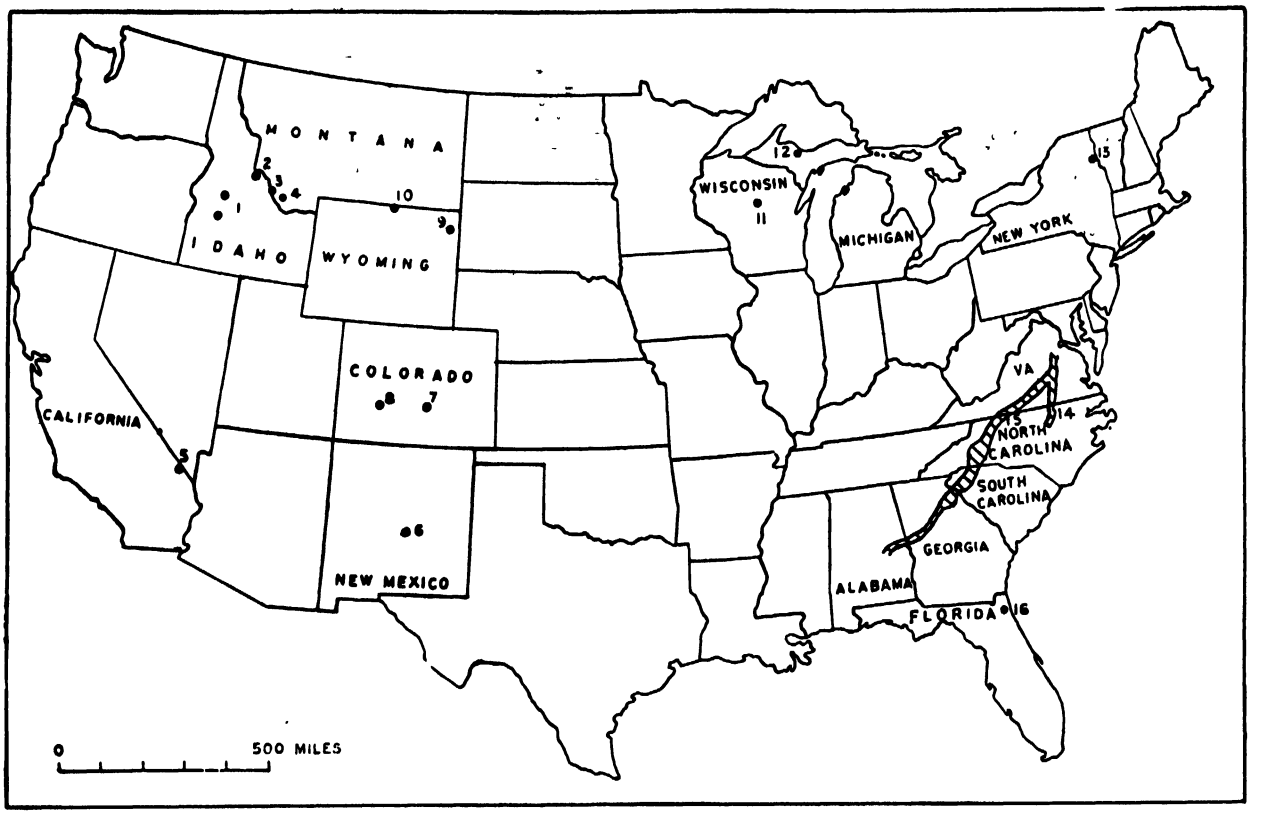


Figure 28. Thorium deposits in the United States (after Twenhofel and Buck, Paper P/301, Session 6B, this Volume.) A belt of disseminated thorium occurrences in ancient rocks occurs along the Atlantic area. (1) Idaho placers; (2) Mineral Hill district; (3) Lemhi Pass district; (4) Deer Creek district; (5) Mountain Pass district; (6) Gallinas district; (7) Wet Mountains (8) Powderhorn district; (9) Bear Lodge Mountains; (10) Little Big Horn River; (11) Wausau area; (12) Palmer area; (13) Mineville district; (14) Eastern monazite belt; (15) western monazite belt, and (16) Jacksonville placer

essentially identical with thucholitic hydrocarbons produced elsewhere by rising heated solutions.

1. The uranium content of the Rand conglomerate is much greater than may be observed for present day placers.
2. Uraninite is not a placer-forming mineral.
3. Gold and uraninite have been found to crystallize together as the result of precipitation from heated solutions in veins located in the Belgian Congo, Mexico and Canada.
4. The complex chemical compositions of the uranium minerals in the basement rocks which encircle the Rand basin preclude their role as a source for the mechanical transportation and deposition of uraninite.

These factors strongly support the theory of rising thermal solutions as the source of the Witwatersrand uranium.

Thorium by Direct Crystallization

Thorium minerals are deposited as direct products of crystallization in pegmatite dikes or thorium-bearing veins. Thorium is also found in accessory minerals formed during the crystallization of igneous masses or as products of recrystallization in metamorphic rocks. Unlike uranium minerals, thorium minerals are not reported as products of crystallization in porous sediments of the Colorado Plateau type, nor do the bituminous sediments appear to yield thorium, notwithstanding the fact that they may be at times rich in uranium. In general, thorium minerals are crystallized under temperatures of several hundreds of degrees Centigrade and under pressures that would prevail thousands of feet below the surface. Such conditions favor areas of igneous and metamorphic rocks.

Because of its chemical characteristics, thorium is closely related in occurrence to zirconium, uranium and rare-earth metals. Many alkalic rocks are thought to become enriched in thorium during the process of magmatic differentiation (P/301).

Pegmatites

Pegmatites rarely yield thorium minerals in recoverable amounts. None of those found in the United States have been found to justify economic development (P/301).

The Norwegian pegmatites have long been known to contain uranium and thorium in varying amounts, and the mineralogical literature is replete with scientific descriptions of these occurrences. In general, both uranium and thorium minerals occur in granite pegmatites. The minerals are oxides, silicates and niobate-tantalates. Thorite occurs as an accessory mineral in the Oslo region. None of the pegmatites appears likely to produce uranium or thorium ore other than as by-products of feldspar mining (P/887).

Thorium-bearing Veins

Thorium and rare-earth-bearing veins found in the United States (Fig. 28) occur in California, Colorado, New Mexico, Montana, Wyoming, and Idaho. Monazite and thorite are the principal thorium-bearing minerals, but other minerals (bastnaesite, thorogummite and fluorapatite) are potential sources of by-product thorium in certain places.

Thorium-bearing veins occur in the Powderhorn District, Gunnison County, Colorado. These are found in foliated pre-Cambrian rocks along silicified and iron-stained shear zones. Masses of carbonate rock also contain weakly radioactive zones. Carbonate-rich veins are likewise said to contain deposits. The thorium mineral appears to be thorite or hydrothorite. Alkalic intrusive rocks are found in the vicinity of known radioactive localities. A genetic relationship between the intrusive rocks and the thorium deposits is suggested by the relative abundance of titanium, barium, strontium, niobium, phosphate, rare earths and the alkalies in both the alkalic rocks and the vein material (P/304).

The most promising thorium deposit in the Powderhorn District, Gunnison County, Colorado is the Little Johnnie vein. This is a mineralized fault zone shear which can be traced discontinuously for more than 3500 feet. The thorium-bearing material occurs in irregular veinlets and thin films with a total width which varies from less than six inches to about five feet (P/304).

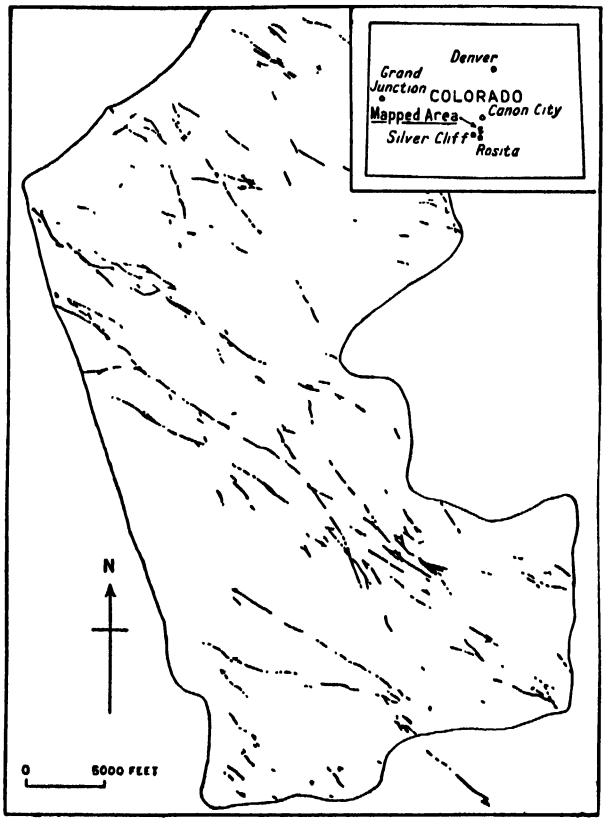


Figure 29. Thorium veins, Wet Mountains, Colorado, USA. (after Singewald and Brock, Paper P/303, Session 6B, this Volume). Many of small thorium-bearing veins form an en echelon network

Thorium occurs in veins in the Wet Mountains of Colorado, the mineralized area measuring 25 miles long and 10 miles wide (Fig. 29). The belt lies along the western slope of the range and trends north north-westward. The rocks are prevailingly pre-Cambrian in age, although cut by dikes of possible Tertiary age. Thorium is found in a crystalline complex cut by at least one stock and by younger dikes (P/303).

Veinlets in zones of shattered rock carry the thorium. Ordinarily the zones are less than 10 feet wide, but locally may approach 50 feet. The shear is heavily impregnated with red and yellow iron oxide minerals, at the same time being highly silicified and feldspathized. Minerals frequently present but variable in distribution include: quartz, barite, carbonate minerals, minor amounts of fluorite and sulphides. Veins cut across boundaries between granite and gneiss without being localized by the lithology or structure. Apparently more radioactivity is found in granite (P/303).

The thorium mineral in the Wet Mountains, Colorado, has been tentatively identified as thorogummite. It is reddish-brown, forms blebs or veinlets, and occurs in concentrations which are erratically distributed along veins as pockets, pods, or lenses. Frequently the thorium-rich minerals are masked by limonite to such a degree that the presence of thorium is detected only through radioactivity. One of the most interesting occurrences of thorium due to direct crystallization occurs in carbonate rocks of Shinkolobwe. Veins of monazite and monazite crystals are reported by Derriks and Vaes (P/105) from parts of the deposit.

Thorium Disseminations in Crystalline Rocks

Two belts of thorium-bearing rocks appear to follow a northeastward trend across the Piedmont of the eastern United States from Alabama to Virginia, a distance of 550 miles, where they join to extend an additional 50 miles northeastward (Fig. 28). The thorium is found in monazite which occurs more abundantly where the rocks have been intensely recrystallized sediments. These intrusives, numerous pegmatite dikes, schists, gneisses and related metamorphic types together constitute a rock complex. Thorium is more abundant where the highest temperatures and pressures prevailed during recrystallization as indicated by the prevalence of such minerals as silimanite, staurolite and kyanite. Thorium is widely distributed in disseminated monazite crystals (P/306).

Age determinations of monazite and zircon in the Alabama-Virginia thorium-bearing belt of the US Piedmont confirm structural data. They suggest that granitic rocks at the margins of the belt were emplaced after similar rocks in the core.

Uranium is associated with graphite-mica-schist in Norway, but in small amounts (P/887).

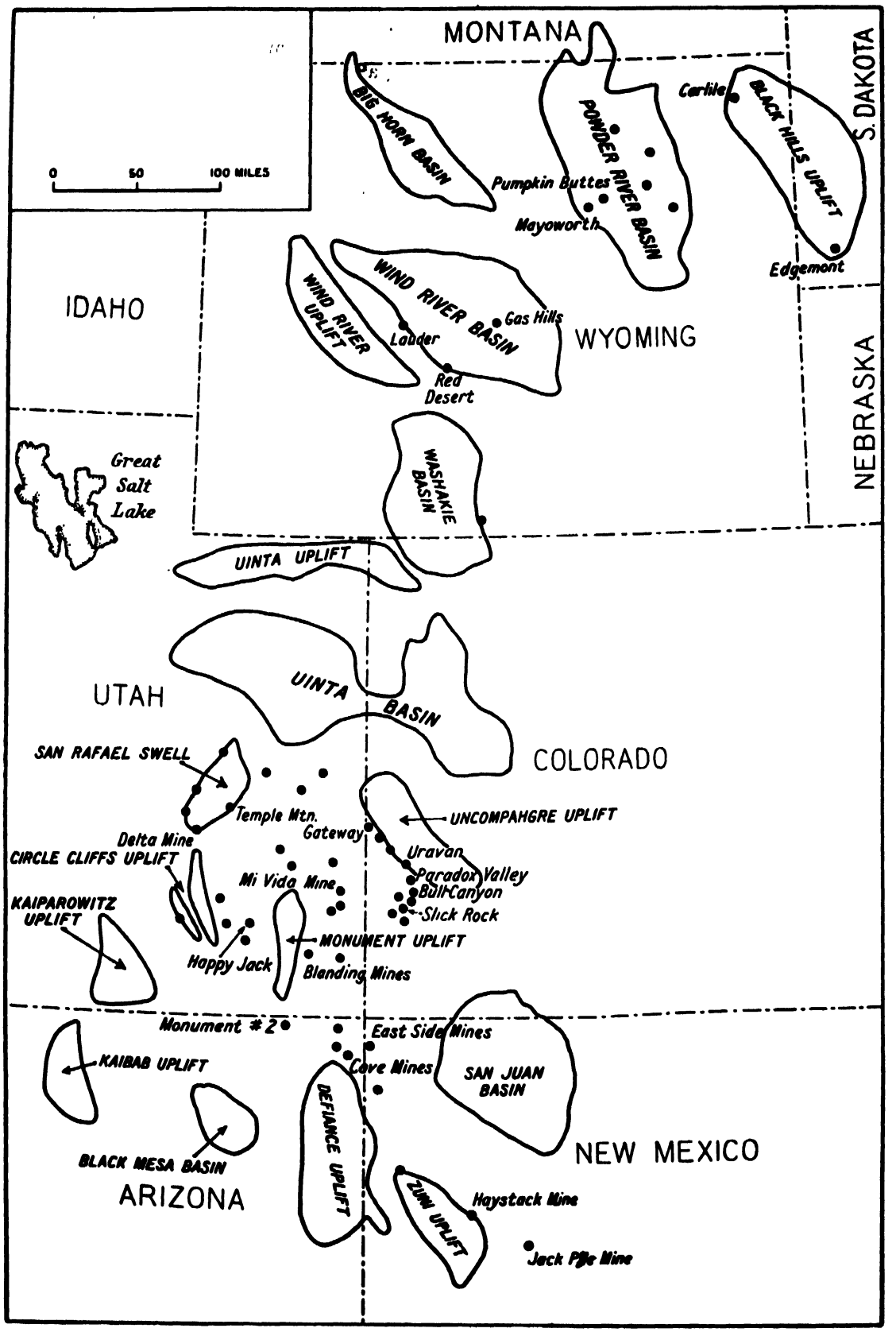


Figure 30. Uranium in sedimentary strata in Western USA. Major sedimentary uranium deposits. Western United States (based on tectonic map of the US). Deposits trend toward an association with regional structural warping, but more particularly to less extensive local structural features

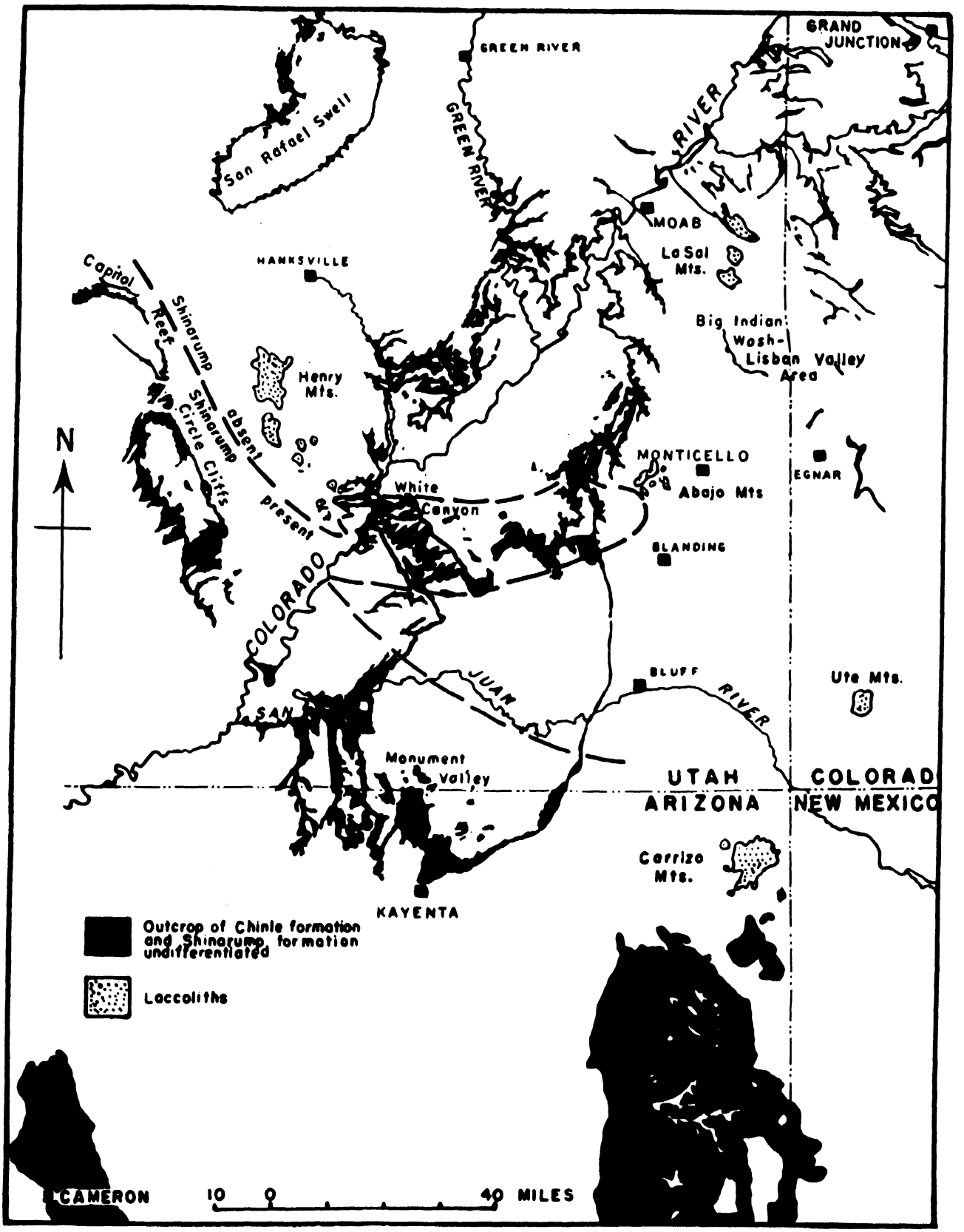


Figure 31. Chinle-Shinarump areas of Colorado Plateau, USA. Chinle and Shinarump formations and laccoliths on the Colorado Plateau (after Isachsen, Paper P/39, Session 6B, this Volume). Highly productive mines are found in this formational unit

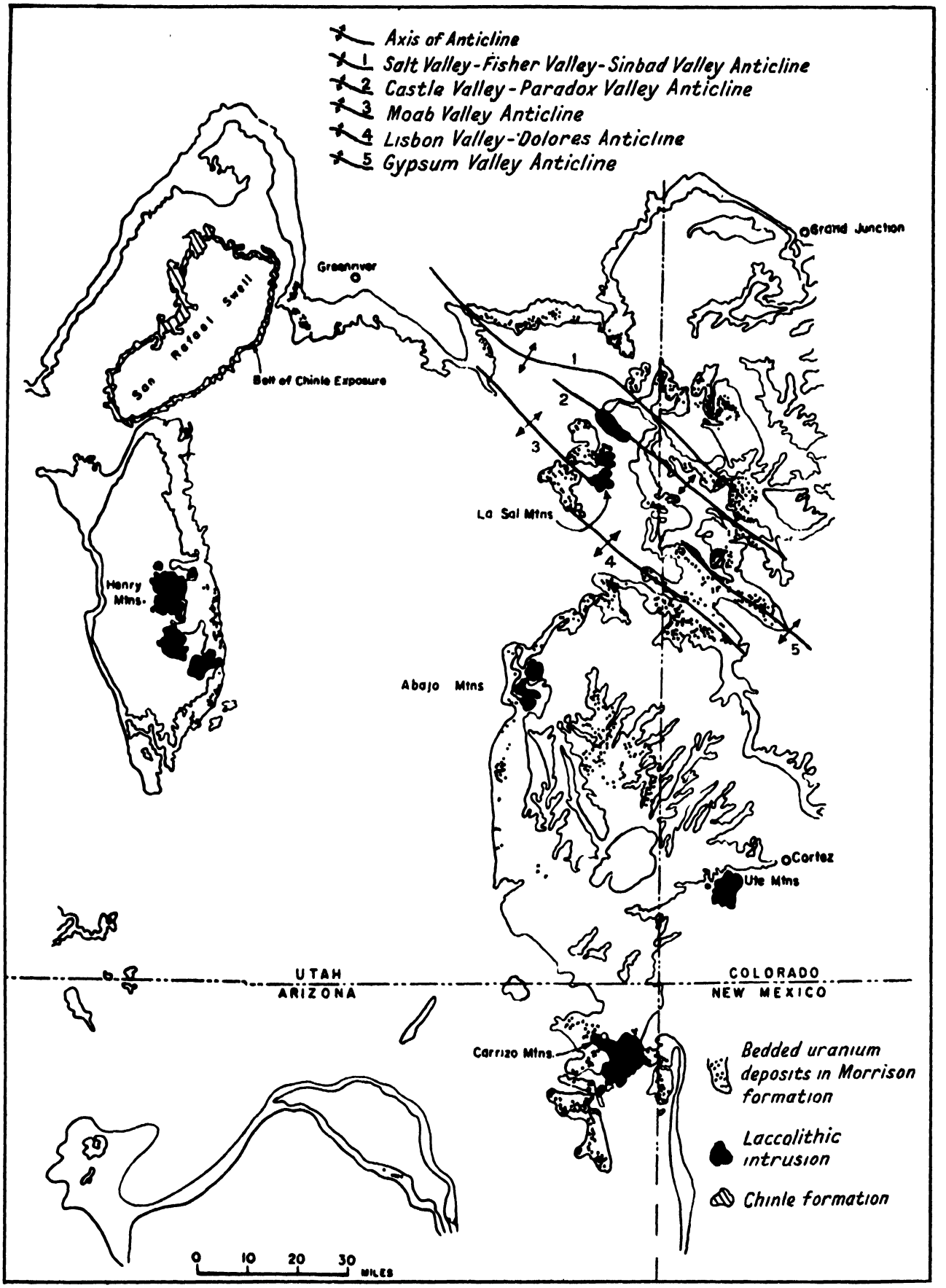


Figure 32. Outcrop area of Morrison formation. Outcrop belts of Morrison formation showing general distribution of uranium deposits (after Wright.[92] Based on M. V. Anthony). The principal producing formational unit of the Colorado Plateau, USA

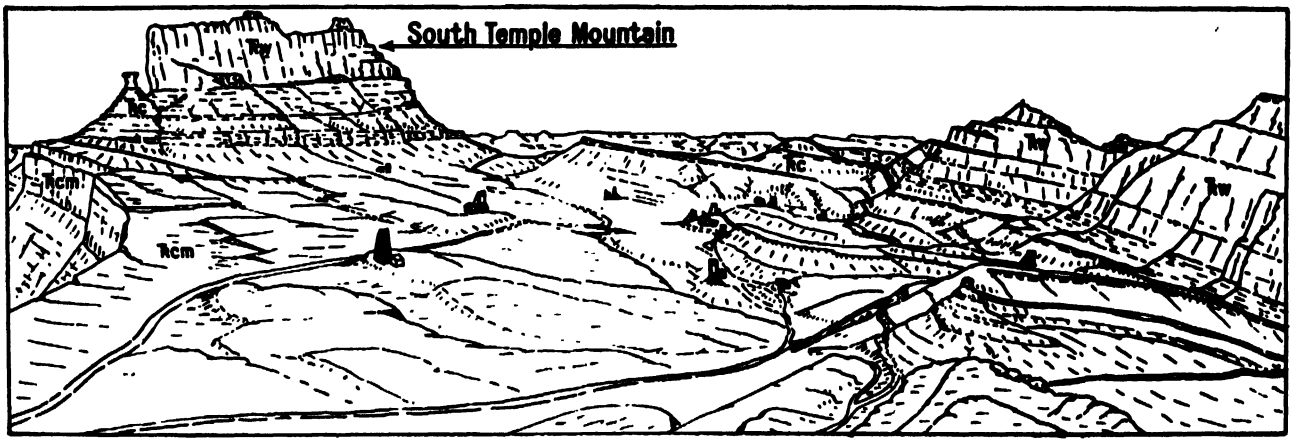


Figure 33. A plateau mining area, USA. Mine shafts penetrate strata in the Mossback conglomerate of the Chinle formation (Trcm) where asphaltic ore is removed at Temple Mountain, Utah

Uranium and Thorium Deposits in Normal Sediments

Uranium Accumulations in Sedimentary Strata

The deposits of the Colorado Plateau have furnished the principal source of uranium in the United States (Fig. 30). Uranium occurs in many formations ranging in age from late Paleozoic to mid-Tertiary. However, deposits which have yielded significant production are restricted mainly to Triassic strata which include the Shinarump or nearly equivalent conglomerates (Fig. 31) and the Chinle formation, and Jurassic strata (Fig. 32) which include the Todilto limestone, Entrada sandstone and Morrison formation (P/473). A view of the Temple Mountain mining district is included in Fig. 33 as an example of a plateau type occurrence.

The larger ore bodies are mainly tabular and horizontally fill a considerable area of permeable strata. Vertically, ore bodies may vary from a few feet to 20 feet thick and the width of a deposit may vary from a few feet to hundreds of feet. Deposits are often elongated parallel to the strike of beds or the long axis of a channel. Ore bodies in limestone are markedly elongate and follow lines of deformation.

Until 1951 the bulk of uranium ore produced in the United States was derived from the fluviatile sediments of the Morrison formation. Discovery of uranium in other formations has decreased the proportionate predominance of Morrison production, but in the aggregate the strata of this formation are still the most productive of the Colorado Plateau (P/474).

In recent years extensive uranium deposits have been developed on the north slope of the Zuni Uplift in northwestern New Mexico in the Morrison formation. Here the ore-bearing unit has been shown to be the equivalent of the Brushy Basin member of the Morrison. Larger deposits occur in relatively coarse grained sandstone strata where the sandstone is thicker (P/38).

In addition to the occurrence in the sedimentary strata of the Colorado Plateau, uranium is found in substantial amounts in sediments elsewhere in the United States. These occurrences include deposits of considerable size in Cretaceous sandstones of the Black Hills region of South Dakota and Wyoming; occurrences in sandstone associated with volcanic ash or tuff in Wyoming, Texas and Nevada; and small deposits in terrestrial sedimentary rocks in Pennsylvania, Oklahoma, New Mexico and other places (P/472).

In the Pumpkin Buttes area, Wyoming, oxidized uranium minerals occur in a red sandstone member of the Wasatch formation (Eocene) (P/46). The ore-bearing strata consist of medium to coarse granular arkosic sandstone. As in the case of fluviatile sandstones of the Colorado Plateau (P/33), the transmissivity of the ore-bearing formation is variable in character. The pattern of ore distribution is restricted. All known deposits are reported to be in fluviatile sandstone and within a stratigraphic interval of 500 to 1000 feet above the base of the Wasatch formation (P/46).

The Pumpkin Buttes area lies in the Powder River Basin, one of several large structural basins of the Wyoming-Montana region. The Bighorn Mountains lie to the west and the eastern slope rises toward the Black Hills uplift. The uranium-bearing strata are almost flat, sloping at 30–100 feet per mile to the northwest. At Pumpkin Buttes they are overlain by younger strata of the White River formation (Oligocene) which form a cap-like erosional remnant. All uranium strata are enclosed by relatively impermeable non-uraniferous rocks (P/46).

Uranium deposits in the southern Black Hills of South Dakota are found in non-marine sandstone belonging to the Inyan Kara group (Early Cretaceous). Deposits occur along the general slope of the Black Hills uplift. The greatest density of deposits occurs in areas where abrupt more or less local changes in the attitudes of strata may be found (Fig. 34), or in almost flat lying strata where permeability, transmissivity and conditions of precipitation are particularly favorable (P/47).

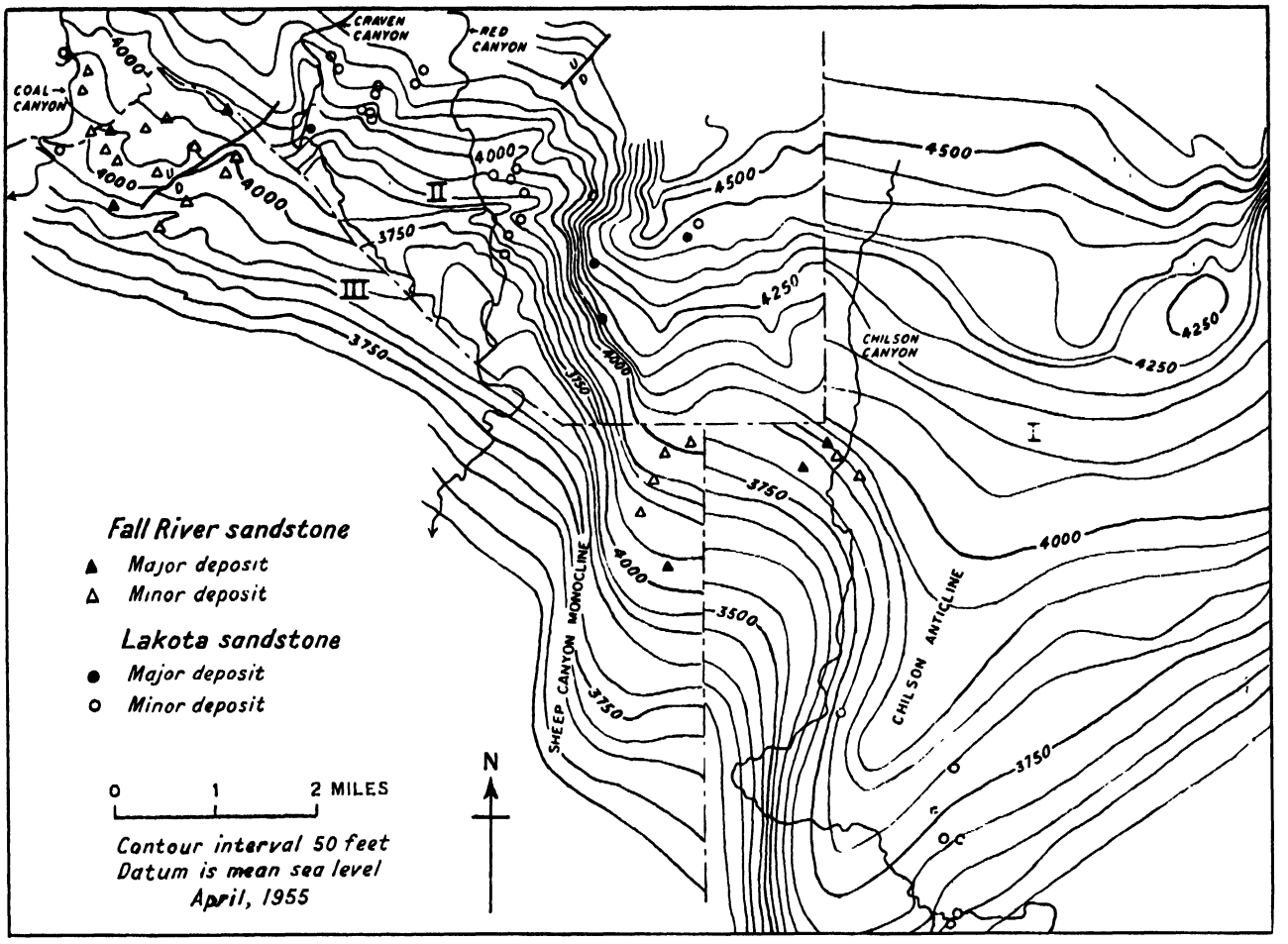


Figure 34. Structural control of mineralization, Black Hills, South Dakota, USA. Structure contours and uranium deposits, Edgemont mining district, Fall River County, South Dakota (after Bell *et al.*, Paper P/47, Session 6B, this Volume). Localization of deposits as shown by structural contours. Area contoured: (I) base of Inyan Kara group, (II) top of ore-bearing Lakota sandstone, (III) base of Fall River sandstone

The sandstones and siltstones of the Black Hills area contain partly oxidized uranium and vanadium minerals in association with carbonaceous material. This has suggested precipitation in a reducing environment (P/47).

Several types of deposits have been recognized in the southern Black Hills. A fine grained sandstone, usually less than 5 feet thick, interbedded with laminated carbonaceous siltstone, contains both partly oxidized and oxidized uranium and vanadium minerals. Thick cross-bedded non-carbonaceous sandstone contains several large carnotite deposits. Lenses of fine grained homogeneous sandstone separated by thin beds of mudstone contain numerous small occurrences of carnotite of little economic importance (P/47).

Uranium is found in sedimentary strata in the USSR. At Yuigur Sai in the Papsk region of the Northern Ferghana[4] the uranium occurrences, which are located in lenses and as impregnations in continental sandstone, resemble those of the Colorado Plateau. In the region in general, however, the occurrences appear to be in oxidized ores which have been concentrated from overlying black shale. Tyuyamunite and carnotite occur in many places between Ferghana and Minussinsk. It is reported by Bain[4] that uraniferous shales are known to occur on the south margin of the Ferghana area and that the uranyl salts from this region have served as a source of radium.

An account of the lithologic composition[66] of the lower Tertiary deposits of the southeastern Ferghana which is based on cores from three localities, indicates the presence of clays, marls, salt beds and carbonate rocks. The occurrence of considerable detrital material suggests an origin in a shallow basin in which lagoons were extensively developed.

Stratigraphic Distribution

Great interest has been attached to the stratigraphic distribution of the uranium deposits in sedimentary formations. Several reasons may be given.

In the search for productive uranium deposits, formational units have proved to be an important guide. Thus the Salt Wash member of the Morrison formation (Fig. 32) and the Shinarump conglomerate near the base of the Chinle formation (Fig. 31) are two of the most widely surveyed formations of the Colorado Plateau. Elsewhere other formations receive equal scrutiny. A list of the forma-

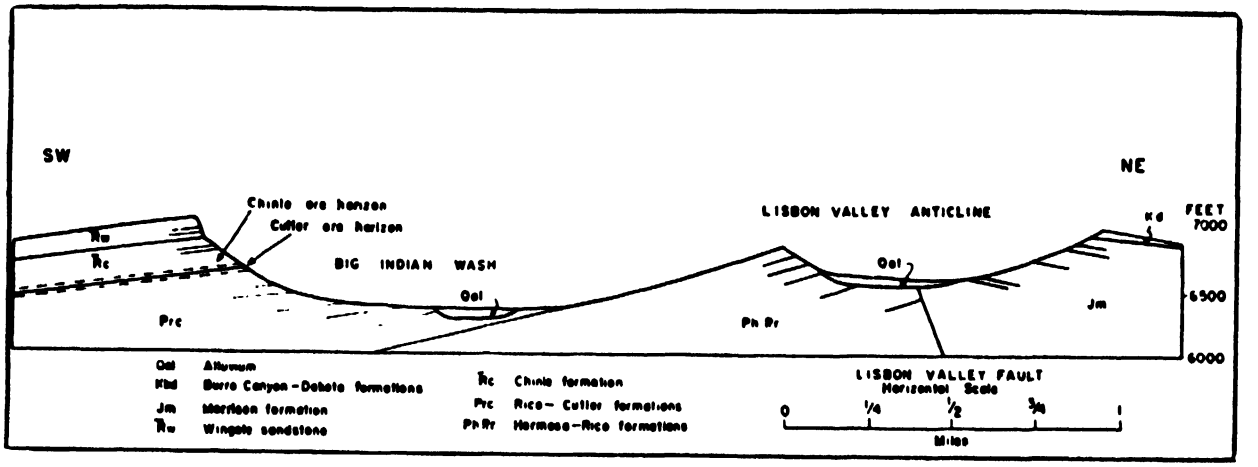


Figure 35. Generalized cross section of Big Indian Wash, San Juan County, Utah, USA (after Wright).[93] One of the major uranium-bearing structures on the Colorado Plateau

tions in which economic deposits have been reported is shown in the accompanying table (Table III).

In the interpretation of origin, considerable significance has been attached to the fact that several formations of widely different age are uranium-bearing. These range in age from Cambrian to Tertiary although great variability exists in the productivity of different formational units. Such distribution emphasizes the introduction into strata of uranium from sources extraneous to the beds in which the ores are now found. The supply would have needed to move along lines that would intersect strata more or less at right angles.

Not only the uranium-bearing formations themselves, but the strata above are of interest in the interpretation of origin. Fine, ejected and settled volcanic ash or tuff may be found in strata which are not far above at least three different uranium-bearing formations. Leaching of uranium from the ash and deposition in the ore-bearing beds below has been proposed by some as a mechanism of ore deposition on the basis of this stratigraphic situation. Others point out that the situation does not apply uniformly to all formations. In any case, stratigraphic information becomes of interest.

Structural Controls

The Lisbon Valley anticline is one of the typical folds of the eastern Utah area which has attracted particular attention in uranium exploration. A section across Big Indian Wash showing the distribution of uranium horizons on the flank of the structure is shown in Fig. 35.[93]

It is believed that regional structure of the Colorado Plateau influences the distribution of the uranium deposits. Major northwesterly trending, deep-seated lineaments appear to have influenced structural trends, igneous centers and ore distribution (P/29).

Although structural lines are in evidence and in a number of places, marked deformation may be observed; the Plateau area has been one of more or less stability since pre-Cambrian time. Laramide (Tertiary) deformation is expressed by a number of broad folds and sharp flexures, but over wide areas the sedimentary beds are nearly horizontal (P/473).

Regional study of the geologic development of the Cordilleran Foreland of the western United States reveals broad scale structural characteristics which are considered significant in the study of uranium deposits (P/28). The Foreland consists of a series of structurally asymmetric basins separated by folded mountains. Throughout the area many of the faults, folds and other forms of flexures observed in study of the surface are considered to originate in deformation within the frequently deeply buried underlying pre-Cambrian basement (P/28).

In many places the trend of folds and faults over a considerable region shows parallelism. In the Foreland, regional maps show that the prominent structures have a prevailing northwest alignment. It is believed that uranium deposits occur in clusters where the northwest trending structures are intersected by later and less evident northeast-trending structures. Wright[93] shows a group of intersection areas encircling the La Sal Mountains (Fig. 36). Deposits are believed to accumulate where more or less parallel groups of faults or folds intersect the northwest trend at acute angles. Deposits are also believed to form near the axial parts of major basins (P/28).

The relationships of the various trends may be exhibited by means of structure contour maps. These must be compiled from knowledge of surface geology, information on thickness of strata, available geophysical data, exploratory information in mining operations and oil well drilling data (P/28).

Throughout the region, repeated deformation of old structures causes even relatively young Tertiary rocks to be slightly folded and fractured. Repeated deformation along old structures has tended to produce mountain margins bounding basins in which thick sedimentary accumulations would result. Such features receive serious consideration in interpreting the conditions of uranium accumulation (P/28).

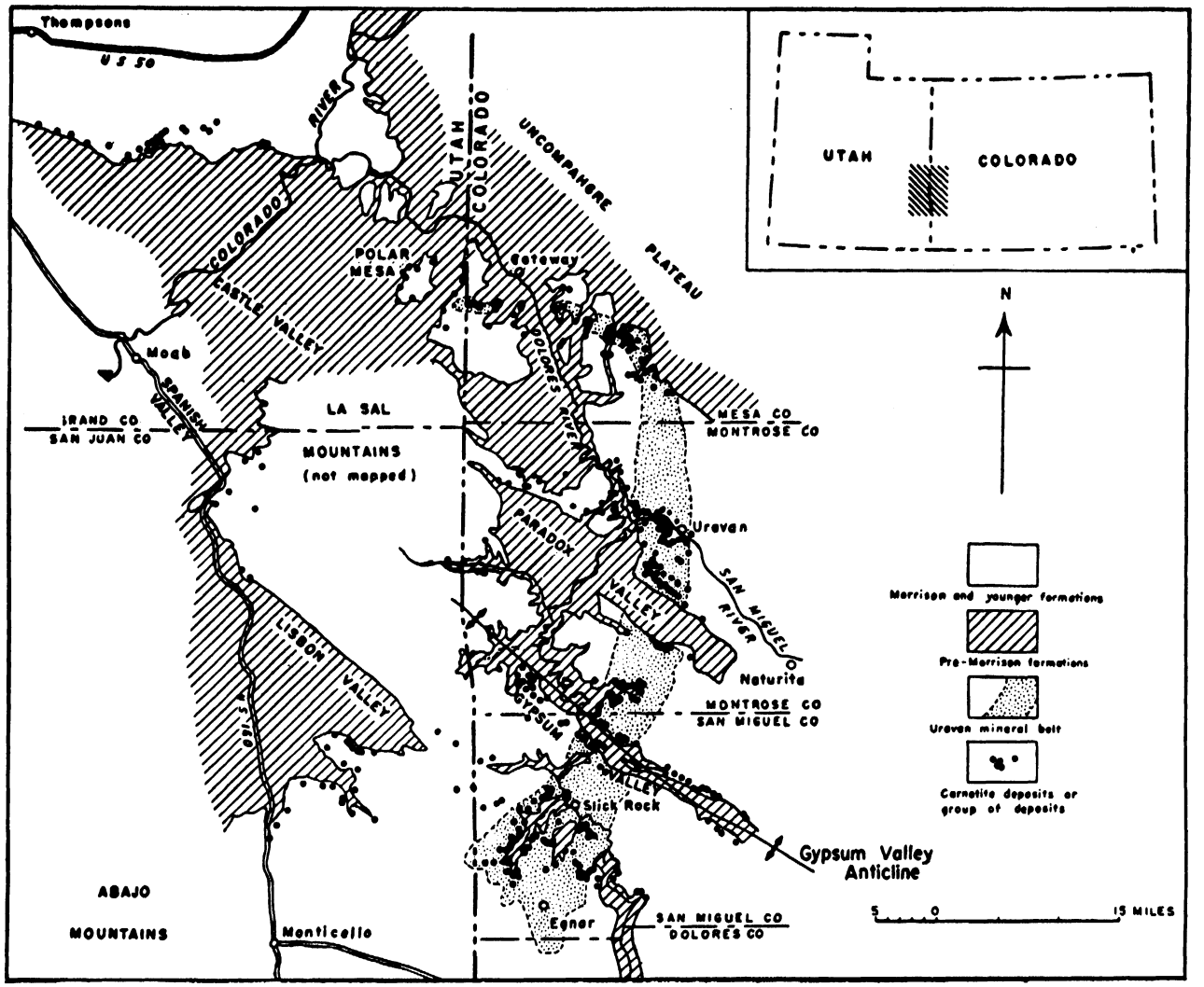


Figure 36. Deposits along structural elements. Map of part of Colorado and Utah, showing the principal carnotite deposits. Map of part of Uravan Mineral Belt, showing widening of the belt along Gypsum Valley anticline. (Based on US Geol. Surv. Bull. 988-A.) (after Wright)[93]
The intersection of structural features tends to localize deposits

At areas of intersection between trends, pathways for the migration of uranium-bearing solutions are created in greater abundance. It would also seem that solutions carrying uranium ions and originating in the basement would tend to come to a focus in such areas.

Sedimentation Features

Study of the sedimentary features of the Morrison formation (Jurassic) of the Uravan district, Montrose County, Colorado, reveals that the principal uranium-vanadium deposits in the district are restricted to the upper sandstone lenses of the Salt Wash member. Individual lenses are enclosed by relatively impermeable mudstone beds. Hence the sandstone lenses do not form extensive aquifers along which ore-bearing solutions might be expected to migrate on a district wide basis. It is improbable, therefore, that the ore-bearing sandstone lenses of the Long Park area are continuous with the ore-bearing sandstone lenses in the nearby Club Mesa area (P/35). The stacking of channels one above another as sedimentation proceeds may produce a formation with highly variable porosity. Such multiple channel patterns studied in Arizona (Fig. 37) indicate the direction in which deposition took place and suggest directions to follow in tracing ore bodies.[60]

The ore deposits of the Club Mesa and Long Park deposits are believed to exhibit an en echelon arrangement which is a reflection of the sedimentary structures of the areas. The long axes of ore bodies are nearly parallel to the strike of the sedimentary features. In general, the trend is eastward (P/35).

Present knowledge agrees with the concept of the Uravan mineral belt extending northward. Ore rolls and fossil logs exhibit a trend related to the average easterly sedimentary trend. No direct ore control relationship has been observed to correlate fractures and faults with ore distribution (P/35).

Sedimentation features which indicate the direction of original transport are of interest in connection with the study of the continuity and trend of uranium-bearing deposits. Such features have re-

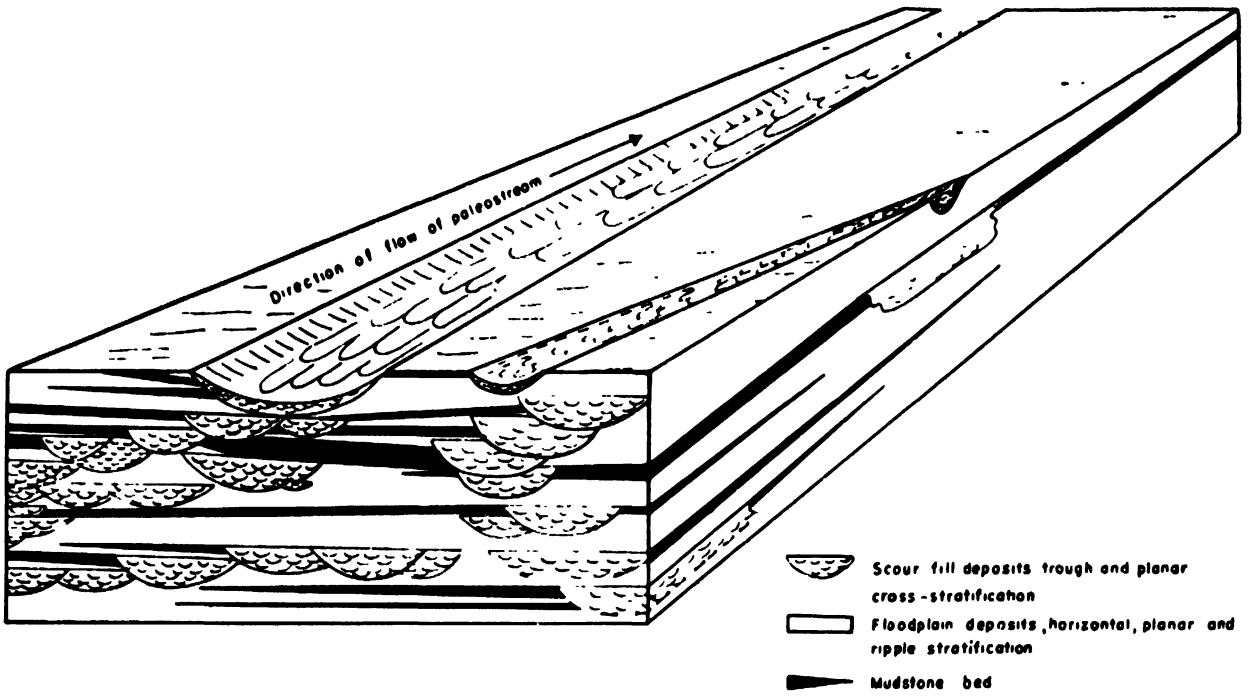


Figure 37. Stacked channels. Schematic diagram showing deposition by a typical lower Morrison stream in the Northern Chuska Mountains area, Arizona (after Lowell).[60] The diagram shows channels above each other as observed in the Morrison formation in Arizona, USA

ceived particular attention in the examination of deposits in sediments in the Colorado Plateau (P/34).

Sedimentary structures (Figs. 38 and 39) within beds which furnish directional data include cross-strata, current lineation and ripple marks. In addition, the channels themselves in which deposits are frequently located are often elongate in the direction of transportation. Fossil log orientations may be used to supplement other data (P/34).

The most significant feature indicating the direction of current flow during sedimentary accumulation is cross-stratification. The down slope directions of cross-strata are assumed to indicate the direction of flow. In a given area the assembly of observable cross-strata attitudes on a map may indicate the flow pattern. Current lineation and ripple marks furnish confirmatory criteria. In some areas the general average of the positions occupied by logs deposited along channels furnishes further directional information (P/34).

Marginal marine and near shore terrestrial sandstones which contain uranium are found in northwestern New Mexico and adjacent parts of adjoining states. Occurrences are associated with local facies changes in sedimentation near regions of post-Cretaceous structural deformation. Uranium minerals are apt to be associated with accumulations of carbonaceous material. The uranium occurrences are found in the Curtis formation (Jurassic) and in some members of the Mesaverde group (Upper Cretaceous). Localities observed lie on the Colorado Plateau, at Black Mesa, Arizona, and in the San Juan Basin, New Mexico (P/43).

Channels

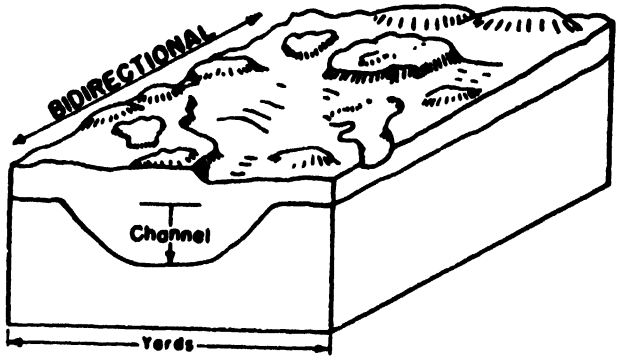
Channels (Fig. 40) play an important role in connection with many uranium deposits which occur in the Shinarump conglomerate of the Upper Triassic. The localization of ore bodies may be attributed to channels and commercial ore is restricted to channel fill (P/39).

Channels represent old stream scours which followed a sinuous course across a slightly tilted or almost flat floodplain. The troughs cut by the streams were filled with gravel, sand and clay. Such features are common sites for uranium accumulation as they now exist buried beneath overlying strata. The channels in the Monument Valley area of southeastern Utah range in width from 15 to 2300 feet and may be scoured as much as 75 feet into underlying strata (P/40).

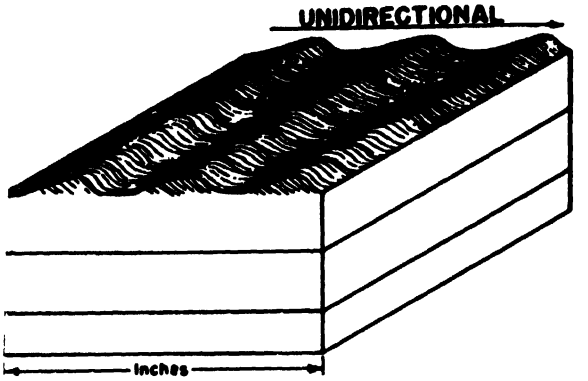
At White Canyon, south of the Colorado River in southeastern Utah, a broad band of Shinarump conglomerate occurs which ranges in width from 8 to 15 miles (Fig. 41). Here the high grade uranium deposits favor channels along the margins within 3000 to 15,000 feet of the edge of the conglomerate area (P/42).

Channels, as they lie buried beneath hundreds or even thousands of feet of overlying strata, constitute a major problem in uranium exploration. Where cut by present day stream courses, cross sections of channels may be recognized on canyon walls. Conglomerate-filled troughs which are frequently gray contrast in color with the more uniform brown sandstone and shale strata beneath. However, the course of the channel in horizontal extent is usually concealed beneath overlying strata and must be determined by drilling (Fig. 42).

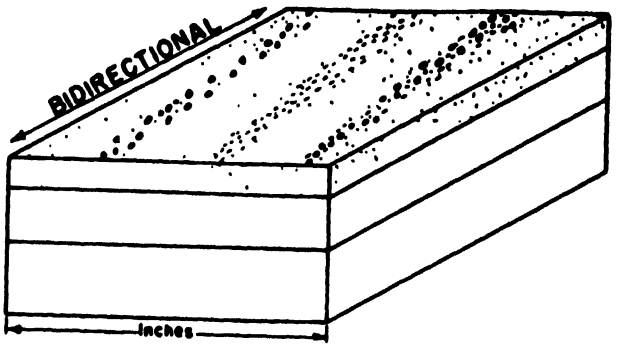
In the Monument Valley area, channels are traced below the surface by drilling and also by geophysi-



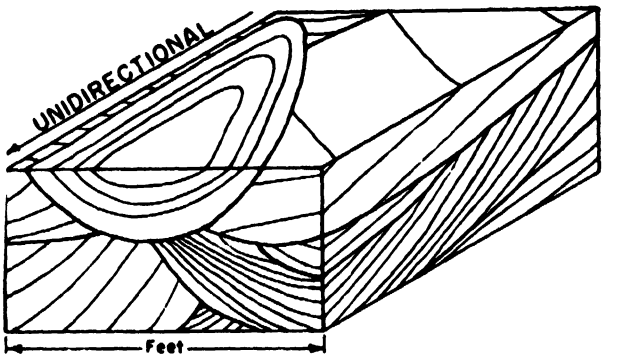
BURIED CHANNEL



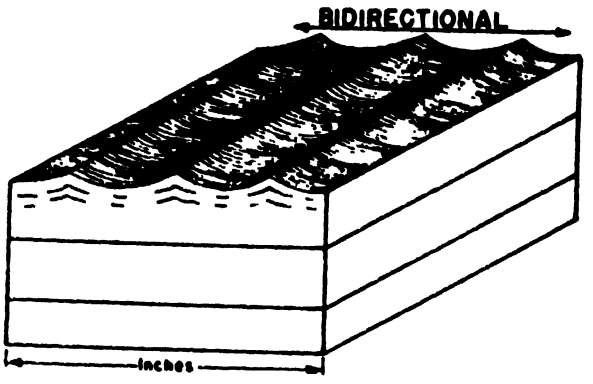
ASYMMETRICAL RIPPLE MARKS



CURRENT LINEATION

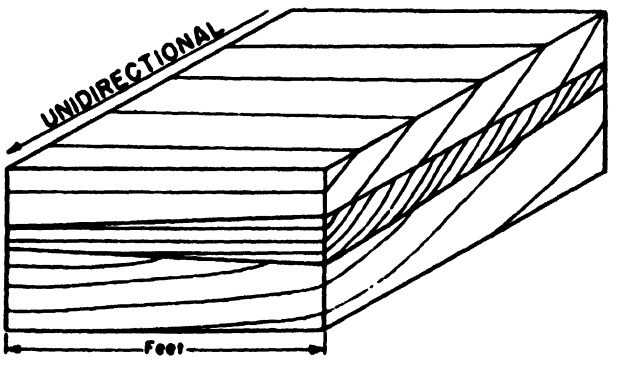


TROUGH CROSS-STRATIFICATION



SYMMETRICAL RIPPLE MARKS

Figure 38. Sedimentary structures — bidirectional indicators (after Poole and Williams, Paper P/34, Session 6B, this Volume). Criteria along exposed channels make possible interpreting flow direction in two ways



PLANAR CROSS-STRATIFICATION

Figure 39. Sedimentary structures — unidirectional indicators (after Poole and Williams, Paper P/34, Session 6B, this Volume). Criteria along exposed channels make possible interpreting flow in a single direction

cal techniques. It has been observed however, that the terrain above certain channels contains swales. These are located by mapping the thickness of stratigraphic members on the basis of geologic maps prepared from air photographs (Fig. 43). Swales may range in width from 1 to 3 miles and exhibit a relief of about 40 feet between their high and low points (P/40).

Roll Ore Bodies

So-called "roll" ore bodies (Figs. 44 and 45) occur mainly in the Salt Wash sandstone member of the Morrison formation (Jurassic) of the Colorado Plateau in the western United States. "Roll" ore bodies are generally layered deposits which cut across the regular sandstone bedding in sharply curving forms (P/36).

Rolls are found mainly near the base of thick sandstone units where numerous, thin, well-defined mudstone layers and thin sandstone layers are interbedded. The long axes of rolls may be continuous for hundreds of feet in the plane of thin sandstone layers. In places rolls may connect with tabular ore bodies or below (P/36).

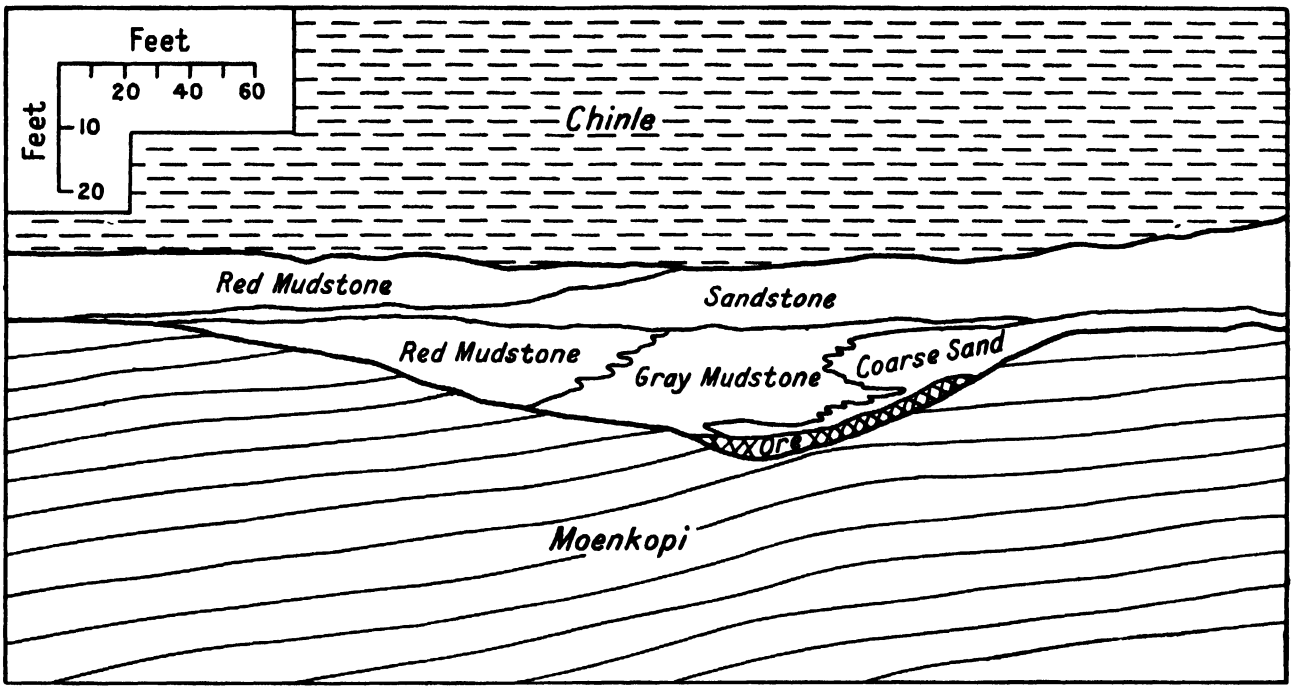


Figure 40. An ore-bearing channel. Cross section, Shinarump channel, White Canyon, Utah, USA (after Miller).[68] The channel has scoured a depression in the underlying formation

It has been suggested that the development of the roll ore bodies is related to the conditions of ore precipitation. Ore-bearing solutions permeating the connate waters in the sediments are influenced strongly by local sedimentary features. It is postulated that roll ore bodies have been formed by precipitation of minerals at an interface between solutions of different composition and density (P/36).

Permeability and Fluid Transmission

The permeability of a rock type may be considered as the capacity of the particular rock to transmit fluids under a hydraulic gradient (P/32). Sedimentary rocks are more permeable parallel to the bedding than across the bedding. In the plane of the bedding they are slightly more permeable parallel to the trend of linear aggregates of sand grains than normal to the aggregates. Other factors being the same, sandstone free from oxidation which is ordinarily light colored is somewhat more permeable than oxidized sandstone which may be dark colored.

The original character of the sediment and subsequent effects resulting in mineral changes influence permeability. In the sediments of the Colorado Plateau the subsequent effects which change the permeability are probably largely minor and the permeabilities measured represent little change from the original permeability of the rock (P/33).

Transmissivity represents the capacity of a sedimentary rock as a whole to transmit fluids. The coefficient of transmissivity is equal to the product of the thickness of a bed by its mean permeability (P/32). Among the rocks of the Colorado Plateau

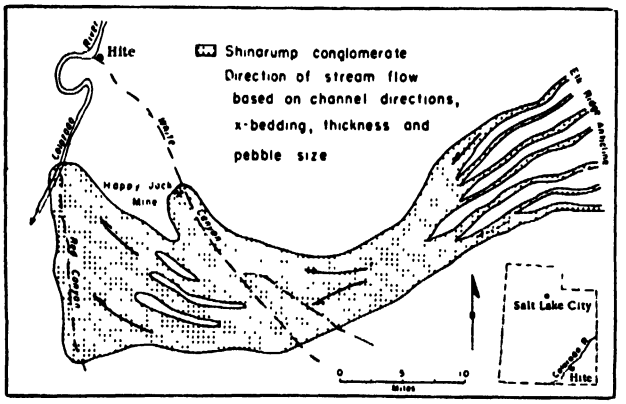


Figure 41. Regional distribution of the Shinarump conglomerate, White Canyon, San Juan County, Utah (after Miller)[68]

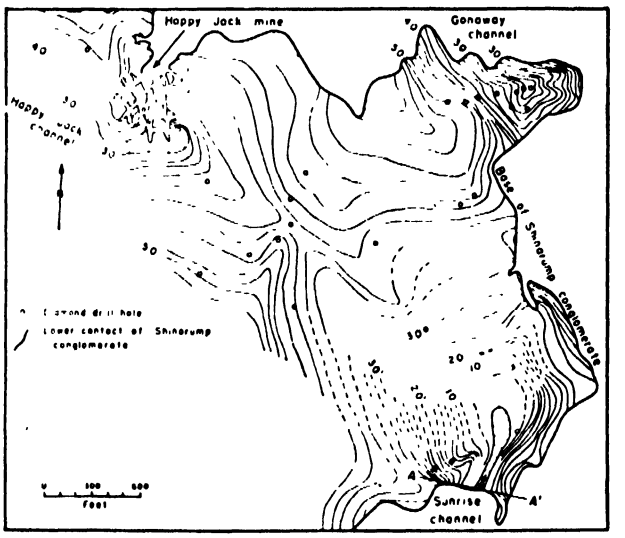


Figure 42. Structural contours along a channel: the Happy Jack mine, White Canyon, Utah, USA was contoured structurally on the basis of surface geological data and the results of drilling. (after Miller).[68] Contours drawn on the base of the Shinarump conglomerate and corrected for regional dip; assumed datum. Contour interval 2'

shales, mudstone, evaporites and limestones are essentially impermeable and hence are non-transmissive. Transmissive rocks include conglomerates, sandstones and siltstones (P/32).

The transmissive rocks may be divided into two types. (1) Eolian sandstones with relatively uniform permeability and thickness have largely the same transmissivity over large areas. (2) Fluvial standstone, siltstone and conglomerate strata which vary in thickness and permeability are highly variable in transmissivity.

Most of the known uranium deposits of the Colorado Plateau are characterized by variable transmissivity. It may also be pointed out that the regional transmissive capacity of fluvial sediments as a whole is low relative to eolian sediments (P/33).

Precipitants

Field and laboratory evidence[63] indicate that precipitants play an important role in the deposition of uranium in sedimentary strata.

In the field, organic materials furnish particularly significant associations. Nuclei of plant debris are frequently surrounded by uranium-impregnated sandstone. Accumulations of plant remains in the so-called trash pockets along buried meanders of old stream channels are apt to represent the sites of ore bodies. Logs may be found in which the entire mass has been replaced by pitchblende.

Asphaltic segregations in sandstone may become at times strongly uraniferous. In the core of such masses the asphalt is hard, brittle and apparently polymerized. Sand grains have been replaced by organic material of petroliferous origin where the uranium mineralization has been most intense. Where both plant debris and petroliferous material have been observed in the same strata a preference has been noted in which the uranium-bearing solutions replace asphalt and leave the plant remnants largely untouched.

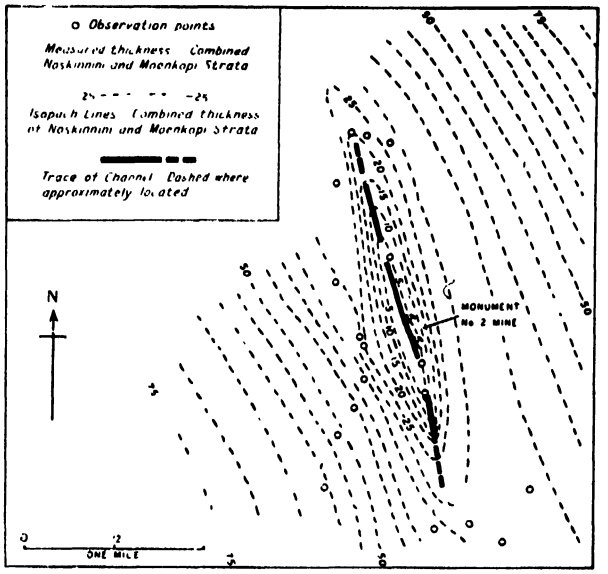


Figure 43. Channel-Swale relationship, monument number 2 area, Apache County, Arizona (after Witkind, Paper P/40, Session 6B, this Volume). Swales may indicate buried channels. Contours showing formational thickness have been used to indicate channels in the Monument Valley area, Arizona, USA

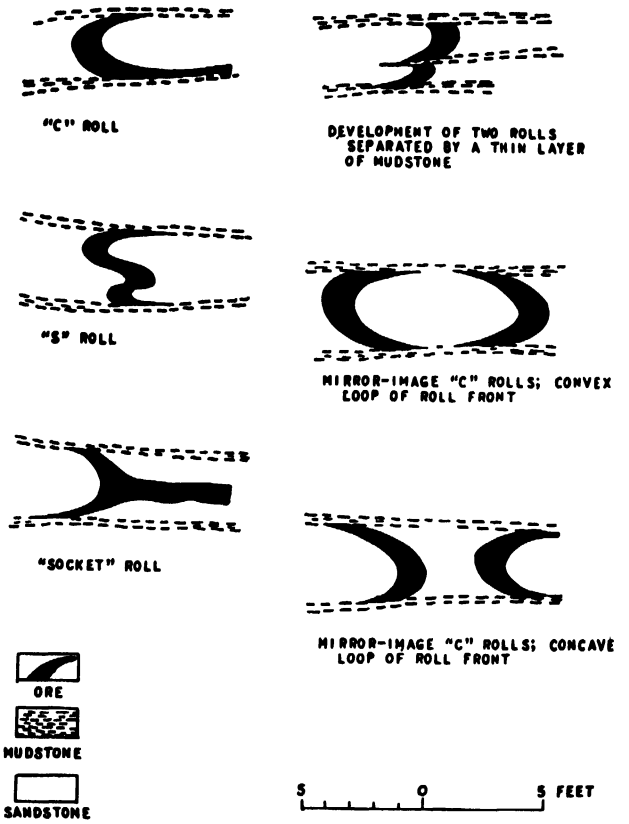


Figure 44. Cross-sectional forms of roll ore deposits (after Shawe, Paper P/36, Session 6B, this Volume). Cross sections of rolls. Unusual cross-section patterns may be attributed to conditions during precipitation

Laboratory study demonstrates that the presence of the S^{--} ion will bring about the precipitation of pitchblende from solution. The sulphur ion may be present in the form of S, SO_2 or H_2S. Sulphur is a common associate of organic material in nature, usually in the form of H_2S; hence further study will be required to determine the extent to which precipitation in uranium deposits is due to the organic material alone and to the associated sulphur-bearing constituent.

Uranium in Bituminous Strata

Uranium may be found under special circumstances in coal, lignite, carbonaceous shale, asphalt or thucholite. The grade in shale, coal or lignite is at times low, being measured in grams per ton, but the tonnages involved may be enormous with deposits underlying many square miles. Shale deposits, stratified, flat lying or only moderately inclined, and suitably close to the surface to permit large scale mining, have been described in Sweden, the United States, Canada and Norway. The most widespread are the bituminous shales of Mississippian and Devonian age which underlie large areas of the eastern, central and mid-western United States and southern Canada. Coal contains uranium in signifi-

cant amounts in some areas although many of the largest and best known coal areas are comparatively uranium free. The "kolm" deposits of Sweden (P/782) and the Great Divide Basin deposits in the western United States (P/287 and P/55) furnish examples of areas in which uranium occurs in coal. Lignite apparently may be more uraniferous than coal. Among occurrences in bituminous strata reported to date, the lignite-bearing beds of the South Dakota area in the United States appear to furnish the largest amount of uranium per ton of material mined.

Asphalt at times contains uranium. Fluid accumulations in petroleum reservoirs, thought to be associated with asphalt-bearing strata, yield the gases helium, radon and argon and, in addition, radium and uranium ions in insolution, particularly in the brines. Hard, brittle asphaltite (thucholite) has accumulated uranium at localities on the Colorado Plateau where hydrothermal solutions bearing uranium contacted asphalt in granular sediments.

Mechanism of Organic Accumulation

Specific minerals which would account for the uranium in the bituminous shales have not been reported. Uranium ions in the sea water are thought to have been adsorbed by the organic matter at the time the shales were deposited. Shales containing the most uranium may have a high content of phosphate, pyrite and organic matter mainly as plant debris. Such shales yield oil by destructive distillation and are low in calcium carbonate (P/51). The role of organic adsorption is supported by experimental observations (P/49) which show that coal will take up uranium from circulating groundwater with the formation of insoluble uranyl humates.

Three mechanisms (P/49) are recognized by which uranium may become fixed in carbonaceous materials: (1) organic material may serve as a reducing agent to convert the soluble uranyl ion (UO_2^{++}) to an insoluble uranous form; (2) the sulphide ion (S^{--}) normally present in carbonaceous substances acts as a reducing agent to convert the uranyl ion to the uranous form; (3) the carbonaceous material becomes a chemical precipitant for the uranyl ions.

Stratigraphic studies indicate that the more uraniferous shales known in the United States were deposited in epicontinental seas. The amount of uranium adsorbed by the shale appears to differ somewhat depending on whether deposition occurred in local marine basins, in geosynclinal areas, along geosynclinal fringe areas or in epicotinental areas.

While adsorption from sea water provides a tenable source for much of the uranium found in black bituminous shale, it has not been generally accepted for all occurrences in natural organic material. Some lignite beds occur beneath tuff-bearing strata known to contain small amounts of uranium. Elsewhere, tuffs may have been removed by erosion, but did overlie lignite for a considerable length of geologic time. Under such circumstances it has been suggested that circulating waters leached uranium from the tuff during some portion of geologic history and carried it downward where it came in contact with the lignite and was adsorbed by the organic matter.

In the case of more important high grade lignite, it has been suggested that a deep seated distant source should be considered for the origin of the uranium ions. The mechanism of emplacement should also include transportation of the uranium laterally through permeable lithologic units (P/286).

Uranium may be adsorbed by asphalt under conditions which suggest replacement by hydrothermal solutions. At the same time the widespread distribution of traces of uranium in petroleum points to adsorption of uranium by the organic matter at some early stage in formation (P/288).

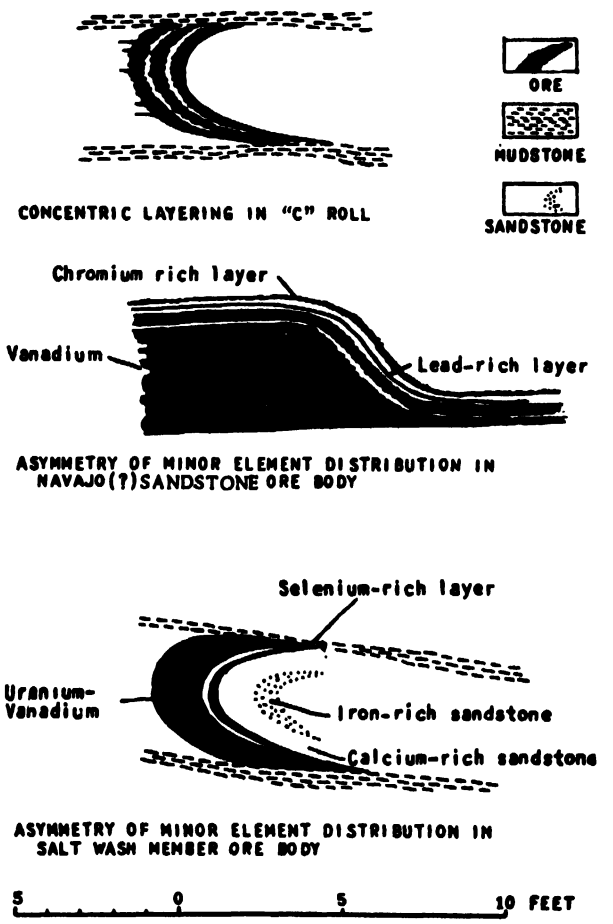


Figure 45. Details of roll ore bodies (after Shawe, Paper P/36, Session 6B, this Volume). Details of roll sections. Close study of rolls emphasizes features due to the action of solutions in permeable strata

Bituminous Black Shales

Significant amounts of uranium are found in the bituminous alum shales of Sweden. The highest values occur in strata of upper-Cambrian and/or lowermost Ordovician age. In seven provinces the alum shale contains about 100 grams of uranium per metric ton. The quantity present in sufficient

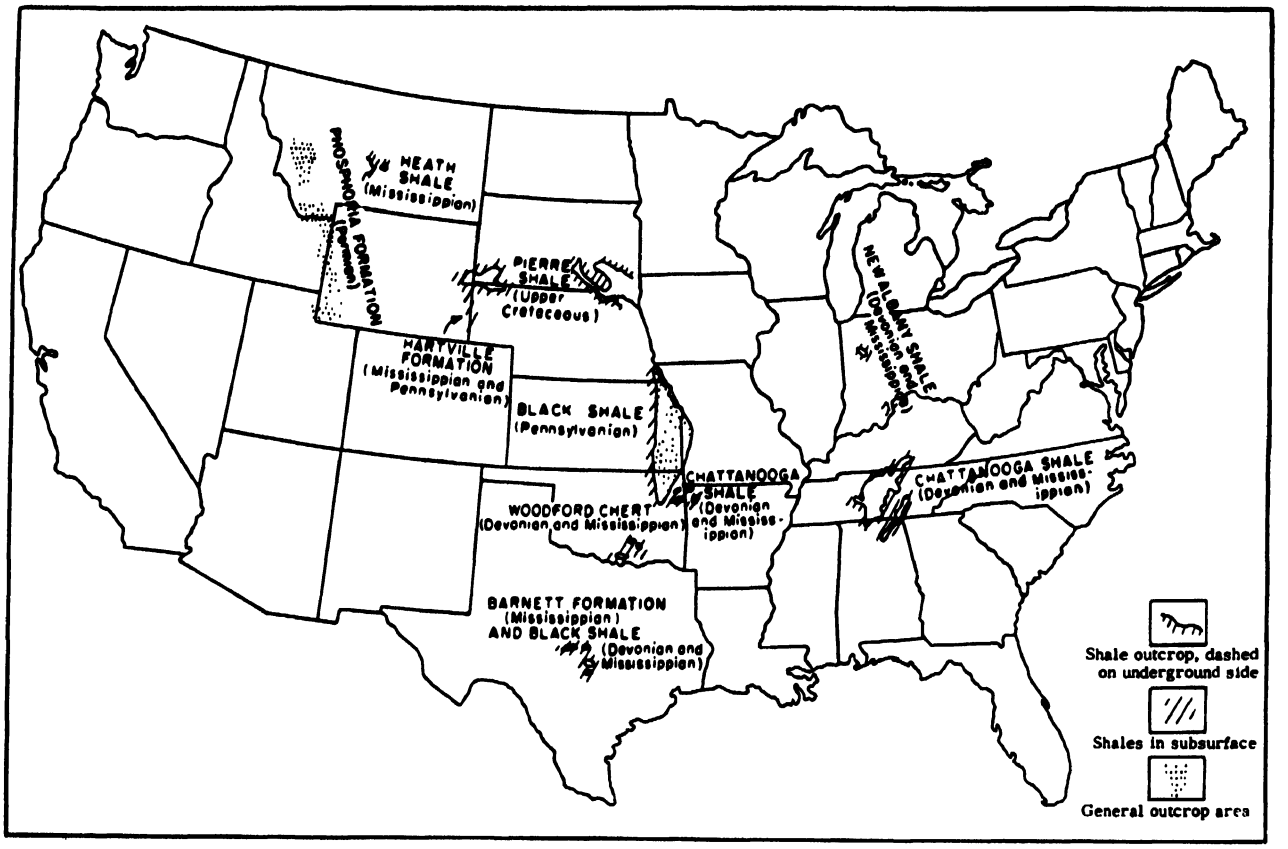


Figure 46. Distribution of significantly uraniferous black shale (after Swanson, Paper P/51, Session 6B, this Volume). Distribution of uraniferous black shale in the USA

amounts to justify mining may be estimated in hundreds of thousands of tons of uranium.

In Norway, uranium-bearing bituminous shales cover large areas. In certain beds there is an average of 100 ppm U (or 0.01 per cent), but thickness and uranium content vary greatly from place to place (P/887).

In the United States, 200 or more stratigraphic units, ranging in age from pre-Cambrian to Tertiary, are known to contain black shale. The shales of Paleozoic age have received the most study from the standpoint of uranium content (Fig. 46). In late Devonian and during early Mississippian times widespread blanket deposits of black shale were accumulated in the eastern and central parts of the United States. The Chattanooga shale and certain equivalents such as the New Albany, Ohio and Woodford formations are representative units. Such shale is about 50 feet thick and in general contains between 0.001 and 0.035 per cent uranium (P/51).

The Chattanooga shale (Fig. 47) is believed to have accumulated slowly in shallow water. It is postulated that the surface on which the shale was deposited was largely flat, but with a slight slope and contained occasional elevations. The connections with the ocean may have been remote, but are indicated by marine fossils now found in the shale (P/52).

The Gassaway member is the principal uranium-bearing unit in the Chattanooga shale. It is uniform in thickness and uranium content over a wide area. It appears most promising from the standpoint of uranium content along the Eastern Highland Rim in Tennessee in an area extending northeasterly from the Alabama state line. The Gassaway includes a lower black shale which averages 7 feet thick, an upper black shale which averages 6 feet thick, and an intermediate gray shale which averages 2.5 feet thick and thins eastward. The Gassaway as a whole contains 0.005 to 0.008 per cent uranium (P/53).

The Chattanooga shale is well stratified although accumulated in shallow water. Apparently disturbing

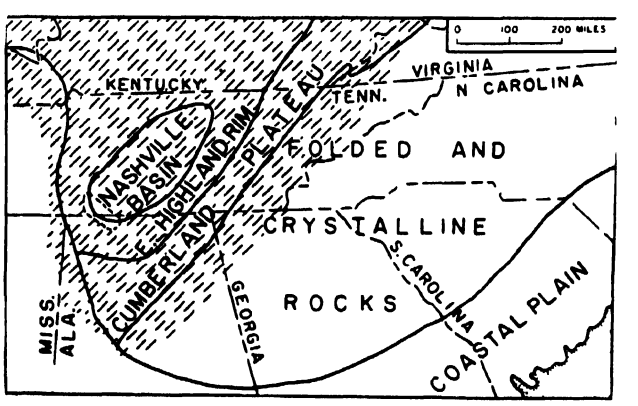


Figure 47. Chattanooga shale: shading shows the approximate area of shale accumulation (after Conant, Paper P/52, Session 6B, this Volume); uraniferous Chattanooga shale. The area of shale accumulation is indicated by shading

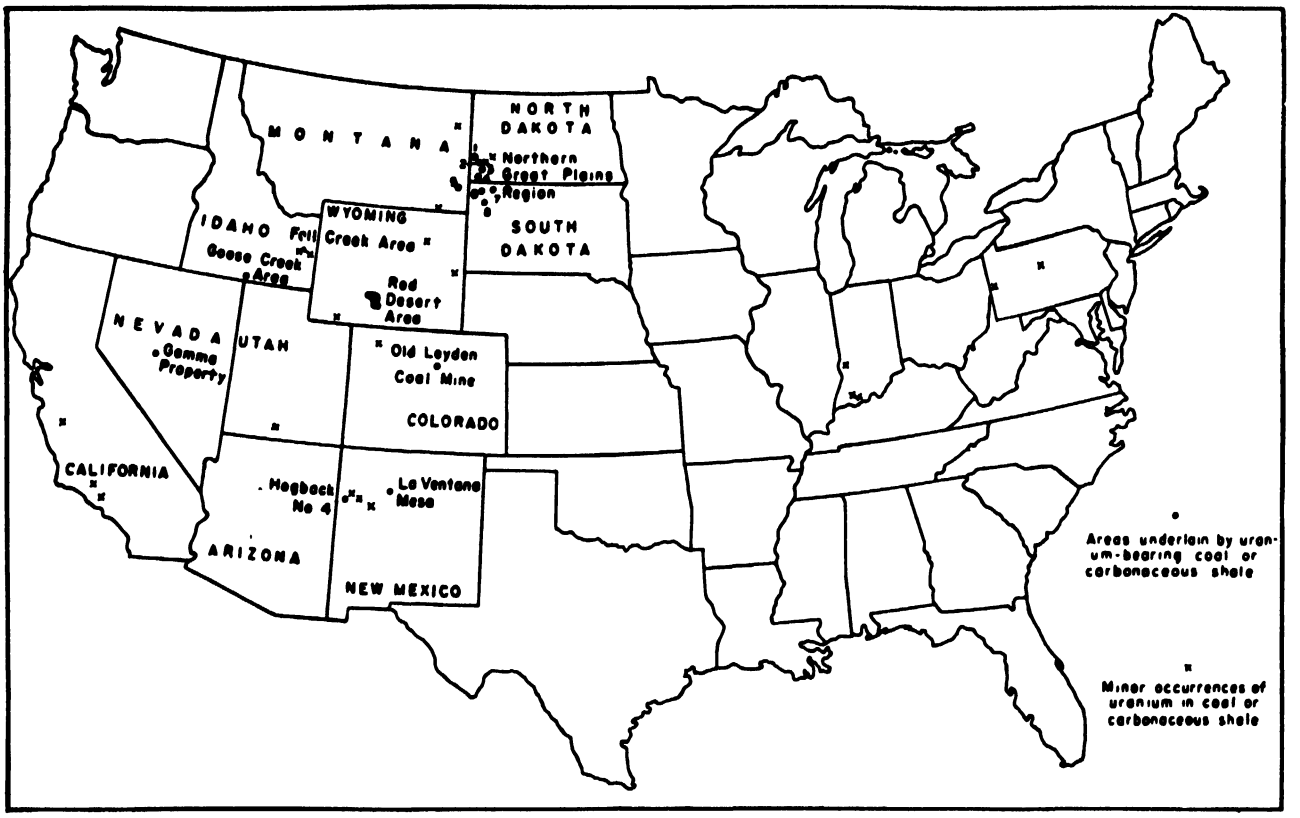


Figure 48. Distribution of uranium-bearing coal and carbonaceous shale in the U.S. (after Vine, Paper P/55, Session 6B, this Volume)

wave action was absent on the floor of deposition. The muds were agitated gently and repeatedly, becoming well stratified. Although the sea was large, the gently sloping bottom, irregular shore, scattered islands and abundant planktonic life explain the absence of strong wave action (P/52).

The shales were apparently subjected to a reducing environment as shown by the presence of abundant plant remains and about 10 per cent pyrite. The plant matter is a mixture of planktonic marine organisms and land plants. These include spores, macerated particles of *Foerstia,* and logs of *Callixylon* several feet long and a few millimeters thick. Uranium is believed to have been abstracted from the sea water by plant debris which had ample time to take up the element before burial. Some of the logs have become films of bituminous coal with as much as 0.02 per cent uranium. This has been explained as due to longer exposure to sea water.

Black shales representing a spread in age from pre-Cambrian to Cretaceous are found in the Rocky Mountains and Great Plains regions of the United States and southern Canada. These have been penetrated in wells drilled for oil and gas and frequently crop out on the surface (P/54).

Shales of Mississippian age, variously named as the Kinderhook, Bakken or Exshaw formations, underlie much of the Williston Basin region of Montana, North Dakota and adjacent parts of Canada. The shales range in thickness from a few inches to 100 feet. Samples from four oil and gas test wells in the Montana-North Dakota area are reported to contain 0.005–0.008 per cent uranium. Gamma ray data from oil well logs have been used to prepare an isoradioactivity map. Here the radioactivity of the shales appears greatest near the northeastern corner of Montana and decreases concentrically outward (P/54).

Formations that contain beds of unusually radioactive black shale include the Brazer limestone of northern Utah, the Heath shale of central Montana, the Minnelusa sandstone of eastern Wyoming and western South Dakota and parts of the Pierre shale of eastern Montana and adjacent states (P/54).

Basal black shales of Cretaceous Dakota sandstone yield uranium ores of commercial grade in northwestern New Mexico. The main occurrences lie around the upturned edges of the San Juan Basin. The shale beds are discontinuous lenses which are interfingered with discontinuous paleostream channel sand lenses. Locally, the shales grade into peats and low rank coals. There are also lenses of sandstone highly contaminated with wood-derived carbonaceous trash. Deposits of uranium in carbonaceous sandstone, carbonaceous sandstone enclosed by shale, black shales interbedded with sandstones and black carbonaceous shales are reported from the Zuni and Nacimiento uplifts on the southwestern, southern and eastern sides of the San Juan Basin (P/50).

No uranium minerals have been recognized in the shales and the uranium is presumably adsorbed by the organic matter. Occasionally, beds of pure black carbonaceous shale or peat overlying paleostream channels are mineralized in preference to the sands

below. Oxidized yellow uranium minerals are found along rock fractures or joint planes in carbonaceous sandstone (the latter a secondary mineralization).

Coal

In the province of Närke, Sweden, a kind of coal, "kolm," has been found with a uranium content of about 3000 grams per ton (or about 0.33 per cent).

Most coal in the United States is essentially free from uranium. In fact, the major coal fields of the Appalachian and mid-continent regions of the United States contain almost no uranium. In the Rocky Mountain region, however, certain large deposits of coal contain uranium (P/55).

An area of about 750 square miles of the Great Divide Basin, of Sweetwater County, Wyoming, is underlain by uranium-bearing coal which occurs in strata of early Eocene age. Locally portions of coal beds may contain as much as 0.016 per cent uranium, but most of the coal contains less than 0.003 per cent. Uranium in ash obtained by burning the coal ranges from 0.005 to 0.023 per cent (P/287).

The Wasatch formation of Eocene age contains up to 700 feet of coal-bearing rocks (Fig. 48). The coal contains the most uranium where directly overlain by conglomerate, possibly of the Miocene age, or where it is adjacent to permeable sandstone beds in the Wasatch formation (P/55).

The coal and associated strata were cyclically deposited in swamps around the margins of lakes which existed in Green River (Eocene) time. To the southwest these strata are interbedded with lacustrine Green River shale and to the northeast with fluviatile arkose sandstone of the Wasatch formation. The total sequence is about 1200 feet thick with the axis of maximum coal deposition trending northwesterly (P/56).

At Creston Ridge, the uppermost coal contains 0.051 per cent uranium near the top of the bed, but coal 20 feet lower contains less than 0.001 per cent. In the basin as a whole, the highest concentrations appear to be localized in coal unconformably overlain by gravels of possible Miocene age. The lower uranium-bearing portions of the coal, which average about 0.003 per cent, are widespread and appear related to the permeability of enclosing rocks. The uranium content is greater to the northeast where the enclosing rocks are coarser grained and more permeable (P/56).

Weakly uraniferous tuffaceous sandstone beds in the Browns Park formation of Miocene age once covered the area of the Great Divide Basin. Portions of the beds now remain as erosional remnants. It has been suggested that groundwater leached the uranium from the tuffaceous strata to be subsequently taken out of solution by the coal. The migration of groundwater was controlled both by the structural features of the district and the interfingering of strata differing in permeability (P/287).

Three possible sources have been suggested for the uranium in the coal: (1) hydrothermal solutions rising along faults; (2) leaching from granite in the region containing traces of uranium; (3) leaching from overlying tuffaceous rocks containing traces of uranium. It has been shown by laboratory experiments that the coal could serve as an adsorbent for uranium from natural waters. Petrographic studies show that uranium in the Carbonaceous rocks is consistently accompanied by traces of gallium, germanium, iron molybdenum, lead, vanadium and the rare earths (P/56).

Lignite

Uranium-bearing lignite deposits are found near the junction of Montana with North and South Dakota about 100 miles north of the Black Hills. Scattered areas of badlands or buttes rise above the rolling prairie. More prominent buttes are underlain by lignite.

Mineralized lignite beds occur throughout 2000 feet of fluviatile deposits of Paleocene and late Cretaceous age. In general, strata are almost flat, being inclined at about 10 to 40 feet per mile northeasterly into the Williston Basin. The uranium content of the organic strata is 0.005 to 0.02 per cent while the ash yields 0.05 to 0.1 per cent. Almost one-fifth of the uranium-bearing lignite is in beds 4 feet thick and close enough to the surface to permit strip mining. Large tonnages containing 0.008 per cent uranium are available.

High grade uranium-bearing lignitic material occurs in the northwest corner of South Dakota in the Ludlow and Tongue River members of the Fort Union formation of Paleocene age. The lignite is found within 100 feet stratigraphically both above and below the plane of contact between the two members. Deposits occur beneath isolated mesas with a total area of about 100 square miles (P/286).

Lignite reserves have been estimated on the order of 100,000 tons, containing some 200 tons of uranium. Lignitic units less than 18 inches thick containing up to 10 per cent uranium contrast with weakly uraniferous material. The uranium is mainly intimately associated with the organic material although rare exposures exhibit autunite and other fluorescent minerals on the cleavage surfaces of the lignite.

Mildly radioactive tuffs and bentonites of Oligocene and Miocene age some 250 feet thick overlap the lignites. Chemical analyses of water from the tuff are reported to show significant concentrations of uranium, arsenic, vanadium, molybdenum and copper. Molybdenum is closely associated with uranium in the lignite in concentrations which range from 0.01 to 1.0 per cent in the residue from burning.

These factors have led to the suggestion that the uranium now found in the lignite was originally a constituent of the volcanic tuff or bentonite. The uranium ions were leached from the tuff strata by percolating waters. The lignitic strata acted as receptors that extracted the uranium by ion exchange or by the formation of organo-metallic compounds (P/57).

Several points of evidence favoring the tuff-leach

theory of origin as applied to the weakly uraniferous lignite are less conclusive when applied to the high grade deposits. The beds of high grade lignite appear to differ from the low grade in chemical and physical characteristics. The high grade beds are also localized relative to paleoground water systems and are not confined to the stratigraphically or topographically highest lignite. The association of molybdenum with the lignite is considered by King to be incompatible with an origin in sedimentary rocks (P/286).

Asphalt

Spectrographic analyses have been made of asphaltic materials from 49 areas in California, Utah, Wyoming, Montana, New Mexico, Texas, Oklahoma and Missouri. The asphalt was extracted from the host rock and calcined. The ash was analyzed chemically for uranium and also semi-quantitatively for other elements by spectrographic methods. Significant amounts of uranium were found in the ash of the extracted oil the maximum amounts being recorded as follows:

State	*U %*
California:	
Chalone Creek	0.50
McKittrick	0.15
Edna	1.9
Los Alamos	0.33
Utah:	
Vernal	0.15
Oklahoma:	
Sulphur	0.22
Missouri:	
Ellis	0.41

The average uranium content of the ash for the 7 areas ranges from 0.028 to 0.376 per cent. With the exception of Chalone Creek, the areas contain large reserves of asphalt-bearing rock ranging from 15,000,000 to 2,000,000,000 short tons. In 13 additional areas the average uranium content ranges from 0.02 to 0.068 per cent uranium in the ash of the extracted oil (P/288).

Host rocks in which the asphalt is found include sandstone, arkose, tuff, limestone, diatomite and alluvium. It has been shown by chemical analyses that the uranium is concentrated as an organo-uranium complex in the asphalt and not in the host rock. Apparently the uranium occurred as an original constituent of the oil or was introduced during the migration of the oil.

Crude oils, oil seeps and petroliferous rocks from the central and western United States have been analyzed for uranium and traces of various metals. Seep oil and other surface accumulations are shown to be generally enriched in uranium in contrast to the crude oil fraction as produced at the well head.

The oil-gas reservoirs of the Wichita–Amarillo uplift of Oklahoma and Texas contain concentrations of uranium in the form of metalliferous asphaltite, a carbonaceous mineraloid similar to thucholite, carburan and huminite. Abnormal concentrations of radon and helium in the Panhandle Field of Texas are associated with uraniferous asphaltite nodules and impregnations. Uraninite, coffinite and thorite have been reported from nodules; but in many, the uranium-bearing compound (possibly a metallo-organic complex) has not been identified. The trace metal suite corresponds to that found in the ash of crude oil.

The gases radon, helium and argon as well as radium, uranium and thorium, occur in certain oil and gas fields in the United States. The uranium content of oil field brines subjected to analysis has been found to be as much as 0.2 ppm. Brines also have a high content of radium and yield radium precipitates on pipes.

The genetic relations involved in the origin of helium and the associated uraniferous asphaltites are not too well understood. Evidence to date indicates that asphaltite must have been localized in rock pores in the presence of petroleum or a combination of petroleum and water. The localization also resulted in the concentration of uranium with other metals in disseminated point-segregates. The process of localization was apparently not dependent on the rock type and was effective over broad structural areas.

Uranium in Phosphate Rock

Two large areas in the United States have been studied to determine the extent to which uranium might be available as a by-product in mining phosphate rock. Marine phosphorites are widely distributed and contain small amounts of uranium which may be partly recoverable under favorable conditions (P/290).

Phosphate deposits are found in the Phosphoria formation (Permian) in Montana, Idaho, Utah and Nevada over an area of 135,000 square miles (P/291). In Florida the Bone Valley formation (Pliocene) yields phosphate rock in an area in excess of 1000 square miles, mostly in Hillsborough and Polk counties. The uranium is believed to have been adsorbed from sea water by the phosphate particles as they accumulated on the sea floor (P/293).

In the western United States, the richest deposits occur in eastern Idaho and adjacent parts of adjoining states. The uranium content of the phosphatic beds ranges from about 0.001 to 0.065 per cent. Phosphate beds more than 3 feet thick which contain more than 31 per cent P_2O_5 generally contain 0.01 to 0.02 per cent uranium. Most of the uranium appears to occur in carbonate fluorapatite (P/291).

The calcium phosphate zone in the lower part of the Bone Valley formation of Florida and the upper part of the Hawthorne formation on which the Bone Valley rests contains about equal parts of quartz sand, phosphate particles and slime.

In the central part of the area in which the Bone Valley formation is found, the phosphate particles are predominantly coarse in contrast to the surrounding area where they are fine. The coarser particles

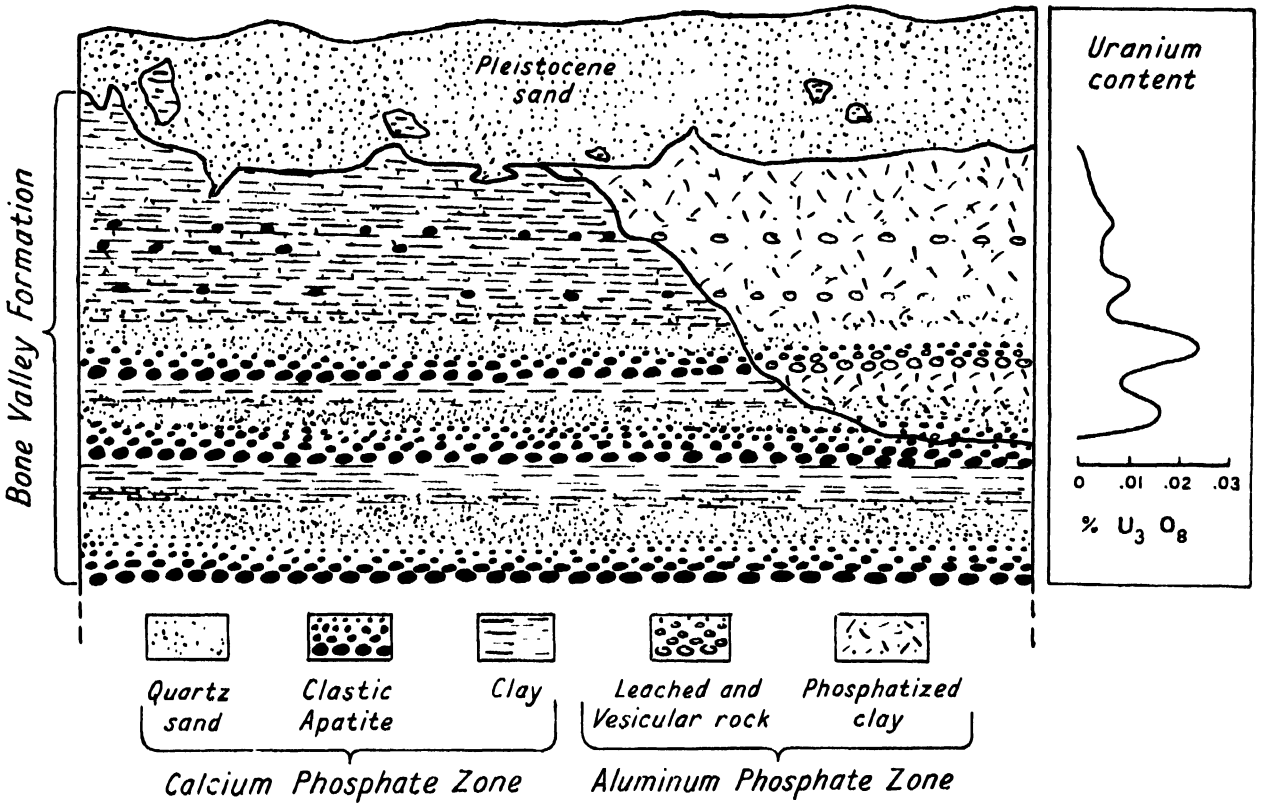


Figure 49. Stratigraphic relations in the aluminum phosphate zone (after Altschuler, Jaffe and Cuttitta, Paper P/292, Session 6B, this Volume). Uranium in leached phosphate strata. The uranium and phosphate exhibit a reversed relationship with uranium increasing as phosphate decreases in the weathered zone

are higher in uranium and lower in P_2O_5 content in comparison with the fine particles (P/293) as follows:

	U %	*P_2O_5%*
Coarse pebble phosphate	0.01–0.02	31.5
Fine phosphate	0.005–0.015	34

A leached zone 6 to 7 feet thick exists at the top of the Bone Valley formation which has been altered by weathering and groundwater action (Fig. 49). Here the carbonate-fluorapatite which prevails below the leached zone has been progressively altered to aluminum phosphate. At the same time, the uranium content which is about 0.008 per cent in the lower unaltered rock is increased to 0.012 per cent (P/292).

The phosphate content below the leached zone is about 15 per cent P_2O_5, and within the leached zone it is about 8 to 10 per cent. The weathering has resulted in adding phosphate to the clay constituent and alumina to the apatite. Carbonate-fluorapatite of the unweathered rock below is incipiently leached and altered at the base of the weathered zone. Above in a middle zone, the calcium-aluminum phosphates crandallite and millisite are found. At the top, the aluminum phosphate wavellite predominates (P/292).

In mining phosphate rock, the upper weathered zone must be stripped in order to reach the underlying rich phosphate deposits. The stripped material contains a substantial amount of quartz, but the latter could be readily removed. In view of this situation, the leached Florida material has been considered as a considerable potential low grade uranium reserve (P/292).

Thorium-bearing Detrital Deposits

The most important accumulations of thorium have been formed by mechanical processes in the course of which thorium minerals have been eroded from older rocks, transported by stream action, and deposited in poorly consolidated sediments. Ordinarily, commercial deposits of this type are geologically youthful, and the deposits are loosely compacted. In contrast, pre-Cambrian quartzites, grits and conglomerates have been found in which thorium has also accumulated by mechanical action. These old rock types are hard, brittle, compact and often have been recrystallized.

It is interesting to note that no important sources of thorium minerals other than of detrital origin have yet been found in sedimentary rocks of an arenaceous type (P/301).

More recent loosely consolidated detrital deposits of thorium have been reported in India, Brazil, Taiwan and the United States. It is stated (P/875) that the littoral of Travancore-Cochin in India contains over a million tons of monazite, a thorium asset of world importance. Thorium is a constant constituent of India monazite to the extent of 8 to 10.5 per cent ThO_2. Indian monazite is also reported to contain 14 rare earths and metals of the cerium group. The

beach sands of the Malabar and Coromandel coasts furnish the main source of Indian monazite. Both coasts have yielded a number of new deposits during the last two years (P/875).

Although each deposit has certain pecularities, the monazite-bearing concentrations are usually black because of the presence of magnetite and ilmenite, or red where garnet is a noteworthy constituent. In general, the primary source of the monazite[4] is the crystalline rock which lies between the projected base of the Deccan lavas and the present land surface. The heavy minerals are brought to the coast by streams to form alluvial deposits which in turn are concentrated by along-shore currents.

The Travancore Coast[87] is the major occurrence, although Hess[32] indicates that the mineral is known on the east coast as far north as the Mahandi River as well as in the Kistna River alluvium. The principal deposits found along the east coast lie south of Madras.

Along the west coast which includes Travancore, strong currents from north to south cause the monazite to accumulate southward. Along the east coast the currents run from south to north with a consequent transference of material northward. From May through September storms aggrade the bays and replenish the parent sand, whereas during the rest of the year gentler waves remove only the light quartz and leave a surface concentration of monazite, ilmenite, zircon and other heavy minerals.

Numerous pegmatites occur along the periphery of the Brazilian Shield.[4] These contain monazite together with rare earth minerals. The monazite is estimated by Friese[29] to contain an average of about 6% ThO_2 and 0.15–0.25% UO_2. The heavy minerals have been concentrated by stream action in Cenozoic sediments and in recent beach bars. The principal deposits lie along the beaches between Cape Frio and Recife where they tend to occur close to the strand line or on elevated bars. Generally, the best monazite deposits have a width of about 10 meters, a length of about 1 kilometer and a thickness of about half a meter. The deposits at Comoxatiba, Guarapary and Macahe are considered[4] to be the richest in Brazil.

Leonardos[59] describes lower grade thorium ores further inland in the recent river deltas and along the streams. Some monazite is also found in the diamond washings at the Pardo River, near Maracao, and at Contas near Bom Jesus dos Meiras. The gold-bearing gravels of the northwestern tributaries of the Rio Parahyba do Sul also contain monazite. Barbosa[6] describes monazite associated with finely divided gold in the stream placers of the Santa Isabel do Rio Preto district which he considers to be of potential economic significance.

Thorium-bearing detrital deposits are found on the island of Taiwan (P/865). Monazite associated with zircon, ilmenite and magnetite occurs in appreciable amounts along present beaches, stream beds and off-shore bars in western Taiwan. The heavy minerals containing thorium, zirconium and titanium are thought to be derived from the erosion of Tertiary strata. The Tertiary strata in turn received their original sediments from monazite-bearing igneous rocks of the oldlands.

Three types of sand deposits are recognized: (1) beach and dune deposits along the north and norhtwestern coast; (2) beach deposits found on barriers off the southwestern coast; and (3) fluvial deposits along stream courses on the southwestern coastal plain.

The heavy sand represents about 2.7 per cent of the crude sand. The estimated reserve of heavy sand is 200,000 metric tons, consisting of 8800 tons monazite, 24,000 tons zircon, 44,600 tons ilmenite and 35,900 tons of magnetite.

In the United States, placer deposits containing thorium-bearing minerals and large enough to justify dredging operations occur in Idaho in the Bear Valley County. The heavy mineral content of the placers has been determined in pounds per cubic yard as follows: euxenite, 1.0; monazite, 0.5; zircon, 0.05; garnet, 10.0; ilmenite, 20.0; magnetite, 5.0 and columbite, 0.2.

Euxenite, a complex rare earth-uranium§-thorium-titanate-columbate, and monazite are the two thorium-bearing minerals in the heavy mineral concentrate (P/305).

In the Hailey area of Blaine County, Idaho, not far distant from the first area, placers with a considerably different heavy mineral content occur. Here the heavy mineral content in pounds per cubic yard is as follows: uranothorite, 0.5; zircon, 0.5; garnet, 0.1; sphene, 1.0 and magnetite, 10.0.

The thorium minerals of the placer deposits were apparently derived from quartz-monzonitic phases of the Idaho batholith, one of the great intrusive areas of the western United States. Euxenite, uranothorite and monazite occur as accessory minerals in the quartz-monzonite. Segregations of these minerals measure from a few inches to tens of feet in diameter. These may contain as much as 0.05 pounds of euxenite per ton at Bear Valley, 0.8 pounds of uranothorite per ton near Hailey and 0.25 pounds of monazite per ton in the vicinity of Cascade (P/305).

Segregations are erratically distributed and concentrations do not appear to occur in or near pegmatite dikes as might be expected. The grade of the placer deposits appears to depend upon the extent to which the segregations of heavy minerals have formed in tributary areas of quartz monzonite. The physiographic development of the region is involved in the interpretation of the transfer of the heavy minerals from the original sites in the batholith to the placer deposits (P/305).

Sediments of the Atlantic Coastal Plain yield thorium. Monazite is sparsely but widely distributed as a detrital mineral in Cretaceous, Tertiary and

§ The uranium content of such an occurrence would be estimated to be on the order of 0.002 per cent or less.

Quaternary strata. Ordinarily, monazite constitutes less than 0.1 per cent of the sediment.

In the United States, monazite (7.5% Th) occurs in pre-Cambrian quartzite in part of the Marquette iron district in northern Michigan. The thorium mineralization is found in the Palmer area on the south limb of the Marquette synclinorium in the Goodrich quartzite of upper Huronian age. Monazite occurs in rounded to subrounded grains believed to be of detrital origin. These are concentrated mainly in the matrix of quartz pebble conglomerate which is interbedded with coarse grained quartzite. Drill core specimens contain up to 54 pounds of monazite per ton while samples from glacial erratics and mine dumps contain as much as 110 pounds per ton. When ground to 150 mesh, the monazite is more than 85% recoverable by gravity separation. In view of the large tonnage of the monazite-bearing quartzite available, the northern Michigan area may represent a considerable potential low grade monazite reserve.

INTERPRETATIONS OF ORIGIN ¶

The conference papers and the literature furnish a variety of interpretations which apply to the origin of uranium and thorium deposits. Space does not allow more than mention of alternative hypotheses, but a brief review of sources and mechanisms of emplacement should aid in recognizing the major problems of genesis.

Original sources to which uranium and thorium are attributed in the formation of deposits are: (1) molten magma, (2) hot fluids, (3) groundwater, (4) surface solutions, (5) sea water, (6) volcanic ash deposits, and (7) deposits exposed to erosion.

1. Molten magma. Direct crystallization of thorium and some uranium occurs in granite and other rock types. Such uranium deposits, with the possible exception of Nigeria, are sub-commercial. End-stage residuum which forms dikes (pegmatites) and mixed rocks (migmatites) furnishes choice specimens, but usually fails to yield commercial deposits.

2. Hot fluids. Deposits are formed through the action of heated fluids. They constitute the most distributed single group and cover a wide range of temperature, pressure and chemical conditions. Uranium deposits which belong to this group include Radium Hill, Shinkolobwe, Great Bear Lake, Athabasca, Joachimsthal, Marysvale and many others. Thorium in the crystalline rocks of India, Brazil and North America is included.

Radium Hill formed under both high pressure and high temperature from solutions which were rich in iron, titanium, rare earths and uranium. This occurrence probably represents crystallization under the highest pressure-temperature conditions of the major deposits. This origin appears to follow closely the end-stage of pegmatitic igneous activity.

Shinkolobwe exhibits an abundance of nickel and cobalt sulphides which were preceded by widespread replacement of dolomite by magnesium carbonate and silicate minerals. Cubic crystals of uraninite as well as the related monazite veins suggest high temperature. The deposit appears to represent pressure-temperature conditions which are lower than those of Radium Hill, but higher than those of the Canadian deposits.

The Athabasca veins of Canada are thought to have originated in solutions at temperatures of 250° to 350°C and to have resulted from surges during widely separated time intervals. Other pitchblende veins of the Canadian Shield may be more or less similar. Precipitation probably occurred deep in the earth's crust.

At Joachimsthal, the prevalence of bismuth and silver may indicate lower temperature conditions than those which prevailed in general on the Canadian Shield. However, the pitchblende is rather similar, and much silver was reported during the early development of Great Bear Lake; the two occurrences, therefore, may be nearly parallel.

At Marysvale, Utah, pitchblende is poorly crystallized and intimately associated with fluorite and pyrite. Clay mineral alteration of the wall rock is intense, although in general base metal sulphides are absent. That temperatures and pressures were lower is shown by the geological environment.

Where pitchblende deposits occupy vertical or steeply inclined fractures, there is ordinarily agreement that deposition took place from heated solutions. When it occurs in flat or moderately inclined strata, opinions as to origin often differ. This situation particularly applies to deposits of the Blind River-Witwatersrand and the Colorado Plateau types.

A major problem of the Colorado Plateau is the source of the uranium-bearing solutions. Thermal solutions, ordinary groundwater and percolating waters which leach from above have been suggested. Leaching would derive uranium from the ash beds which are abundantly distributed through the plateau strata. Ordinary groundwater would find the uranium in pre-existing deposits. Thermal solutions would transport the uranium ions through crustal rocks which exist below the sediments and represent the last phase of igneous activity.

Many difficulties arise in the interpretation of the origin of stratified ore bodies. Ores accumulate in channels, although evidence of the vertical movement of solutions is observed only occasionally, and deposits terminate abruptly above and below. Laboratory evidence indicates that in time pitchblende may be precipitated at temperatures as low as 50°C.

Veins at Los Ochos and Placerville on the Colorado Plateau cut across plateau sediments yet correspond in mineralization to plateau type ore bodies. A wide vertical distribution of ore-bearing strata in many formations exists. Upward migration of magnesium and calcium as an accompaniment to ore-bearing solutions has been observed at Temple

¶ References have been omitted from this section in order to provide continuity and brevity. However, the discussion is derived largely from the preceding pages where specific references are given.

Mountain. Broadly distributed faults and fractures adequate for the vertical migration of solutions have been recognized. Igneous activity occurs both around and within the plateau in numerous places. The age of pitchblende appears to be younger than the enclosing strata which indicates later emplacement. Many elements which accompany pitchblende emplacement are uncommon constituents of the accompanying sediments. Some of these elements form minerals which, if found in vein deposits, would be assumed to have been derived from below. Hard, brittle petroliferous materials which contain enough uranium to form ore apparently have been polymerized as a result of abnormal heating. That the oxidized minerals of the plateau strata were not the first to form is indicated by remnant masses of pitchblende and coffinite. Microscopic study and field observation indicate precipitation from solution. Such factors would point to an origin from heated solutions.

The emplacement of uranium in ancient sediments of the Blind River-Witwatersrand type has been subject to two interpretations. In one, the ore was transported from an ancient source and deposited as the sediments accumulated. In the other, deposition occurred from heated solutions. These ores lie along channels, and their boundaries are reasonably sharp both above and below. The major features of the deposits are sedimentary, although the theory of mechanical transportation and emplacement encounters source difficulty due chiefly to the character of the mineralization. Close study of the minerals indicates that the uranium must have been introduced after the sediments were deposited and probably prior to the cementation which reduced permeability. Here again the weight of evidence appears to favor thermal solutions.

3. Groundwater. As heated solutions rise they encounter groundwater, but the extent to which metal ions originate at depth in hot fluids or are merely transported from place to place by groundwater remains to be determined. Major deposits where the origin of the ions may be traced to hot crustal fluids are well known. The deposition of radium-bearing material out of equilibrium has been observed in groundwater around oil fields, although uranium production from such an origin is not reported. If groundwater is important as a major originating agent, it should receive much more careful study than it has received in connection with the origin of uranium and thorium.

4. Surface solutions. Uranium is subject particularly to the oxidizing action of surface and near surface waters, and the end products of this process are oxidized uranium minerals. Deep weathering of pitchblende occurs in permeable areas which are subject to a fluctuating water table as at Rum Jungle, Shinkolobwe and Gunnar. Wide distribution of uranium by this method is doubtful.

5. Sea water. The theory of widespread distribution of small amounts of uranium in organic shales and phosphate rock by adsorption from sea water during accumulation appears to be widely accepted. Yet the uniformity of such distribution indicates that other conditions must be considered in order to account for local concentrations of ore in areas such as South Dakota.

6. Volcanic ash deposits. In the Wyoming-South Dakota area, some authors devote particular attention to uranium concentrations in sedimentary strata as being due to the leaching of overlying ash deposits by surface waters. However, others who have worked in the area attribute the origin to rising thermal waters. Although the literature provides important items in support of both hypotheses, until more information is available on the uranium content of volcanic ash and the distribution of uranium in strata both above and below known deposits, the origin may not be explained properly.

7. Deposits exposed to erosion. Thorium-bearing placers of India, Brazil and Idaho are derived from the mechanical destruction of pre-existing thorium-bearing rocks. Although thorium minerals have resistant properties which permit widespread transportation prior to accumulation in detrital deposits, uranium minerals disintegrate in this process. However, uranium may be found in minor amounts with thorium.

In conclusion, it should be noted that the Conference papers as well as the literature indicate important progress toward a better understanding of the natural occurrence of uranium and thorium. No other similarly short period in history has witnessed such an accumulation of knowledge about two naturally occurring elements. The results of these studies have established geological patterns of occurrence which are fundamental to the maintenance of a continued supply of raw material. A great mass of information is now available to provide supplies for the peaceful uses of atomic energy. At the same time, these studies contribute to a better understanding of the occurrence of other metals which are useful in peaceful applications.

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REFERENCES**

1. Allen, E. T. and Zies, E. G., *A chemical study of the fumaroles of the Katmai region*: Nat'l Geogr. Soc. Conf. Tech. Papers, Katmai Series, v. 1, no. 2, p. 75–155 (1923).
2. Anonymous, *Uranium soars to prominence in South Africa's gold fields*: Eng. Min. Jour., v. 154, p. 72–76 (1953).
3. Arrol, W. J., Jacobi, R. B. and Paneth, F. A., *Meteorites and the age of the solar system*: Nature, v. 149, p. 235–238 (1942).

** This section lists publications (apart from papers) submitted to the Conference and reports selected from the literature.

4. Bain, G. W., *Geology of the fissionable materials*: Econ. Geol., v. 45, p. 273–323 (1950).
5. Bannister, F. A. and Horne, J. E. T., *A radioactive mineral from Mozambique related to davidite*: Min. Mag., v. 29, p. 101–112 (1950).
6. Barbosa, C. do P., *Monazita de Santa Isabel do Rio Preto*: Sk. Map, Inst, Nac. Tec., Rio de Janeiro, p. 17 (1948).
7. Barth, T. F. W., *Theoretical petrology*: New York, John Wiley and Sons, Inc., p. 387 (1951).
8. Bateman, J. D., *Recent uranium developments in Ontario*: Econ. Geol., v. 50, p. 361–372 (1955).
9. Brown, H. S., *A table of relative abundances of nuclear species*: Reviews of Modern Physics, v. 21, p. 625–634 (1949).
10. Bullen, K. E., *A hypothesis on compressibility at pressures of the order of a million atmospheres*: Nature, v. 157, p. 405 (1946).
11. Buttenbach, H., *Minéralogie du Congo Belge*, Brussels, M. Hayez, p. 183 (1925).
12. Cohen, W. J., *A note on pitchblende and uraninite*: Annual Report for June 30, 1952 to April 1, 1953, United States Atomic Energy Commission, RME–3046, p. 58–63 (1953).
13. Collins, C. B., Lang, A. H., Robinson, S. C. and Farquhar, R. M., *Age determinations for some uranium deposits in the Canadian Shield*: Geol. Assoc. Canada, Proceed., v. 5, p. 15–41 (1952).
14. Cooper, R. A., *Mineral constituents of Rand concentrates*: J. Chem. Soc. S. Afr., v. 24, p. 90–95, 264–266 (1923).
15. Davidson, C. F., *The gold-uranium ores of the Witwatersrand*: Min. Mag., v. 88, p. 73–85 (1953).
16. Davidson, C. F. and Bennett, J. A. E., *The uranium deposits of the Tete district, Mozambique*: Min. Mag., v. 29, p. 291–303 (1950).
17. Davidson, C. F. and Bowie, S. H. U., *On thucholite and related hydrocarbon-uraninite complexes*: Bull. Geol. Surv. Gt. Britain, no. 3, p. 1–19 (1951).
18. Derriks, J. J. and Vaes, J. F., *Le gite d'uranium de Shinkolobwe*: Geol. Dept. L'Union Miniere du Haut Katanga, p. 67 (1955).
19. Ellsworth, H. V., *Thucholite, a remarkable primary carbon mineral from the vicinity of Parry Sound, Ontario*: Am. Min., v. 13, p. 419–441 (1928).
20. Ellsworth, H. V., *Rare-element minerals of Canada*: Econ. Geol. Series, no. 11, Canada Dept. Mines, p. 242 (1932).
21. Everhart, D. L. and Wright, R. J., *The geologic character of typical pitchblende veins*: Econ. Geol., v. 48, p. 77–96 (1953).
22. Faul, H., ed., *Nuclear geology, a symposium on nuclear phenomena in the earth sciences*: New York, John Wiley and Sons, Inc., p. 414 (22a page 264, 22b page 267, 22c page 270) (1954).
23. Fisher, N. H. and Sullivan, C. J., *Uranium exploration by the bureau of mineral resources, geology and geophysics, in the Rum Jungle province, northern territory, Australia*: Econ. Geol., v. 49, p. 826–836 (1954).
24. Fischer, R. P., *Uranium-bearing sandstone deposits of the Colorado Plateau*: Econ. Geol., v. 45, p. 1–11 (1950).
25. Fleischer, M., *Recent estimates of the abundance of the elements in the earth's crust*: US Geol. Survey circular 285, p. 7 (1953).
26. Foshag, W. F., *Problems in the study of meteorites*: Am. Min., v. 26, p. 137–142 (1941).
27. Fraser, J. A., Crackingstone, Saskatchewan: Dept. Mines and Tech. Surveys, Geol. Survey Canada, Paper 54–8, 1 map (1954).
28. Fraser, J. A. and Robinson, S. C., *Preliminary description of the geology and mineralogy of the Gunnar deposit, Saskatchewan*: Canadian Mining Journal, v. 75, p. 59–62 (1954).
29. Friese, F., *Mineralvorkommen der südlichen Serra dos Oymores, Staat Espirito Santo, Brasilien*: Zeitschr, prakt. Geologie, v. 18, p. 143–146 (1910).
30. George, D'Arcy, *Mineralogy of uranium and thorium bearing minerals*: US Atomic Energy Comm., RMO–563, p. 198 (1949).
31. Gruner, J. W., *The uranium mineralogy of the Colorado Plateau and adjacent regions*: Guidebook No. 9, Utah Geol. Soc., Utah Geol. and Mineral Survey, Salt Lake City, p. 8 (1954).
32. Hess, F. L., *Industrial minerals and rocks*: New York, Am. Inst. Min. Met. Eng., p. 525 (1937).
33. Holmes, A., *The construction of a geological time-scale*: Trans. Geol. Soc. Glasgow, v. 21, pt. 1, p. 117–152 (1947).
34. Hoover, H. C. and Hoover, L. H., *Georgius Agricola de re metallica*: trans. from the first Latin edition of 1556, London, The Mining Magazine, p. 637 (1912).
35. Isachsen, Y. W., Mitcham, T. W. and Wood, H. B., *Age and sedimentary environments of uranium host rocks, Colorado Plateau*: Econ. Geol., v. 50, p. 127–134 (1955).
36. James, W. F., Lang, A. H., Murphy, R. and Kesten, S. N., *Canadian deposits of uranium and thorium*: Min. Eng., v. 187, p. 239–255 (1950).
37. Joubin, F. R., *Uranium deposits of the Algoma District, Ontario*: Trans. Can. Inst. Min. Met., v. 58, p. 431–437 (1954).
38. Kay, M., *Sediments and subsidence through time*: *The Crust of the Earth*, Geol. Soc. Am. Memoir 61, p. 665–684, in press (1955).
39. Kerr, P. F., *Mineralogical studies of uraninite and uraninite-bearing deposits*: US Atomic Energy Comm., Interim Technical Report, 44 p. (1950).
40. Kerr, P. F., Brophy, G. P., Dahl, H. M., Green, J. and Woolard, L. E., *Alteration and uranium mineralization, Marysvale, Utah*: Geol. Soc. Am. Memoir, in press (1955).
41. Kerr, P. F. and Holland, H. D., *Differential thermal analyses of davidite*: Am. Min., v. 36, p. 563–572 (1951).
42. Kerr, P. F. and Lapham, D. M., *Report on a nodule from Temple Mountain, Utah*: Annual Report for June 30, 1953 to April 1, 1954, US Atomic Energy Comm., RME–3096, pt. 1, p. 7–15 (1954).
43. Kerr, P. F., Kelley, D. R., Keys, W. S. and Bodine, M. W., Jr., *Collapse features, Temple Mountain uranium area, Utah*: Annual Report for June 30, 1954 to April 1, 1955, US Atomic Energy Comm., pt. 3, in press (1955).
44. Kerr, P. F., and Kulp, J. L., *Pre-Cambrian uraninite, Sunshine mine, Idaho*: Science, v. 115, p. 86–88 (1952).
45. Kerr, P. F. and Robinson, R. F., *Uranium mineralization in the Sunshine mine, Idaho*: Min. Eng., v. 5, p. 495–511 (1953).
46. Kidd, D. F., *A pitchblende-silver deposit, Great Bear Lake, Canada*: Econ. Geol., v. 27, p. 145–159 (1932).
47. Kidd, D. F., *Great Bear Lake area, Northwest Territories*: Geol. Surv. Canada, Summ. Rept., pt. C, p. 1 (1932).
48. Kidd, D. F. and Haycock, M. H., *Mineragraphy of the ores of Great Bear Lake*: Geol. Soc. Am. Bull., v. 46, p. 879–960 (1935).
49. Koczy, G., *Further uranium determinations on sea water samples*: Akad. Wiss. Wien, Math.-naturwiss, Kl., Sitzungsber., Abt. IIa, 158. Band, 1.–5. Heft, p. 113–122, (trans. see Lyons, J. B.) (1950).

50. Kulp, J. L., Bate, G. L. and Giletti, B. J., *New age determinations by the lead method*: Geol. Assoc. Canada, Proceed., v. 7, pt. 2, p. 15–24 (1955).
51. Lang, A. H., *Canadian deposits of uranium and thorium*: Geol. Survey Canada, Paper 51–10, 157 p. (1951).
52. Lang, A. H., *Canadian deposits of uranium and thorium (Interim Account)*: Geol. Survey of Canada, Econ. Geol., ser. no. 16, 173 p. (1952).
53. Lang, A. H., *Uranium orebodies*: Canadian Min. Jour., v. 73, p. 57–65 (1952).
54. Lang, A. H., (1953) *Uranium in Canada*, Preliminary (Corrected edition): Dept. Mines Tech. Surveys, Ottawa, Canada, p. 1–7 (1952).
55. Lang, A. H., (1954) *Uranium in Canada*, Preliminary: Dept. Mines Tech. Surveys, Ottawa, Canada, p. 1–7 (1953).
56. Lang, A. H., (1955) *Uranium in Canada*, Preliminary: Dept. Mines Tech. Surveys, Ottawa, Canada, p. 1–5 (1954).
57. Larsen, E. S., Jr. and Phair, G., *The distribution of uranium and thorium in igneous rocks*: Faul, H., ed., Nuclear Geology, New York, John Wiley and Sons, Inc., p. 75–89 (1954).
58. Lovering, T. G., *Progress in radioactive iron oxides investigations*: Econ. Geol., v. 50, p. 186–195 (1955).
59. Leonardos, O. H., *Monazita no Estado da Bahai*: Mineracao e Metallurgia, v. 2, p. 138–144 (1937).
60. Lowell, J. D., *Applications of cross-stratification studies to problems of uranium exploration, Chuska Mountains, Arizona*: Econ. Geol., v. 50, p. 177–185 (1955).
61. Lyons, J. B., (trans.) *Further uranium determinations on sea water samples*: Trace Elements Memorandum Report 305, US Geol. Survey, 13 p. (1951).
62. Murphy, R., *Mineralogy at Eldorado mine (Northwest Territories)*: Can. Inst. Min. Met. Trans., v. 49, p. 426–435 (1946).
63. Miller, L. J., *Uranium ore controls of the Happy Jack deposit, White Canyon, San Juan County, Utah*: Econ. Geol., v. 50, p. 156–169 (1955).
64. Nier, A. O., *Isotopic constitution of radiogenic leads and the measurement of geological time*: Phys. Rev., v. 55, p. 153–163 (1939).
65. Nininger, R. D., *Minerals for atomic energy*: New York, D. Van Nostrand Co., Inc., 367 p. (1954).
66. Osipova, A. I., *Materialy k litologischeskoi i fatsialnoi kharakteristike ot lozhenii paleogena yugovostochnoi Fergany*: Akad. Nauk SSSR, Doklady, t. 64, no. 3, p. 381–384 (1949).
67. Pabst, A., *Brannerite from California*: Am. Min., v. 39, p. 109–117 (1954).
68. Page, L. R., *Interim report of geologic investigation Lost Creek schroeckingerite deposits, Sweetwater County, Wyoming*: US Geol. Survey, TEM–183–A, p. 1–3 (1950).
69. Page, L. R., *Uranium in pegmatites*: Econ. Geol., v. 45, p. 12–34 (1950).
70. Parkin, L. W. and Glasson, K. R., *The geology of the Radium Hill uranium mine, South Australia*: Econ. Geol., v. 49, p. 815–825 (1954).
71. Perry, S. H., *The metallography of meteoric iron*: US Nat'l Mus., Bull. 184, 206 p. (1944).
72. Poldervaart, A., *Chemistry of the earth's crust*: Geol. Soc. Amer., Memoir 61, p. 119–144, in press (1955).
73. Rankama, K. and Sahama, Th. G., *Geochemistry*: Chicago, The University of Chicago Press, 912 p. (1950).
74. Rasor, C. A., *Uraninite from the Grey Dawn mine, San Juan County, Utah*: Science, v. 116, p. 89–90 (1952).
75. Reinecke, L., *Origin of the Witwatersrand system*: Trans. Geol. Soc. South Africa, v. 33, p. 111–133 (1931).
76. Robinson, S. C., *Mineralogy of uranium deposits, Goldfields, Saskatchewan*: Geol. Survey of Canada, Bull. 31, 128 p. (1955).
77. Rosenzweig, A., Gruner, J. W. and Gardner, L., *Widespread occurrence and character of uraninite from the Triassic and Jurassic sediments of the Colorado Plateau*: Econ. Geol., v. 49, p. 351–361 (1954).
78. Rowe, R. B., *Notes on geology and mineralogy of the Newman columbium-uranium deposit, Lake Nipissing, Ontario*: Geol. Survey of Canada, Paper 54–5, p. 1–25 (1954).
79. Satterly, J. and Hewitt, D. F., *Some radioactive mineral occurrences in the Bancroft area*: Ontario Dept. Mines, Geol. Cir. no. 2, p. 1–62 (1955).
80. Schundt, H. and Moore, R. B., *Radioactivity of the thermal waters of Yellowstone National Park*: US Geol. Survey Bull. no. 395, 34 p. (1909).
81. Scott, H. S., *Decrepitation method applied to minerals with fluid inclusions*: Econ. Geol., v. 43, p. 637–654 (1948).
82. Spence, H. S., *Character of the pitchblende ore from Great Bear Lake, Northwest Territories*: Can. Min. Jour., v. 53, p. 483–487 (1932).
83. Spence, H. S., *The pitchblende and silver discoveries at Great Bear Lake, Northwest Territories*: Canada Dept. Mines, Mines Branch, Invest. Min. Res. and Min. Ind., no. 3, p. 55–92 (1931).
84. Stieff, L. R., Stern, T. W. and Sherwood, A. M., *Preliminary description of coffinite—a new uranium mineral*: Science, v. 121, p. 608–609 (1955).
85. Thoreau, J. and du Trieu de Terdonck, R., *Le gite d'uranium de Shinkolobwe–Kasolo (Katanga)*: Extrait des mem. publies par l'Instit. Colonial Belge, tome I, fasc. 8, Bruxelles, Hayez, 46 p. (1933).
86. Thoreau, J. and du Trieu de Terdonck, R., Bull. Geol. Soc. Amer., v. 46, p. 941–942, (abstract) (1935).
87. Tipper, G. H., *The monazite sands of Travancore*: Geol. Survey India, Rec., v. 44, p. 186–196 (1914).
88. Traill, R. J., *A preliminary account of the mineralogy of radioactive conglomerates in the Blind River Region, Ontario*: Can. Min. Jour., v. 75, p. 63–67 (1954).
89. Urey, H. C., *The planets, their origin and development*: New Haven, Conn., Yale University Press, 245 p. (1952).
90. Walton, Matt, *The earth beneath*: Yale Scientific Magazine, v. 29, 11 p. (1955).
91. Weeks, A. D. and Thompson, M. E., *Identification and occurrence of uranium and vanadium minerals from the Colorado Plateaus*: US Geol. Survey Bull. 1009–B, 62 p. (1954).
92. Worzel, J. L. and Shurbet, G. L., *Gravity interpretations from standard oceanic and continental crystal sections*: Geol. Soc. Amer. Memoir 61, p. 87–100, in press (1955).
93. Wright, R. J., *Ore controls in sandstone uranium deposits of the Colorado Plateau*: Econ. Geol., v. 50, p. 135–155 (1955).
94. Wyant, D. G., *Lost Creek (Wamsutter) schroeckingerite deposit, Sweetwater County, Wyoming*: US Geol. Surv., TEM–10–B, p. 1–9 (1952).
95. Zückert, R., *Die Paragenesen von gediegenem Silber und Bismut mit Kobalt-Nickel-Kiesen und der Uranopackblende zu Skt. Joachimsthal in Böhmen*: Preuss. Geol. Landesanstalt, Mitteilungen der Abt. fur Gesteins-, Erz-, Kohle- und Salz-Untersuchungen, Heft p. 69–132 (1926).
96. Zückert, R., Geol. Soc. Amer. Bull, v. 46, p. 942–943, (abstract) (1935).

Nuclear Fuel for the World Power Program

By Jesse C. Johnson,* USA

Power with which to drive machines has been the most important force in relieving man from physical drudgery and providing leisure for spiritual and mental development. Unfortunately, power expansion already is being limited in many parts of the world by the growing shortage of water resources and fossil fuels. But now, there is the prospect of a nuclear power era which may have as far-reaching influence as the Industrial Revolution.

The nuclear power era will have abundant fuel resources. The problem will be the efficient and economic utilization of these nuclear fuels. The location of nuclear power plants will not be determined by the availability of a local fuel supply. Nuclear fuel can be transported by air to any part of the world and transportation costs will have no measurable effect upon the cost of power.

The world's energy resources in the form of nuclear fuels far exceed those of all other types of fuel. There are adequate resources of uranium and thorium for a long range expanding world power program.

Uranium will be the important nuclear fuel for the foreseeable future according to the present pattern of development and planning. Most reactor programs to be discussed at this Conference depend upon uranium as the source of fissionable material, although thorium also may be used.

Since uranium will be a primary source of fuel for nuclear power, it is appropriate for this conference to consider present and potential uranium resources, and the operations related to uranium production. Furthermore, in many countries a survey for radioactive minerals will be the first major project in their study of a nuclear power program.

Most information on uranium has been developed during the past seven years because of its military importance, much of this information has been a guarded secret. Now the emphasis is on the peaceful uses of atomic energy. The information that may contribute to the development of these uses throughout the world is to be shared. The exchange of information and ideas at this conference should greatly accelerate already fast-moving developments in all phases of atomic energy.

The Western Nations which are cooperating in developing uranium production have achieved notable success. New sources of uranium have been found and brought into production. Former operations have been expanded and ore reserves extended. Information on uranium deposits and the nature of their occurrence has been greatly increased. Special instruments and techniques have been developed for use in exploring for radioactive minerals. New metallurgical processes for extracting uranium from ores have increased recoveries and reduced the cost of production. By-product uranium is being recovered commercially from very low grade materials.

In 1948 the uranium supply of the Western Nations was almost entirely the product of two mines, one in the Belgian Congo and the other in Northern Canada. In the past, there had been little general interest in uranium and throughout most of the world there had been no serious search for it. Even now vast areas, promising from a geological standpoint, are relatively unexplored.

Today there are major uranium operations in the Belgian Congo, Canada, South Africa and the United States. Australia, France and Portugal also are producing uranium with favorable prospects for substantially increased production.

This uranium production program to a large extent has been carried out by private industry operating under the profit incentive system. However, government exploration and metallurgical research programs have played a major role in supporting private operations and speeding developments.

Expenditures by the United States for exploration and development of exploration methods have amounted to approximately $46,000,000, and for metallurgical research and pilot plant operations over $12,000,000. In 1948 the United States was considered by many to have relatively poor uranium prospects. Ore reserves are now increasing more rapidly than at any time since the program commenced.

One of the important conclusions to be drawn from the information gathered during the past seven years is that commercial uranium deposits of considerable size may be found in many areas and under a variety of geological conditions. It long has been known that in the earth's crust uranium is about as plentiful as lead or zinc, and is about 100 times more plentiful than silver. However, it was rather generally assumed that concentrations in commercial deposits might be rare. This has not proved to be the case.

* Director, Division of Raw Materials, US Atomic Energy Commission.

Because active prospecting and exploration have been undertaken in only a few countries, and these countries are as yet only partially explored, we are not now in a position to estimate the uranium resources of the world. As the nuclear power program grows and the search for uranium is extended, more and more information will become available about the resources for the future. There is every reason to believe that these resources will be far larger than those we are considering today. However, the areas now producing or under active development assure an adequate supply of uranium for a long-range power program.

On the basis of present developments and geological evidence, resources of the producing nations of the West are estimated to be between one and two million tons of uranium. This is uranium that can be produced at moderate cost, at an average of about $10 a pound for U_3O_8 in a high grade concentrate. Although the use of nuclear power is expected to expand rapidly once industrial scale operations prove it to be economical, it may be 1970, or even 1980, before there is a substantial uranium requirement for power purposes. In the meantime, the high production rate of the present program cannot be maintained unless there is a military demand or government stockpiling.

In the more distant future, the fuel requirements for the atomic age may come from the vast low grade uraniferous phosphate and shale deposits. Reserves of commercial phosphate rock in the United States alone are estimated at five billion tons and the uranium content at 600,000. These reserves would be greatly increased by including low-grade phosphatic rock not presently considered commercial. The United States also has an estimated 85 billion tons of marine shale averaging slightly more than one-tenth of a pound uranium per ton. This represents a reserve of five to six million tons of uranium.

Known deposits of uraniferous phosphate rock and shale in other parts of the world equal or exceed those of the United States in grade and tonnage. For example, the phosphate deposits of Morocco, estimated at twenty billion tons, are uranium-bearing. The Scandinavian Peninsula and other Baltic territories contain very large deposits of uraniferous shale. Uranium-bearing coal and lignite also have been found in a number of countries.

The cost of extracting uranium as the primary product from phosphate and shales may be between $30 and $50 per pound. If valuable by-products can be recovered the cost may be reduced. Furthermore, uranium can be recovered at moderate cost as a by-product from some commercial phosphate fertilizer and chemical operations. This already is being done. Approximately 10,000,000 tons of commercial phosphate rock are mined annually in the United States. If all of this rock was processed to phosphoric acid, in excess of 1000 tons of by-product uranium oxide might be recovered annually.

Between the commercial uranium deposits of today and the high cost uranium resources of the more distant future, there are deposits that could supply uranium at a cost of between $10 and $30 a pound. The resources in this economic class are not well known but they must be large, perhaps several million tons of uranium. These resources will include deposits of types now being mined but which are outside the economic limits prevailing today. We already know of some such large reserves but most of the information on resources in this category must come from future exploration. Experience gained from the present uranium program has demonstrated that higher prices will bring in new sources of production and increase available reserves.

The rapid expansion of uranium production within a very few years has been possible because of major technological advances in exploration and metallurgy.

Geiger and scintillation counters have made it possible for almost any one to become a prospector and in areas of uranium excitement that has been the case. In the hands of geologists, these instruments have greatly speeded systematic exploration and reduced failure to recognize inconspicuous outcrops of radioactive mineral. Highly sensitive scintillation counters weighing as little as five pounds are available for ground surveys. Instruments weighing from 50 to 100 pounds are used for airborne surveys. Several valuable uranium deposits have been found by low-level aerial surveys. High-level flying in broad reconnaissance surveys has been directed toward locating favorable areas for more detailed investigations.

With sensitive scintillation logging instruments, used in connection with electric logging, it is possible to determine the position, thickness and approximate grade of mineralization, and to differentiate the various rock types encountered in a bore hole. Instruments have been developed for logging bore holes as small as two inches in diameter.

Although these instruments now are considered indispensable in uranium exploration, the basic work still is detailed field geology and laboratory research. One of the major contributions of the extensive exploration program of the past few years has been the development of scientific information on uranium mineralogy and on the nature and occurrence of uranium deposits. This is information of permanent value and will aid the geologist in any area and at any time. Several geological papers have been prepared for presentation at the technical sessions or publication in the Proceedings of this Conference.

Major advances also have been made in uranium metallurgy and the processes developed during the last few years have become standard for all new mills. Uranium recovery should be about 90% for nearly any type of ore. The cost of processing may vary widely, largely because of the differences in chemical consumption for different ores and in the size of the milling operations. However, for most

uranium operations the cost of milling should range from $5 to $15 per ton of ore. Large plants with favorable metallurgical and operating conditions can have milling costs below $5 per ton. These are the costs that should prevail in most established mining and industrial communities. In isolated areas where fuels, chemicals and labor are expensive, milling cost will be correspondingly higher. It is evident that the cost of milling is an important factor in determining the grade of ore that can be treated profitably.

Probably the most important development in extraction of uranium is the use of ion exchange resins. Ion exchange resins may be used to recover uranium from clarified solutions or directly from pulp. Recovery from pulp eliminates thickening and filtering problems and reduces soluble losses to a minimum. A high grade uranium precipitate, 60% or more U_3O_8, is obtained without intermediate up-grading steps. Although ion exchange has been used in water purification for a long time this is the first commercial application for metal recovery.

Solvent extraction, which has been widely used in the chemical industry, also has been adapted to uranium extraction. Both ion exchange and solvent extraction processes presently are used only in connection with acid solutions. Recent experiments, however, indicate that ion exchange also may be used for recovery of uranium from alkaline solutions. Either acid or alkaline solutions may be used to dissolve the uranium from the ore. Acid solutions are generally more effective but are not economic for high lime ores.

Uranium metallurgy will continue to be improved and new chemical processes will be developed. But no longer is there a wide margin between the costs and recoveries being obtained by efficiently operated modern plants and the results which might be considered theoretically practical. However, a major reduction in the cost of milling certain types of ore could result from a cheap, efficient method of mechanical concentration, such as flotation. This would provide a higher grade product for treatment by the more expensive chemical processes. Research laboratories are working on flotation and other possible methods of mechanical concentration.

This general review of production and resources indicates that uranium no longer can be considered a rare metal. There are extensive deposits throughout the world and there are processes for extracting the uranium economically. Uranium production already developed is sufficient for a major nuclear power program of world-wide extent. Additional production can be obtained when needed. When the vast low grade resources are required, more efficient use of nuclear fuel through improved conversion of "breeding" may offset the higher uranium cost.

Distribution and Characteristics of the Uranium Deposits and Occurrences in the Argentine Republic

By V. Angelelli,* Argentina

The purpose of this paper is to outline the distribution and characteristics of some of the uranium deposits and occurrences in the Argentine Republic.

We do not propose to be complete in every respect, since the surveys to date have not led to any definite conclusions as to the origin of these deposits and occurrences. We must further draw attention to the fact that exploration has not been sufficient in all cases to provide data for the formulation of more accurate ideas on the mineralization and characteristics at depth.

Nevertheless, we feel that the paper is a contribution to the geological-genetic knowledge of the uranium minerals in Argentina. It is based on the research and conclusions of the geologists and technicians of the Comisión Nacional de la Energía Atómica and other institutes which, in one way or another, have been and are currently concerned with the solution of these problems, as well as on the field observations of the author.

The geological-mining investigation of the country with respect to radioactive minerals is recent. The systematic survey of every part of the territory where the existence of uranium is expected has been in progress for less than three years.

The earlier studies, which were sporadic, were made as a consequence of casual findings of these minerals upon reexamination. Thus, in 1936, while a pegmatite which carried columbite was being investigated in the Sierra de Córdoba, the existence of uranium minerals in Argentina was established. Later, between 1946 and 1948, studies were made to determine the possibilities of the rocks of the crystalline Sierras of Córdoba and San Luis, as well as the uranium-bearing quartz veins discovered at that time near the city of Mendoza.

On the basis of the earlier exploration, and other data, the Commission initiated in 1952 the investigation of the Argentine subsoil in search of uranium minerals, and promoted the mining for this material. Thus, the necessary services for fulfilling these objectives were established, and the prospectors were given much encouragement by mineral purchase prices that constituted an incentive for their search. The activities of the geologic personnel of the Argentine National Committee on Atomic Energy resulted in the discovery of various deposits and occurrences. They are now complemented by persons and private organizations which enable discoveries in regions of known uranium mineralization. This, in turn, stimulates the development of mining consciousness along this line of Argentine extractive industry.

DISTRIBUTION OF DEPOSITS AND OCCURRENCES

Here, we shall consider the locations of the radioactive deposits and occurrences in their various structural units, with a brief summary of the composition of each (Fig. 1).

On the basis of this evidence, we conclude that the uranium minerals occur at random in any of the units mentioned and that to a substantial extent they are related to the Tertiary eruptive cycle, since the orogenesis of that age more or less affected them.

They are very widespread. In effect, although all of the territory has not been explored, the occurrences lie from near the Bolivian border to the central part of Neuquén, in a north-south direction, and about 50 km from the Chile-Argentina border in some places to the central zone of the country, from east to west.

The oldest mineralization is represented by uraninite-bearing pegmatites, in the crystalline basement, particularly in the mountains of Córdoba and San Luis, and less frequently in those of Valle Fértil (San Juan), Velazco (La Rioja) and others. These elevations belong to the Sierras Pampeanas which rise above the central plain of the country as blocks, or masses. They rest in the east against other younger structural units in the provinces of San Juan, La Rioja, Catamarca, etc. They consist of pre-Cambrian crystalline schists (gneiss, micaschists and amphibolites, quartzites, limestone, etc.) with intrusions of granite, granodiorite, serpentine, etc., as well as at times, effusive Tertiary rocks.

Other than the aforementioned pegmatites, we should cite the monazite-bearing ore of the Valle Fértil (San Juan) chain, the fetid fluorite of La Marquesa (San Luis), and the uranium minerals in the travertine deposits of the previously mentioned province which are upper Tertiary.

In the Precordillera, a geological unit which precedes the formation of the Andean cordillera geosyncline, the uranium-bearing quartz deposits of Presidente Perón, Soberanía and Independencia, oc-

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* Comisión Nacional de la Energía Atómica, Argentina.

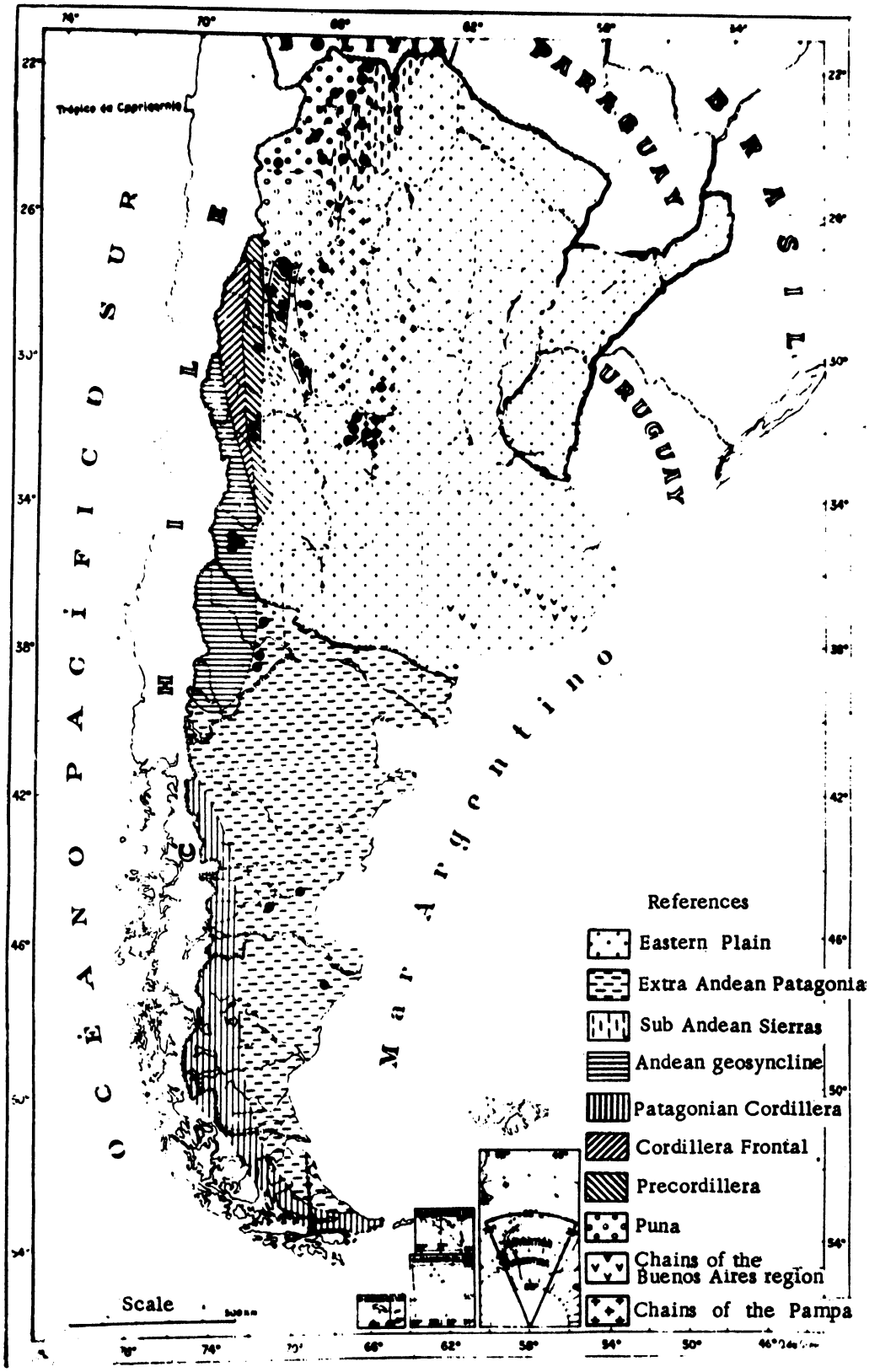

Figure 1. Structural map of the Argentine Republic showing the position of the deposits and uranium occurrences

cur in the Triassic areas of Mendoza, as well as in the Tertiary copper and uranium-bearing sandstones of Huaco and in fluorite veins, with low radioactivity, of the same zone. They occur in San Juan and in the asphalt schists of the Noric period (Triassic) which outcrop to the west and southwest of the city of Mendoza; they have a very low uranium content.

Affected by intense orogeny are some Cambro-Ordovician, Devonian, permo-Carboniferous, Triassic and Tertiary sediments which extend from south of Mendoza to north of La Rioja, aside from the Triassic and Tertiary. To this structural unit also belongs the nickel and pitchblende deposit of San Santiago (La Rioja), which outcrops in crystalline schists.

The cordillera structure which includes the cordillera of the Andean geosyncline, the frontal cordillera and Patagonian cordillera extends from south of Mendoza to north of La Rioja. The first and last of the units mentioned consist of upper Triassic, Jurassic and Cretaceous marine sediments with intrusions of dioritic and granodioritic rocks, as well as Tertiary effusives of the same magma. On the other hand, the frontal cordillera consists of Paleozoic sediments, mostly carbonaceous, which also contain large masses of Permo-Triassic granite.

In this structure, the existence of copper and uranium minerals was established in a large area south of Mendoza, where they impregnate the upper Cretaceous (Eva Perón—Agua Botada, Cerro Mirano and Pampa Amarilla deposits). The various asphaltite deposits of the province of Mendoza which have a low uranium content should be mentioned also.

This area is almost unknown from the standpoint of the occurrence of radioactive minerals, due principally to topographic and climatic conditions.

In the Famatina system, which lies between the Sierra Pampeana of Velazco to the east and precordillera to the west, a vast uranium-bearing area is present. It includes, among others, the deposits of Santa Brígida and San Victorio. This range consists essentially of Cambro-Ordovician and carbonaceous sediments with pre-Carboniferous intrusions of granite and granodiorite, as well as Tertiary effusives; the latter are correlated with the copper, gold, silver, and uranium deposits of the region.

The Subandine Sierras which lie along the eastern edge of La Puna in the provinces of Salta and Jujuy consist of the upper Mesozoic and Tertiary sediments which rest on Devonian, as well as on Ordovician and Cambrian formations. They contain carbonaceous material which shows a certain amount of radioactivity, namely in the zones of El Cucho (Jujuy) and Escoipe (Salta).

La Puna, located in the northwest corner of the country, is an elevated block which extends from north of La Rioja to the south, as far as La Quiaca to the north, and therefore extends into Bolivian territory. In this region and on its margins, the various parts of the structural unit mentioned above recombine so that we have the occurrence of schists belonging to the crystalline basement, Cambro-Ordovician and Mesozoic sediments, together with intrusions of granite and granodiorite, and an abundance of Tertiary and Quaternary effusives and basalts. In this environment, we find the deposits of copper and uranium and nickel and uranium in the mines called Esperanza and La Niquelina respectively, in Salta. In addition, we find the thorium of the Rangel range, the uranium in aragonite deposits of this province, as well as certain copper-uranium veins plus the alluvial gold and tin deposits of Orosmayo, Rio Cincel and others. These heavy minerals have a low uranium content, and all occur in Jujuy.

Beyond the Andean part of Patagonia, a large region which extends from Rio Colorado on the north to the Straits of Magellan on the south, and in which there are outcrops of Paleozoic sediments with Triassic effusives, Jurassic, Cretaceous and Tertiary complexes, and substantial flows of basalt, we find occurrences of oxidized minerals of copper and uranium in cretaceous sandstones and bodies of asphaltites which show low radioactivity. Occurrences also are found in the central area of Neuquén, in the radioactive oil-bearing sandstones of the Cretaceous at Comodoro Rivadavia and in the copper-bearing veins of Tres Cerros (Santa Cruz) which show low radioactivity.

URANIUM MINERALS

The recent investigations show the presence of the following mineral groups:

Hypogene Minerals

With a single exception these include the simple oxides, uraninite and pitchblende.

Uraninite

Uraninite has been recognized in numerous pegmatites of the Sierras of Córdoba and elsewhere. It occurs as isolated crystals, at times interlocked, as well as in small irregular masses between books of mica or in masses of garnet and triplite. The principal form is the cube, 5 to 10 mm to an edge, which occasionally may be 2 and 3 cm. The outer areas of this material show intense alteration to gummite and other compounds. This accounts for the low specific gravity which varies between 5.4 and 6.1. Analyses made by A. Chaudet[1] show:

	1*	2†
Loss on ignition	5.55%	2.35%
Insolubles	0.30%	1.00%
UO_2	23.10%	28.38%
UO_3	63.00%	61.12%
ThO_2 and rare earths	1.67%	0.25%
PbO	5.00%	5.20%
Fe_2O_3	trace	trace
Al_2O_3	trace	trace
CaO	0.70%	trace
P_2O_5	none	0.06%
ZrO_2	no determ.	trace
Total	99.32%	98.36%

* Cerro Blanco, El Tigre Valley, Sierra de Comechingones.
† "Cerro Blanco" Mine, Sierra de Comechingones, Córdoba.

This mineral also was identified by X-ray diffraction in the uranium rich material of the Eva Perón deposit, where, along with carbonaceous (thucholite) and asphaltic materials, it impregnates lenses of fine to medium grained sandstone. It accompanies copper sulphides.

Pitchblende

This was first identified in samples from "San Santiago" mine, La Rioja, where it occurs in thin and irregular stringers, 1 mm or less. It is steel black, and disseminated in or around niccolite. The main mass usually includes niccolite and calcite.

It also occurs in the ore deposits of the Sañagasta, La Rioja region where it is altered and forms stringers and irregular masses which are as much as 10 mm thick. It is dark with a drab tinge, and is associated with fluorite, calcite, copper minerals and fragments of wall rock (slate). A sample from the San Victorio mine, analysed by E. Alonso, shows:

Sample	*per cent*
Moisture	0.4
Insolubles	1.8
UO_2	18.4
UO_3	51.0
ThO_2	trace
Rare earths	1.0
PbO	2.9
CuO	3.9
V_2O_5	0.2
CaO	6.3
FeO_2	6.1
Al_2O_3	trace
ZrO_2	1.9
Loss on ignition and unknown elements	6.1
Total	100.0

Pitchblende is the primary mineral of the quartz veins at the Presidente Perón and Soberanía, Mendoza deposits. Microscopic examination shows it, in a dendritic form replacing quartz, or botryoidal surrounding quartz and calcite. It is observed also as spherulites in quartz. Associated with this mineral is a drab yellowish material with a radial structure which is thought to be gummite.

Thucholite

The presence of this light asphaltic-carbonaceous material in the Eva Perón deposit is established. It is associated with uraninite and copper sulfides.

Among the multiple oxides, is the probable presence of euxenite closely associated with columbite in the Las Tapias beryllium mines, Córdoba. This occurs in masses of spodumene.

Supergene Minerals

The eight species identified are described below:

Gummite

Gummite is found in various pegmatites of the Córdoba mountains and elsewhere. Pieces of orange-yellow gummite with some uraninite which weigh as much as 4 kg have been extracted from the Angel mine, Córdoba, where they are associated with muscovite as well as other secondary uranium compounds. It is also observed as a thin stringer 1 to 2 mm thick and as a yellow, orange and brown coating of crystals of uraninite. The analysis made by A. Chaudet[1] shows:

	Per cent		
	1	*2*	*3*
Loss on ignition	6.10	8.80	7.00
Insolubles	3.80	3.04	2.50
UO_2	no determ.	0.81	no determ.
UO_3	82.19	80.97	78.13
ThO_2 and rare earths	0.40	2.15	0.05
PbO	6.93	5.20	10.92
CaO	1.64	trace	1.10
Totals	101.06	100.97	99.70

1. Orange variety, La Chiquita mine, Córdoba.
2. Orange-yellowish variety, Angel mine, Córdoba.
3. Yellow variety, El Tigre ravine, Córdoba.

As a soft, earthy-looking material, reddish brown or dark orange, it is associated with altered pitchblende in the San Victorio mine.

Uranophane

This is the most important mineral in the Santa Brígida, San Victorio, and other deposits of the Sañogasta area. It forms rather pure stringers which may reach several centimeters in thickness. At times it impregnates the vein or slate wall rock. Usually it is accompanied by tyuyamunite, and has a high rare earth content.

As above, it represents the principal compound of the Presidente Perón and Soberanía ores, where it is associated, in the upper workings of the mine, with schroeckingerite, gypsum, etc. It occurs as a thin coating on fractures in the quartz, although it also exists in the breccia. It forms, as indicated previously, fibrous radial aggregates or spherulites.

Finally, mention should be made of its nearly exclusive association with fetid fluoride at the La Marquesa, San Luis deposit. It forms radial fibrous aggregates which penetrate the cracks and fissures of the fluorite, and also impregnates the granite host rock. The chemical analysis of a sample from the Santa Brígida mine, made by C. Gordillo, shows:

Sample	*Per cent*
SiO_2	13.25
H_2O	13.85
Al_2O_3	3.05
Fe_2O_3	0.05
CaO	5.00
MgO	0.08
PbO	3.00
CuO	0.48
V_2O_5	0.86
Rare earths	2.90
ThO_2	0.30
UO_3	56.01
Total	98.83

Beta-uranophane

This mineral has been identified among the oxidized uranium minerals of the La Chiquita pegma-

tite mine, Córdoba, as well as in the ore of the Porota deposit at Valle Hermoso, La Rioja. Here, it appears as star-like acicular aggregates, associated with malachite and slate.

Autunite

A phosphate, this mineral appears in various pegmatites of the Sierra de Córdoba, where it is disseminated thinly in quartz, feldspar and mica. It also surrounds nodules of uraninite and gummite, and forms tabular crystals, which are very thin, and at times grouped in scales or films. To a lesser degree, it occasionally occurs in the ore of the Presidente Perón, La Marquesa and Eva Perón deposits.

Schroeckingerite

This mineral occurs rather often in the upper levels of the Presidente Perón, Soberanía and Independencia deposits, where it is intimately associated with uranophane. It occurs in tabular crystals which are rectangular and hexagonal in section, and 0.5 to 5 mm in diameter. They are isolated or grouped in rosettes or globular scales which coat the sides of fractures in quartz, or they may occur in cavities in the argillaceous or sandy wall rock.

Phosphuranylite

This phosphate, has been identified in the uranium minerals of the Presidente Perón deposit.

Carnotite

This is the principal secondary mineral of the Eva Perón deposit. It forms thin yellowish films, associated with copper and iron oxides, which coat the surface of the rounded materials, as well as cement the uranium-copper conglomerate of this deposit. Similarly, it is noticed in very pure earthy, lenticular, small masses, in the base of the conglomerate, as well as in the sandstone of the southern boundary of this deposit, namely in Agua Botada.

It occurs in the uranium-bearing ores of La Cieneguita in Catamarca, where it forms thin films along the diaclases principally of yellowish lutites. It is associated with oxidized copper minerals and manganese oxide.

Tyuyamunite

Earlier studies show the presence of this uranium and calcium vanadate in the Eva Perón, Santa Brígida and San Victorio ores.

CLASSIFICATION OF THE DEPOSITS

Since the geology of the structures in which the deposits and occurrences of uranium has been discussed, as well as the uranium mineralogy and associations, we shall endeavor to give a genetic classification which is tentative since, in some cases, there are difficulties of interpretation and in others, the surveys are inadequate. Therefore, we shall follow this order: (*a*) pegmatites, (*b*) hydrothermal deposits, (*c*) sedimentary deposits, (*d*) deposits made by alteration and circulating solutions, and (*e*) asphaltic deposits.

Pegmatites

These are pre-Cambrian: there are many pegmatites of granitic origin in the Sierra de Comechingones (Córdoba), Sierra of San Luis, and, less commonly, in the Sierras of Valle Fértil (San Juan) and Velazco, (La Rioja) etc. These rocks are rich in microcline, quartz and muscovite, and contain, among the various minerals and accessories: uraninite, beryl, apatite, triplite, garnet (almandine), and occasionally, columbite, etc. Some pegmatites of the Sierra Valle Fértil contain small to medium-sized masses of monazite.

Hydrothermal Deposits

Except for the pegmatitic-pneumatolitic deposits of the Rangel mountains located in the Puna of Salta which consist mostly of thorium-bearing quartz veins, with or without feldspar, the origin of these deposits is meso- to epithermal. They fill fissures or faults, with some replacement metamorphism, and are related to acid to intermediate rocks, although some do not seem to be related to any rock.

The primary rocks are crystalline schist (quartzite), metamorphosed slates, agrillaceous or sandy sediments, and eruptive rocks. Deposits are observed along the contacts of these rocks. The gangue consists mostly of quartz, carbonates and fluorite. Occasionally, there are inclusions of the primary rock.

The age of the deposits and occurrences is not established definitely due to the lack of major determining elements; however, many are part of the Tertiary eruptive cycle.

The most frequent association is uranium-copper; cobalt is not present in the uranium-nickel suite. In addition to the uranium-fluorite association, the discovery of radioactive lead and molybdenum minerals in meteoric zones, as well as the presence in some wolframite mines, of radioactive bismuth minerals should be mentioned.

The deposits which belong to this group include:

U: Presidente Perón and Soberanía, in Mendoza and La Marquesa in San Luis; Santa Brígida, San Victorio, and others, in the zone of Sañogasta, in La Rioja. The ores of these deposits show: U-Cu: (low vanadium) Esperanza, in Salta; and La Cieneguita in Catamarca. U-Ni: San Santiago in La Rioja; and La Niquelina in Salta.

Sedimentary Deposits

To this group belong the Triassic bituminous lutites of Mendoza Province. These have a very low uranium content, and have not been studied sufficiently. Also, the gold and tin bearing alluvials of Orosmayo, Rios Cincel, Candado and others, Jujuy should be mentioned.

Deposits due to Alteration and Circulating Solutions

We include here, in view of some similarity with the deposits of uranium and copper of the Colorado Plateau (USA), the deposits of southern Mendoza, namely Eva Perón, Agua Botada, Cerro Mirano, Pampa Amarilla, and other occurrences. It is pos-

sible that future investigation may establish the origin.

The theory of origin must account for the presence of uranium in the carbonaceous materials of the El Cucho (Jujuy) and Escoipe (Salta) zones, as well as in the malachite and azurite impregnated sandstones of the area of Plaza Huincul, Neuquén; in some radioactive manganese minerals in the province of Mendoza, and also perhaps in the travertine (San Luis) and aragonite deposits (Salta).

Asphaltic Deposits

Bodies and veins of asphaltite, the ashes of which contain up to 1% uranium occur in Mendoza and Neuquén.

DESCRIPTION OF THE DEPOSITS

We shall give here a short resume of the geology and main characteristics of some of the deposits mentioned in the other sections, grouped according to origin (Fig. 2).

Pegmatites[3]

Pegmatites with uraninite and other uranium minerals have been known for a number of years in the crystalline Sierras Pampeanas of Córdoba and San Luis and also, although this is more recent, the Sierra de Velazco (La Rioja), Sierra de la Huerta (San Juan) and Sierra de Ambato (Catamarca). These rocks are related in all instances to ancient granitic intrusions in older pre-Cambrian gneiss, micaschist, amphibolite, etc.

The area where they are most frequent and best studied is the upper part of the Sierra de Comechingones (Córdoba), between San Javier and Merlo, a distance (straight line) of 35 km. The length of these pegmatites is very variable, and reaches, in exceptional cases, 1 km or more. The width varies from a few decimeters to several meters, and up to 100 or more in certain bodies. In general, they are oriented approximately north-south and they follow the foliation of the enclosing schists. They are not always veins, although this form is predominant, but may be in irregular bodies, at times fairly large, from which there are many projections.

The pegmatites are rich in quartz, microcline and muscovite, with some associated plagioclase (oligoclase); the accessory minerals include garnet (almandine), beryl, triplite, tourmaline, apatite and, rarely, gahnite and zircon. To these, we may add uraninite and, in some cases, columbite, tantalite, molybdenite, pyrite and chalcopyrite.

The uraninite appears in cubic crystals, in small masses inside books of muscovite, as well as in garnet and even in triplite.

Among the supergene minerals of uranium we may mention gummite, uranophane, autunite and renardite: these last three impregnate masses of mica, feldspar and quartz which may weigh up to 20 or more tons.

This type of deposit includes the Angel mine, to the west of Merlo, which contains beryl in lenses and columbite in small masses of a few hundred of kilograms; the Cerro Blanco mine; the Al Fin Hallada pegmatite, with gummite and altered uraninite in masses of feldspar and quartz; the Beatriz mine, with autunite which impregnates mica and feldspar; and others, in the Sierra de Comechingones belong to this group.

In the Sierra of San Luis mention may be made of the beryllium mine of Santa Ana which contains uraninite and masses of uranium-bearing triplite and plagioclase; of La Esmeralda, with quartz, feldspar and beryllium; and also of Piedras Rosadas and San Fernando, in the Quines area where there are oxidized uranium minerals due to the alteration of uraninite in the pegmatites.

In the Cora Vivi beryllium deposit of the Sierra de Velazco (La Rioja), secondary uranium compounds indistinctly impregnate the beryl and other components of the pegmatite.

Due to the sporadic and scattered distribution of the uranium minerals, the production from these pegmatites is insignificant and, at times, only recovered as a by-product of mica, feldspar, and beryl mining.

Except for material very rich in gummite and uraninite, with up to 55% U_3O_8 the concentration of the disseminated masses varies between 0.30–0.40%.

Hydrothermal Deposits

The San Santiago[4,10] mine, which used to be called Solitaria, is some 35 km north of the village of Jagüe and 280 km by road northwest of the City of Chilecito in the General Sarmiento Department, Province of La Rioja. Located on the rim of the Cumichango ravine in the southern part of the sierra of the same name, and at a height of 2400 meters above sea level, this deposit was worked for its nickel content in the middle of the last century. Outcrops of crystalline schist are found near the deposit. Quartzite, amphibolite, micaschist and pre-Cambrian dolomite, with an orientation and depth which vary since they are somewhat folded also occur. They are cut, in general, by pegmatites and aplites, as well as by lamprophyres which, although they are less frequent, are larger.

To the west of the deposit, in contact with the basement complex is the Paganzo I formation (Devonian-carboniferous), which consists of sandstone, arkose and clay. All of these occur in the region of the mine and are displaced by movements which generally are Tertiary. This disturbance caused many post-mineralization breaks which occur in the vein as closely spaced fractures. Some of these cut the vein more or less directly at right angles, with direct displacements to the north, and others cut it obliquely without any major shift.

Beyond the deposit is a series of outcrops, the thickness of which is more than one hundred meters, which strike from SW-NE to E-W, and dip of 50 to 60° NW or north. The new workings reveal at present a tabular vein which is oriented N 65° E,

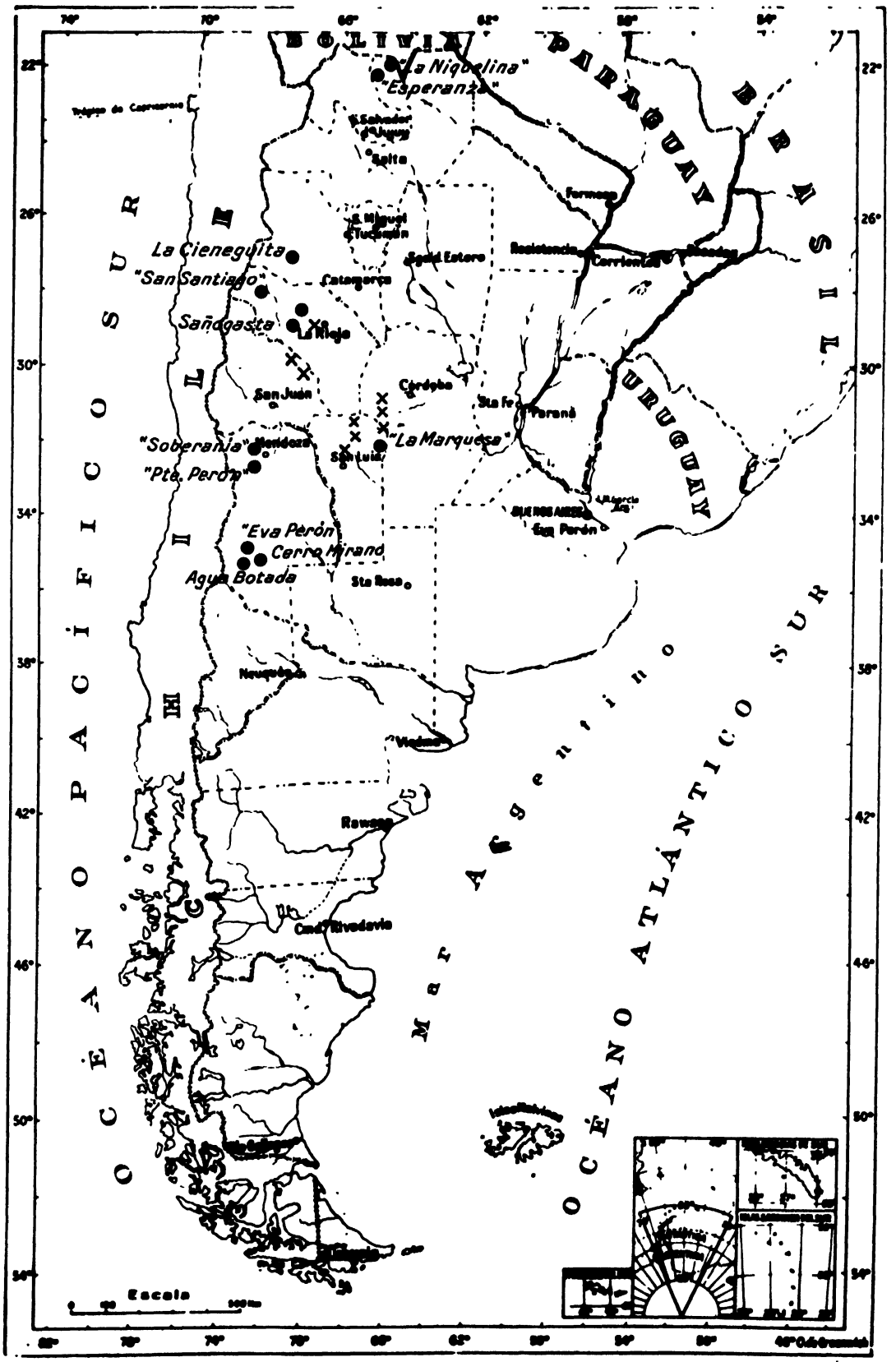

Figure 2. Uranium deposits in the Argentine Republic: ● principal deposits; x uranium bearing pegmatites

and is unconformable with the quartzite, which forms the primary rock, and dips 50 to 65° N. This vein, which extends under the ravine mentioned, has a thickness of several centimeters and well defined wall rock. It is cross cut in its eastern part by a fault which shifts it about 10 m.

The mineralization consists of niccolite associated with pitchblende and a small amount of pyrite, chalcopyrite, sphalerite and galena in a gangue of calcite and some quartz, as well as fragments of the wall rock.

The texture of the vein is massive and within the calcite which is the principal filler, we find the useful minerals, namely niccolite and pitchblende. Niccolite occurs in small nodules or blocks, in short lenses, or in irregular patches which are about 10 cm thick and very pure, and which form pockets of variable size. The niccolite is brecciated in parts of the middle level of the mine, but not at depth.

Pitchblende occurs as thin films on the niccolite or disseminated through it.

There are two generations of calcite: a pink, which is correlated with the deposition of the niccolite and pitchblende; and white, which is associated with pyrite, chalcopyrite, sphalerite and galena.

In the host rock which is often pyritized, we also find penetrations of thin stringers of niccolite, as well as white calcite with greater frequency.

Genetically this is a deposit which probably has its origin in a mesothermal solution fissure filling. There is no direct connection with any sort of eruptive rock in the zone, although possible correlation with a hidden mass of granite cannot be ruled out. Granite outcrops a few kilometers from the deposit.

The average concentration in the mineralization at depth shows values of 8% Ni and 0.70% U_3O_8. Selected samples show 17% Ni and > 1% U_3O_8.

Sañogasta[7]

In the southern part of the Famatina mass between the Guanchín ravine to the north and Manzano to the south, we find a zone some 40 km long and 10 km wide, in which various occurrences and uranium deposits have been noted.

Among the first deposits recognized and to be studied is the Santa Brígida group of mines, and that made up of the San Victorio, San Sebastián and Fidelidad, 3 km apart. They are located on the north rim of the Miranda ravine, 3 and 6 km to the west of the Sañogasta village, and 29 and 32 to the S-SW of the City of Chilecito, 1500 m above sea level in the Eva Perón Department.

The principal rocks in the zone, which includes the two groups of mines mentioned are: Paleozoic slates (Cambro-Ordovician) which are metamorphosed and are grayish green to dark gray and fractured; biotitic granite, white to grayish, Permo-Carboniferous and intrusive in the slates beforementioned.

Both of these rocks are intruded by bodies and veins of lamprophyre, as well as intermediate effusives. Tertiary, Pleistocene and recent terraces and transport also are present. In addition, there are veins of quartz and calcite; the latter has copper and uranium mineralization in varying amounts.

In the region of the Santa Brígida group we find quartz stringers, some with epidote, and veins with abundant calcite. These traverse distances which are at times appreciable, and have intercalated slate near dacite along the slate-granite contact. These beforementioned deposits are located half way up the Loma del Pozo height.

The calcite veins, with a general NW-SE strike and dip of 70–80° SW, frequently show sinuous anastomosing veinlets which in turn are affected by post-mineralization faults in the host rock.

The northern group, namely that of the San Victorio mine, lies in a region of rounded slate hills which rise above the surrounding territory. There the slates have a smaller areal extent and show marked fracturing. They are interlayered with less abundant dark banks of quartzite. Penetrating the formation are relatively small irregular bodies of dacite and other effusives, as well as lamprophyre, in the immediate vicinity of the veins. Occasionally, there are thin quartz stringers.

Four veins have been explored up to now in this group: two, have an ESE-WNW direction, and the other two run NNE-SSE with almost vertical dips. The mineralization in the oxidized zone, varies from a few decimeters to a few meters. The length of the ore bodies is variable.

Mineralization in this group and in the previously mentioned one consists of uranophane with some tyuyamunite in stringers and masses, at times very pure, or as thin films which impregnate the wall rock; gummite which is yellowish-red or dark orange and is associated with altered pitchblende in the deeper workings; oxidized copper compounds (carbonates and silicates) and iron hydroxides which impregnate the slate and vein. Among the primary minerals we may mention pitchblende in small irregular masses and in thin veins; a small amount of pyrite, chalcopyrite and chalcocite, the latter occurring with a certain degree of frequency in one of the veins.

The gangue consists of white calcite in abundant masses in some parts of the veins; a dark violet fluorite in veins and veinlets as well as fragments of the wall rock, barite and a small amount of epidote.

As to origin, it is assumed that these fissure fillings are related to hydrothermal solutions which are correlated with the Tertiary eruptive cycle.

The content of the minerals extracted from these deposits is 1% U_3O_8.

Aside from the deposits mentioned, reference is made to others such as that of the Guanchín ravine, in slate; that of the Manzano ravine, in granite with copper minerals; the Porota deposit in Valle Hermoso on the western slope of the Sierra del Famatina, in slate with copper minerals, etc.

Finally, we should draw attention to the continued finding of new deposits as a consequence of the intense exploration in this mountain region.

La Marquesa[6]

This mining project is located on the western slope of the Sierra de Comechingones in the Río Seco valley some 8 km to the northeast of Villa Larca, at an elevation of 1300 m above sea level in the Department of Chacabuco, Province of San Luis.

This ravine in granite was worked along a fracture about normal to the axis of the chain.

The principal rock in this area is a pink granite, sometimes light gray, medium grained and which appears to be somewhat porphyric. This granite, which at times has a xenolith cover, is related to the large batholith of the Sierra de los Gigantes-Sierra de Comechingones. This ancient batholithic intrusion in the pre-Cambrian crystalline schists is related to the pegmatites, tungsten deposits, etc.

In the region of this mine which is 3 km to the east of the opening of the Rio Seco fracture on the left rim, the granite consists of microcline, quartz and biotite with a few lamellae of muscovite. It shows various systems of diaclases of which those oriented NE-SE and NNE-SSW predominate, with dips of 75° ENE and 55° ESE, respectively. They are further affected by a series of main faults some with local torsion and oriented NE-SW. There are other lines of minor fractures which also served as channels for the ascending mineralizing solutions.

In the immediate vicinity of the mining camp there are various veins which carry green and bluish fluorite associated with a small amount of quartz; one, fills a short granitic breccia 10 m in width. This, as well as other fluorite deposits along the ravine to the top of the chain, show very low radioactivity. However, the black vein which is approximately 150 m to the ESE of the mining site on the south rim of the ravine, is mined for its uranium content.

These various bodies tend to have a lenticular form with lateral veins which are more or less parallel and oriented from ENE to WSW. They are a few decimeters thick and associated or combined with thin stringers in various direction. The main dip of these bodies is 70 to 75° SSE, with local variations.

Mineralization is represented by a dark blue very opaque fluorite of the fetid variety, which is accompanied by another which is a little lighter and formed in a different way. In this mass we can find remnants of crushed granite. The wall rock contains a purplish clay material which is derived from the alteration of the granite and crushing of the fluorite by post mineralization movements.

The mass of fluorite and granite which shows considerable meteoric alteration, is indistinctly impregnated by uranophane which coats the walls of fractures or diaclases in both materials. This mineral also fills faults and fractures in thin lamellae up to 1 mm. The impregnation in the granite shows thicknesses which are at times 40 or 50 cm or even exceeding that thickness.

At the present working depth, it has been impossible to identify the primary uranium mineral which is thought to be pitchblende related to one of the two generations of fluorite mentioned above.

It is felt that this deposit is mesothermal and that it is related to the regional granitic intrusion.

The U_3O_8 content of the minerals extracted from the mine is 0.30 to 0.50%.

Presidente Perón, Soberanía and Independencia [5, 12]

Some 17 km by road to the west of the city of Mendoza is the Presidente Perón deposit. It is at the south end of a uranium-bearing area which extends intermittently over some 7 km in an approximately north-south direction and in which we find at 2 and 4 km to the north of the deposit mentioned, the Soberanía and Independencia mines respectively, in the Department Las Heras, Province of the Mendoza.

This strip, which is just within the limits of the Pleistocene terraces, along with the foothills of the Precordillera, is at a height of 1450 and 1500 m above sea level.

The oldest geologic unit which outcrops in the vicinity of the deposits is the Cambrian which consists of calcareous rocks and calcareous sandstones that are unconformable on sediments of the Rhaetic period to the east, and on probable Devonian formations to the west.

Formations of the upper Triassic which correspond to the Rhaetic and Noric, occur in this area, and immediately to the east, Eocene sediments.

The Noric forms the Estratos de Potrerillos and Cacheuta which consist of sandstone, conglomerate bentonite, and varicolored clays.

The lower Tertiary complex includes "red conglomerate", with associated dark-red sandstone; the "anhydrite zone", with sandstone and massive gypsum inclusions and "variegated clays", with beds of multicolored clays and argilaceous sandstone with a small amount of gypsum.

The orientation of these sediments is generally north-south with a dip of about 50 to 70° east. However, they show considerable variations, due in part to the fact that they have been disturbed by various faults.

These deposits are in the west flank of a synclinal structure, the center of which consists of continental Oligocene-Miocene sediments along a tectonic line between the Rhaetic and Eocene.

The rock in which the quartz veins occur shows a breccia-like aspect along with many shear planes from the deformation which preceded and followed mineralization.

In the uraniferous strip previously mentioned there are two or three quartz veins which are parallel and are a few decimeters thick. These are associated with stringers and thin branches which irregularly penetrate the clay, bentonite and, at times, sandy materials, which belong to the primary rock.

These veins tend to be lenticular and show variable development both in the longitudinal and vertical directions.

The principal mineral is massive quartz which is strongly fractured and often shows a breccia-like structure. It is accompanied by calcite and gypsum gangue.

In the meteoric zone, which reaches a depth of 15 to 20 m, the following minerals are seen: uranophane, as a thin film or patina, which mostly coats the walls of the diaclases and fractures in the quartz; schroeckingerite, in crystals or crystalline aggregates and abundant in some parts of the veins of the Soberanía mine; meta-autunite and phosphuranylite, in smaller quantities. They are accompanied by iron and manganese oxides, and copper carbonates.

The mineralization of this zone is not only limited to the veins *per se,* but also is found in the wall rock which it more or less impregnates over a lateral distance of several decimeters.

There is at depth, a dark material which contains pitchblende in very fine films, and dendritic and botryoidal forms. This occurs in the mass of brecciated quartz, and is accompanied by compounds rich in manganese oxide and uranium which coat the side walls of the veins and diaclases. In addition, there is scattered pyrite and magnetite.

These deposits which have similar characteristics, are thought to be low-temperature hydrothermal types, possibly related to a deep seated intrusion connected with the upper Tertiary eruptive cycle.

The assay of the minerals varies between 0.30 and 0.70% of U_3O_8 according to their type.

La Cieneguita

Some 20 km to the southwest of Tinogasta village, in the Department of the same name, Province of Catamarca, a recent discovery was made of a uraniferous strip which extends in a southerly direction from Las Higueritas in the north, to the Río Colorado in the south, and covers approximately 14 km.

This consists of yellowish lutite, 3 to 5 or more meters in thickness, intercalated in other reddish lutites. The usual dip is between 45° and 50° west. To the east there are faults due to tectonic disturbances. These sediments belong to a complex which is related to the lower Tertiary or Triassic, and which is overlain by tuffs, sandstones and conglomerates.

The previously mentioned yellowish lutites have thin films of carnotite and other oxidized compounds of uranium along their bedding planes and diaclases. At times, these are accompanied by secondary copper minerals. The distribution of these minerals is irregular, and in some places they form uranium-rich concentrations. In addition, the occurrence of chalcocite and chalcopyrite veinlets is noted.

It is assumed that these uraniferous occurrences are hydrothermal and related to the Tertiary eruptive cycle.

La Niquelina[2]

This mine is in the region of Tuctuca, on the eastern slope of the Sierra de Santa Victoria (Department of the same name), 73 km to the southeast of the village of La Quiaca at an elevation between 4500 and 4700 m above sea level.

The deposit lies in an area of Cambro-Ordovician slate and quartzite which has a general NS to NNE-SSW trend, and a dip of 50° to 60° or more to the west.

The deposit consists of a system of three veins which are oriented north 30–40° west, and dip between 70° NE to almost vertical. In addition, there are stringers and diaclases which are vertical and trend E-W.

These veins which lie in slate or along the contact with quartzite, vary from several decimeters to over one meter in thickness and are mineralized with niccolite, galena, sphalerite, pyrite and chalcopyrite, in a quartz and siderite gangue. There is an abundant breccia of the wall rock.

Aside from the minerals mentioned, the presence of pitchblende in fine stringers, particularly in niccolite impregnated quartzite, is recognized.

This deposit, which will soon be intensively explored for uranium, is due to hydrothermal solutions, probably mesothermal, which filled cracks and fissures. There is some replacement metamorphism which may be related to a deep seated intrusion.

Esperanza[2]

This prospect is located in the valley of the Río San Juan, 85 km in a straight line from Iturbe station, at an elevation of 2600 m above sea level, in the Department of Iruya, Province of Salta.

It lies on the eastern slope of the Sierra de Zenta in a Cambro-Ordovician slate area. It consists of two veins which intersect at an acute angle: one carries galena in a barite gangue, and the other copper minerals (bornite and chalcocite) in dolomite, quartz or wall rock. The latter, oriented east 15° south with a dip of 80–85° north at depth, forms a copper rich mineralized block which shows some radioactivity which occasionally is strong due to the presence of pitchblende.

This is hydrothermal, but the source of the solutions is unknown.

This mine has been worked at various times for copper and lead. The recognition of uranium in the ore is recent.

Deposits due to Alteration and Circulating Solutions—Malargüe[8, 9]

About 40 km southwest of the town of Malargüe, in the Department of General Perón, Province of Mendoza, in the foothills of the Andean chain, a large uraniferous area occurs. It contains the Cerro Huemul (Eva Perón), Agua Botada, Cerro Mirano and Pampa Amarilla deposits and lesser occurrences.

These deposits occur in a youthful region of piedmount plains with rounded peaks which are capped

by andesitic and basaltic intrusives. They are found at an elevation of 1850 to 2200 m above sea level.

This zone, geologically, is similar to the southwest flank of the Pampa Amarilla anticline. On the eastern side the Triassic prophyries, Bayocense-Caloyence sandstone, Tithonian-Neocomian bituminous sand, and Diamantian (upper Cretaceous) sandy or argillaceous conglomerates from the main outcrops.

At the deposits, the Diamantian continental sediments predominate. They consist of heterogeneous polygenic conglomerate and conglomeratic yellowish to dark sandstone, arkosic sandstone of a yellowish to grey color, and layers of reddish or grey clays which alternate with the previously mentioned sediments. This complex is cut occasionally by thick veins and dikes of hornblende andesite which is Mollelitic (Oligocene). In some deposits this cuts the mineralized layers in various directions. There are heavy accumulations of Quaternary material in certain areas, which show radioactivity that is two to three times above the "background".

The mineralization is as localized in the conglomerate and conglomeratic sandstone as it is in the fine grained sandstone. Those are characterized in every case by a certain amount of asphaltic material.

In the meteoric areas, carnotite predominates, particularly in the Eva Perón and Agua Botada mines where it is associated with uranophane and a small amount of autunite. In addition, there is malachite, azurite and iron hydroxides derived from the sulphide alteration.

The presence of uraninite has been shown at depth by X-ray diffraction. This is associated with thucholite in asphaltic material, as well as bornite, chalcopyrite, chalcocite, pyrite, sphalerite and galena; the last two occur at Eva Perón.

These minerals are disseminated in small gains within the cementing material of the conglomerates and sandstones. Both in "Eva Perón" and Agua Botada in particular, there are dark fine-grained sandstones which show a high concentration of asphaltic material and uranium.

The mineralization occurs between two layers of clays which are several decimeters to one meter or more in thickness. They form lenticular bodies of various dimensions.

With respect to origin, it is believed at the moment that the presence of asphaltic material in the conglomerates and sandstones is due to the thermal action of deep seated intrusions which are pre-Mollelithic and overlie the Titono-Neocomian bituminous sands. The later origin of the uranium and sulfides is not established, and there is insufficient data to attribute a hydrothermal origin to them. Therefore, a possible origin is assumed in which uranium, copper, etc., are contained in descending solutions derived by alteration from other sources, and precipitated by the asphaltic material which acted as a reducing agent.

The Eva Perón deposit is located on the western slope of the Cerro Huemul, 46 km by road to the southwest of Villa Malargüe; it consists of mineralized coarse conglomerate with lateral sandstones and argillaceous facies. It trends, in general, north 10° west and dips about 30° west. To the south of this body which is elongated and of appreciable dimensions, and separated by an andesite dike, another outcrops which with an interruption extends as far as Agua Botada. It therefore covers 2 km. The upper part of the first body is well exposed with no overburden. It has been explored by means of trenches, and its deeper part was observed by drifts. The assay varies between 0.30 and 0.70% U_3O_8, with a Cu content of 2.5 to 4%, and V_2O_5 content of about 0.1–0.2%.

In Agua Botada, a southern extension of the Eva Perón, the existence of an appreciable uranium concentration has been established. It has assays which are similar to those of the Eva Perón, and the mineralization occurs in fine-grained sandstone. There are two horizons separated by about 10 m, of which the lower is the more important.

At a distance of 9 km (in a straight line) to the southeast of Eva Perón we find the Cerro Mirano on the northeast flank of which in its upper part, copper-uranium deposits outcrop. These are of the same name. There are two prospects separated by a short distance in compact fine grained sandstone. These outcrop in a NW–SE direction, and dip 8–10° SW. At the surface oxidized minerals of copper and uranium occur, and at depth, uraniferous asphaltic material is associated with sulfides. Mining indicates that uranium rich areas alternate with those of lower uranium content.

In Pampa Amarilla, 6 km in a straight line to the south of "Eva Perón", there are various outcrops of oxidized copper and uranium minerals. These occur in superficial friable sandstones. This is a recent discovery, and is being explored.

REFERENCES

1. Ahlfeld, F. and Angelelli, V., *Las Especies Minerales de la República Argentina*, Unv. Nac. Tucumán Inst. Geól. Miner. Pub. 458, Jujuy (1948).
2. Angelelli, V., *Recursos minerales de la República Argentina I. Yacimientos Metalíferos*, Inst. Nac. Invest. Cienc. Nat. Museo "Bernardino Rivadavia". II Cienc. Geól., Buenos Aires (1950).
3. Angelelli, V. and Varese, F., *Exploración geológico-minera de las Pegmatitas Uraníferas de la Sierra de Comechingones—Córdoba y San Luis*, Direc. Gral. Fab. Mil., Buenos Aires unpublished (1947).
4. Barrionuevo, Luis A., *Informe sobre los Trabajos de Exploración y Explotación de la mina de Níquel y Uranio "San Santiago—Jagüé. Dpto. Gral. Sarmiento. La Rioja*, Direc. Gral. Fab. Mil., Buenos Aires unpublished (1954).
5. Belluco, A., *Las Vetas de Cuarzo Uranífero del Yacimiento "Presidente Perón,"* Direc. Nac. Energ. Atóm., Buenos Aires unpublished (1955).
6. Cabeza, J. J. J. and Marinkeff, K., *Informe Preliminar de la Mina "La Marquesa". San Luis*, Direc. Nac. Energ. Atóm., Buenos Aires unpublished (1953).

7. Cabeza, J. J. J. and Marinkeff, K., *Las Manifestaciones Uraníferas de las Inmediaciones de Sañogasta. Dpto. Eva Perón, La Rioja,* Direc. Nac. Energ. Atóm., Buenos Aires unpublished (1953).
8. Linares, E., *El Yacimiento "Eva Perón". Malargüe. Mendoza,* Direc. Nac. Energ. Atóm., Buenos Aires unpublished (1955).
9. Ortega, F. A., *Yacimiento "Eva Perón", Cerro Huemul, Mendoza,* Direc. Nac. Energ. Atóm., Buenos Aires unpublished (1952).
10. Quiroga, P. J. and Granero Hernández, A., *Informe Geológico-Minero de la Mina "San Santiago", Jagüé, Dpto. Gral. Sarmiento, La Rioja,* Direc. Gral. Fab. Mil. Buenos Aires (1952).
11. Rigal, R., *Las Minas de Columbita y Tantalita y el Descubrimiento de Minerales de Uranio en Cañada de Alvarez (dpto. Calamuchita) Córdoba,* Direc. Min. y Geol. Bol No. 45, Buenos Aires (1948).
12. Varese, F. and Tabacchi, M. H., *Informe Geológico-Minero de la Mina "Soberanía" Dpto. Las Heras, Prov. de Mendoza,* Direc. Gral. Fab. Mil., Buenos Aires unpublished (1948).

The "Eva Perón" Deposit, Malargue, Mendoza

By E. Linares,* Argentina

In this work, which is a part of a larger project by the author, we give a summary of our current knowledge of the geology, petrography and mineralogy of the uranium-copper deposit known as the "Eva Perón."

As a first step, in order to obtain the conclusions described and to ascertain the genesis of the deposit, we made topographic-geological surveys of the zone, mapping on a scale of 1:2500. A geological section was also made across the mineral-bearing zone which shows all the outcrops, particularly in the zones which are mineralized.

Later, in the laboratories of the Atomic Energy Commission, we conducted the necessary petrographic and mineralogic determinations.

LOCATION AND GEOGRAPHICAL CHARACTER OF THE ZONE

Location

The uranium and copper deposit known as "Eva Perón" is in the Huemul Mountain (1987 meters above sea level), Province of Mendoza, Department of General Peron, district of Malargue, location Agua Botada, 46 km to the south of the town of Malargue, county seat of the department named, 480 km from Mendoza, capital of the province, and 240 km from the city of San Rafael.

Communications

From Malargue, the deposit can be reached by National Highway No. 40, which connects with the village of Barbas Blancas about 65 km to the southwest. Some 200 meters before kilometer 376 on the said road, is the entrance to the mining camp, which is one kilometer to the north of this road.

The National Railroad known as General San Martin, has a branch which connects San Rafael with the town of Malargue, and is extended to the La Calle River, 23 km to the south of this town. This railroad is 25 km, approximately, to the northeast of the deposit.

The deposit is shown on Fig. 1, with its means of communication, as well as the location of the Cerro Mirano uranium-copper deposits and Pampa Amarilla.

Camp

The Eva Perón property has a camp properly installed to meet all the needs of the personnel working there. The supplies required are obtained at Malargue.

Climate

The climate of the zone is the temperate dry continental type. The summers are pleasant, while the winters are cold and dry; yearly rainfall rarely exceeds 250 mm, and in the winter, snowfalls of some size are not exceptional. This is a zone of strong winds, generally prevailing from the west.

Natural Resources

Near the valley in the Huemul Mountains, small natural drinking water sources are to be found which serve the camp. The Agua Botada River, which runs to the west of the camp, is dry only during the summer.

The vegetation consists of small trees, and is xerophilous. Although lumber is not abundant, there is enough to meet the current needs of the camp, and it is supplied by algarrobo (a legume), jarilla (*Zygophyleaceous*) and others.

Geomorphological Characteristics

The region has a youthful topography with nearly horizontal pediment deposits. It is dominated by mountains, which are generally capped by andesitic intrusions and basaltic extrusions such as the Huemul Mountain, the Mirano Mountain, the Sierra de la Ventana, etc.

In the region of the deposit proper, the relief is somewhat rounded although, in some places, due to erosion of the sandy Diamantian conglomerate, which covers two-thirds of the area under study, it is somewhat more angular.

In the vicinity of the deposit, as at Arroyo Seco and Agua Botada, there is a nearly flat flood plain which, as the only marked geomorphological feature, shows low rises underlain by Quaternary tuff deposits which are amply distributed throughout the region. Thus, the underlying rocks are covered by a thick layer of recent sediments, which makes geological observations very difficult.

REGIONAL GEOLOGY AND GEOLOGY OF THE DEPOSIT

Regional Geology

The region in which the Eva Perón deposit is located lies geologically on the southwestern side of the Pampa Amarilla anticline.

On the east side of this structure, and due to a topographic depression, are outcrops of porphyries,

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* Comisión Nacional de la Energía Atómica, Argentina.

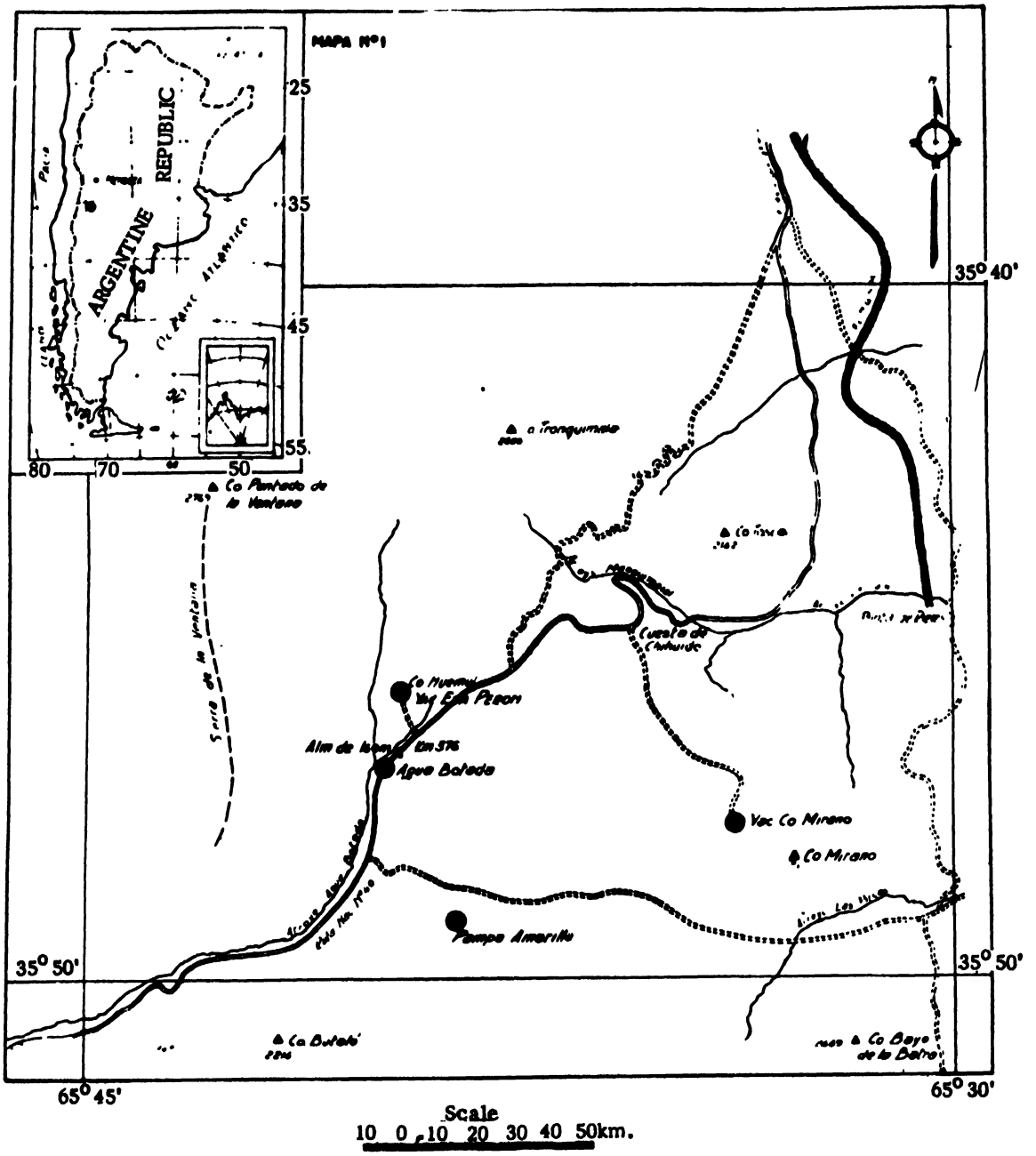

Figure 1. Location of the Eva Perón deposit, of the Agua Botada area, and of the Cerro Mirano and Pampa Amarilla deposits

keratophyres and porphyrites of the "Upper Triassic Porphyritic Series" (Choiyoilitense, Carnic age), as well as purplish and greenish tuffs of the "lower Chiui Strata". They are followed, discordantly, by the sandstones of the Bayocic-Calovic, which are overlain very likely above an unconformity by masses of gypsum of the Auquilcoic (Rauracian-Sequanian).

The gypsum-bearing complex, known as "Main Gypsum", also is unconformable with bituminous and calcareous layers of the Titonian, which, in this area, mark the beginning of the great Cretaceous marine transgression, which lasted until the middle of the "Transition layers" period of the Huitrinian.

The "Transition layers", with clayey calcareous strata belong to an area in which there is a change of facies from a typical marine deposit lower to a continental one, overlying it.

The next units, which belong to the base of the upper Cretaceous, correspond with deposits, which, as already stated, are continental in origin. These sediments consist of arkosic sandstones, the color of which ranges from yellow to gray, of yellow sandstone conglomerate and clays which range from red to variegated. These belong to the Diamantian (upper part of the Andine cycle, according to Groeber) and in some of its sandy and conglomerate strata, the mineralized bodies of uranium and copper are to be found.

On these sediments, in the eastern sector of the zone being studied, one finds discordant green

sandstones, and calcareous and marine clays, as well as lacustrine clays of the Rocanian (upper Cretaceous).

The andesitic intrusions of the Mollelitic (Oligocene), are very irregularly distributed throughout the whole zone, and very extensive. The most important characteristic of these andesites is that they contain hornblende crystals, the length of which at times reaches 5 to 6 mm.

In the western sector are the Tertiary basalts of the Palaocolitic, which make up a large portion of the Sierra de la Ventana. In the vicinity of the Agua Botada River, and occupying a fairly large zone, we can see the Quaternary tuffs (Ignimbrites), which are abundant south of Mendoza and in parts of Neuquén.

Geology of the Deposit

In the vicinity of the Eva Perón deposit, various types of rocks of various geological ages occur. The following list shows them, as well as their respective ages:

Accent:	
Modern fill	Gravels, muds and sands
Quaternary:	
Ignimbrites	
Tertiary:	
Oligocene (Mollelitic)	Hornblende andesites
Upper Cretaceous:	
Rocanian	Green calcareous sandstones
Diamantian	Sandstone conglomerate
	Yellow to gray sandstones
	Vari-colored sandstones
	Red and gray clays

UPPER CRETACEOUS

Diamantian

In the area where the Huemul Mountain rises, where the deposit is located, the rocks of the Diamantian cover a great part of the eastern and western folds of the mountain system. They are limited in the upper part of the system, both east and west, by the andesitic intrusion. In the eastern fold, the andesites which limit the Diamantian culminate in the Huemul Mountain, while on the western fold the andesitic body which caps the crest is located behind the camp covering the western fold of the Huemul Mountain, which falls into the Agua Botada River.

A geological section along an E–W line shows:

(*a*) Andesite dike which cuts the sediments of the Diamantian. Andesites contain essentially phenocrysts of feldspar (acid plagioclase), hornblende and quartz, with a porphyritic texture. Most characteristic are hornblende crystals, of prismatic habit, with dimensions which may reach 5 to 6 mm.

(*b*) 3.80 meters—reddish and very limonitic clay.

(*c*) 1.60 meters—light gray clay. At times, it shows fine streaks of limonitic material.

(*d*) 2.00 meters—coarse to medium-grained conglomerate, and conglomerate-like medium-grained sandstone. The conglomerate is yellow varying to grayish and reddish brown, although in the lower portion it is blackish, due to the presence of an abundance of asphaltic material. This conglomerate consists of: abundant rolled material, sub-angular to round with an average size of between 5 and 20 mm but occasionally of larger dimensions which reach 3 to 4 cm, of quartz bearing porphyries, rhyolitic porphyries, prophyrites, quartz, chalcedony, feldspars, mica flakes, pyroxenites, amphiboles, as well as crystals of fluorite, zircon and garnet. The cement is sandy, somewhat calcareous; calcite is the main constituent.

(*e*) A mineralized stratum occurs which at various levels contains copper and uranium minerals. In the upper part of the fold (Trenches I, II, III) it shows abundant impregnations of secondary minerals of copper and uranium, while at the 0 level gallery the same stratum shows a very dark cement. Thucholite is present in abundance, as well as uraninite.

(*f*) 4.00 meters—light gray clay, whitish.

(*g*) 6.70 meters—coarse to medium-grained conglomerate, yellow to grayish, very compact, with intercalated gray sandstones, of fine to medium grain.

(*h*) 20.00 meters—red limonitic clay which partly shows lenses of light gray clay or intercalations of fine-grained sandstone, gray in color. Makes up the base of the fault.

(i) 3.60 meters—arkosic sandstone, yellow to gray, made up of potassic feldspar and quartz as the main components. Accessories are zircon, garnet and magnetite. Calcareous cement, principally calcite.

(*j*) 4.30 meters—conglomerate, medium to fine-grained, yellow; passes gradually to the above formation at depth.

(*k*) 5.70 meters—red clay.

(*l*) 7.50 meters—conglomerate, medium to coarse-grained, yellow.

(*m*) 17.60 meters—reddish clay; going up, passes gradually to a dark red clayey sandstone, fine-grained.

(*n*) 18.50 meters—alternates of yellow conglomerate, alternating with fine yellow sandstones.

(*o*) 5.40 meters—fine-grained sandstone, cement made up of a silica-bearing material, dark red, very limonitic. The parts in contact with the andesite are very compact, probably due to thermal metamorphism.

(*p*) 3.80 meters—medium to fine-grain sandstone, yellow. The upper part of this stratum is completely metamorphosed.

(*q*) Andesite dike.

All of these sediments belong to the lower part of the upper Cretaceous (Diamantian), in which, although various types of rocks are found, they are consistently continental. Of all the Diamantian outcrops, the most important for the purpose of this work are the yellow and gray arkosic sandstones and the yellow to dark conglomeratic sandstones, since they are mineralized.

The conglomerate and mineralized sandstones show within the deposit itself, a number of lateral changes in facies. Thus in some locations, the very

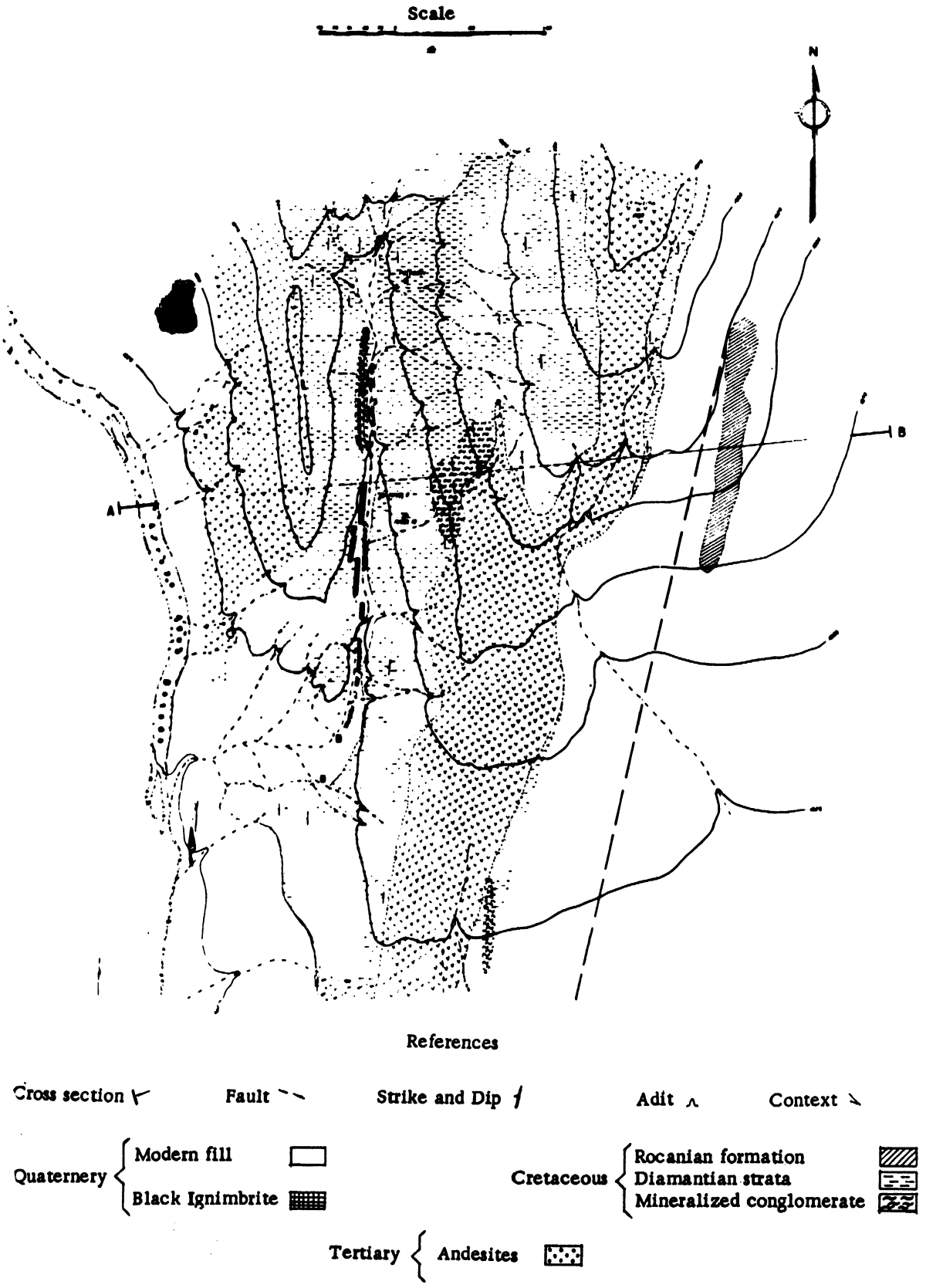

Figure 2. Eva Perón deposit: Topographic-geologic map—Zone of Malargue—Province of Mendoza

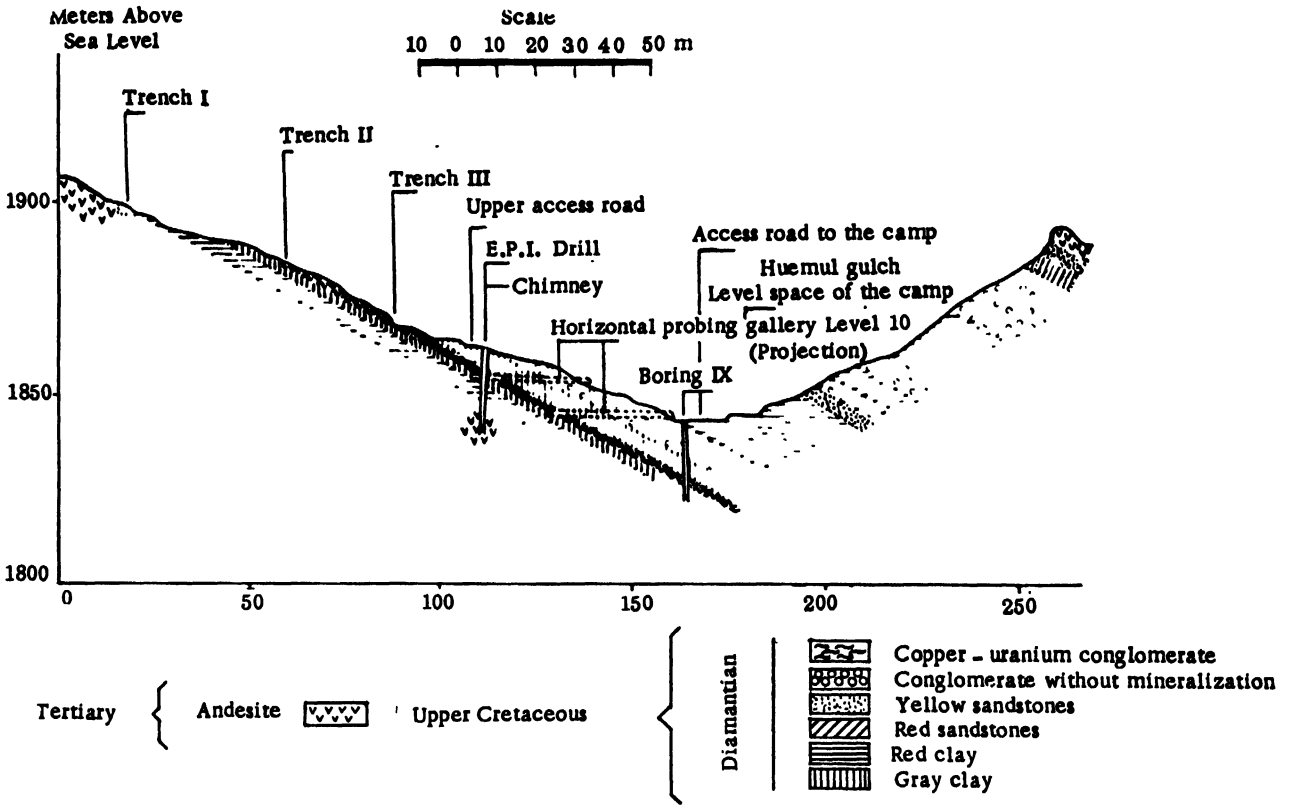

Figure 3. Eva Perón deposit: Cross section A-B

coarse sediments, as one moves up or down, give way to a fine-grained yellow sandstone with a silica cement, while in others the change is to a gray sandstone. These changes in facies, which take place over short distances, as well as the presence of organic material (pyrobitumen-asphaltic), particularly in the lower levels of the mineralized strata, are two factors which must be considered in view of the part which they may have played in the origin of the metalliferous deposit. This is emphasized by the fact that, in a gallery at the zero level, the mineralization is located in a dark cement conglomerate with an abundance of asphaltic material and the mineralized zone disappears progressively toward the north and south as it passes to a dark sandstone to become totally lost following complete replacement of the conglomerate by this sandstone; it is worthy of mention that there is no associated organic material.

This deposit which is made up of various lenticular bodies, is located in a conglomerate member with an outcrop on the west fold of the tectonic system which forms the Huemul Mountain; the general orientation is 350° to 359°, with dips between 25° and 31° to the west. According to the studies carried out by Stipanicic, the "Eva Perón" deposit is localized in the lower third of the Diamantian.

The oxidation zone of the deposit corresponds to the contacts of the mineralized zone which outcrops by coincidence over a considerable length with the flank of the mountains. The mineralization among the copper minerals is here represented mostly by malachite, azurite, and chalcanthite, with a small amount of bornite, while for uranium, one mainly finds carnotite, aside from uranophane, tyuyamunite and traces of autunite; in addition, the presence of organic matter was observed, but in smaller amounts. The iron oxides (limonite) are amply distributed in this zone and even color some parts of the conglomerate a reddish brown.

At depth, where the primary minerals are found, the conglomerate is a dull black with an abundance of asphaltic material, where one finds, in addition to uraninite and thucholite, the copper and iron sulfides, such as chalcopyrite, bornite, pyrrhotite and pyrite. Also, the presence of galena and sphalerite is confirmed.

In the exploratory trenches which have been examined in the study of the mineralized zone in the upper levels, the U_3O_8 assays vary from each other by 30% to 60%, while those from the underground workings at level 0 vary from 40% to 70%. At this level there are zones with a higher assay, reaching over 1%, but these occur only in local concentrations. The copper content of the deposit, according to the chemical analyses, varies between 2.5% and 4%, the vanadium content is 0.10%.

Rocanic

In the eastern fold of the Huemul Mountain and in small contacts located to the south, there are outcrops of marine and lacustrine sediments of the Rocanic period. These consist of green calcareous sandstones oriented approximately north-south, with dips of somewhere between 15° and 30° to the east.

A great fault, dipping north-south, establishes contact in these zones between the Rocanic layers and those of the lower third of the Mendozian, the vertical displacement being some 600 meters. It should be stressed that all the smaller fractures which are present in the deposit, such as those which are observed in the section along the Arroyo Seco, as well as those present in the Agua Botada medium, must be related to the large aforementioned fault.

TERTIARY

Mollelitic

The mollelitic are represented by gray andesites which are very rich in hornblende and are irregularly disseminated throughout the area. In the center of the deposit they have a large areal distribution since there are two dikes separated by the Huemul Mountain faults which are approximately parallel.

One, the most easterly, forms the top of the Huemul Mountain and extends south for over two km. In parts, it is hidden by the recent cover, but reappears in the zone of Arroyo Seco and further to the south, in Agua Botada. In the latter, the extensions of the andesitic body are present as veins which at times are parallel or subparallel with the strata.

This andesitic body has metamorphosed a large part of the Diamantian conglomerate and sandstone with which it has been in contact. Its effects are seen also at the deposit, with its mineralized strata, and in the southern end of Trenches I and II, as well as the nearby slopes. The presence of mineralization on the opposite side of the andesitic body which seems to be an extension of that at camp, seems to indicate that the andesite has cut these strata and rules out the possibility that the mineralization is related to the andesitic eruptive cycle.

The other andesitic body outcrops on the western fold of the Huemul Mountain along the slope to the Agua Botada River. It is smaller than the other, but it does form a large part of the fold from one of the cusps at the crest behind the camp to the river.

QUATERNARY

Ignimbrites

The ignimbrites cover the surface to the southwest of the deposit. There are four distinct types, readily differentiated by their color: black, dark, pink, gray. They are superposed and the oldest is the black variety, which, aside from being the most developed, always underlies the other varieties and in some places extends beyond the limits of the others. The dark variety is concordant and is extensive; it is overlain by the pink variety which is less extensive and covers the others. Finally, we have the gray colored type.

MINERALIZATION

As already stated, the mineralization of the sandstone conglomerate consists in the upper levels (oxidized zone) of the copper minerals, malachite, azurite and chalcanthite; carnotite, tyuyamunite and traces of autunite represent the uranium minerals. Limonite is abundant together with a small amount of pyrite.

At depth, we have identified the presence of chalcopyrite, bornite and chalcocite as the copper minerals; pyrite, pyrrotite and magnetite among the iron minerals, and uraninite and thucholite among the uranium minerals.

The supergene minerals include malachite which occurs as botroidal, kidney shaped masses, is brilliant to emerald green and very widely distributed in this zone, as is observed in Trenches I, II and III. At some places, malachite is intimately associated with uranium minerals, whereas at others, we find prismatic azurite crystals which are elongated and are an intense blue. There are smaller amounts of chalcanthite which occur in kidney-shaped masses which are whitish blue and generally are associated with malachite.

On the basis of microscopic observation, we have come to the conclusion that the copper minerals are later than the uranium minerals.

Among the latter, we confirmed the presence of carnotite which is the most abundant secondary uranium mineral in the deposit. It occurs as thin lemon-yellow films, which coat the conglomerate and at times form fine very rich stringers in fractures in the wall rock. An incomplete chemical analysis of the carnotite of the Eva Perón deposit shows the following composition:

	Per cent
Moisture	2.1
SiO_1 residue	13.7
Fe_2O_3	8.8
K_2O	6.5
V_2O_5	14.4
U_3O_8	47.3

The presence of tyuyamunite which is less common, as well as autunite has been observed in surveys with ultraviolet light.

At depth, we can find chalcopyrite in botroidal or kidney shaped masses which are lemon yellow and not very abundant. Chalcocite and bornite are rare.

Cubic crystals of pyrite 1 to 2 mm on a side are abundant and irregularly distributed through the conglomerate along with small crystals of magnetite.

Among the uranium minerals in the primary zone, the existence of uraninite has been verified, as well as that of thucholite, a light carbonaceous resin-like material, with a density of 1.7. It does not ignite although it can be burned with some difficulty with a blowpipe, without giving any smoke or tarry residue.

CONCLUSIONS

On the basis of present data, the following conclusions seem reasonable.

(*a*) The mineralization is located in the lower third of the Diamantian yellow sandstone and sandstone conglomerate.

(*b*) The deposit is lenticular and the various mineralized bodies coincide with zones in which the sediments were more porous and permeable.

(*c*) The mineralization is later than upper Cretaceous (lower part), since the minerals impregnate not only the sandstone conglomerate but also fill diaclases, fractures and slickensides. On the other hand, mineralization must have taken place before the Oligocene, since the mineralized areas are cut and separated by andesite dikes of the Mollelitic period, which recently is referred to the Oligocene.

Within the interval mentioned, the process which created the uranium and copper mineralization could only be related to the Chilelitic magmatic period which until a short time ago was thought to be upper Cretaceous, but now is referred to the Paleocene.

(*d*) As to the genesis of the deposit, the following hypothesis can be formulated: (1) deposition and consolidation of the uranium and copper-bearing sediments, or of the arkosic sandstones and sandstone conglomerate of the Diamantian; (2) distillation of the bituminous materials from the bituminous muds of the Titono-neocomian, and migration of these products toward the more porous sediments of the Diamantian; this phenomenon was very likely related to the first manifestations of the Chilelitic magmatic period; (3) correlated with the Chiletitic period, but coming immediately afterwards, solutions deposited the uranium and copper minerals through the more porous and permeable zones of the Diamantian sediments; (4) it is possible that the earlier asphaltic bituminous material in these layers acted as a concentrating agent for these minerals, due to adsorption phenomena.

REFERENCES

1. Angelelli, V., *Yacimientos de Minerales de Uranio de la República Argentina,* Rev. Mundo Atómico. A. VI, No. 20, Buenos Aires (1955).
2. Groeber, P., *Mesozoico,* Geografía de la República Argentina, T. II, Ira. parte, Buenos Aires (1952).
3. Groeber, P., *La Alta Cordillera entre las latitudes 34° y 29° 30',* Rev. del Inst. Nac. de Invest. de las Cs. Natur., Tomo I, No. 5, Buenos Aires (1951).
4. Groeber, P., *Observaciones Geológicas a lo largo del Meridiano 70; 4. Hojas Bardas Blancas y Los Molles,* Rev. Assoc. Geól. Arg., T. II, No. 4, Buenos Aires (1947).
5. Moore, G. W., *Extraction of Uranium from Aqueous Solution by Coal and Some Other Materials,* Ec. Geology, V. 49 No. 6 (1954).
6. Ortega, A., *Yacimiento "Eva Perón", Cerro Huemul, Provincia de Mendoza,* Unpublished information of the D.N.E.A., Mendoza (1952).
7. Pandolfi, C. L., de, *Algunas Observaciones sobre la presencia del mineral primario de uranio en el Yacimiento "Eva Perón",* Unpublished information of the D.N.E.A., Buenos Aires (1954).
8. Stipanicic, P. N., *Anotaciones sobre los yacimientos cupro-uraníferos del sur de Mendoza,* Unpublished information of the D.N.E.A., Buenos Aires (1952).
9. Wright, R. J., *Ore Controls in Sandstone Uranium Deposits of the Colorado Plateau,* en Ec. Geology, V. 50, No. 2 (1955).

Uranium-Bearing Quartz Veins of the "President Perón" Deposit, Mendoza

By A. Belluco,* Argentina

LOCATION AND GEOMORPHOLOGY OF THE AREA

The President Perón deposit lies near the lower slopes of the Precordillera of Mendoza, in the Las Heras department, 17 kilometers by road to the west of the city of Mendoza. It extends on both sides of the Los Papagayos River, 250 meters to the east of Puesto Chambón, and 1300 m to the west of Puesto Lima.

At about 2000 and 4000 m to the north of this deposit, the outcrops of the Soberanía and Independencia mines occur. They belong to the same vein system of uranium-bearing quartz. Since these rocks are identical, we shall limit ourselves to a description of the President Perón deposit.

The area is intersected approximately by meridian 68° 58′ and parallel 32° 53′ (Fig. 1). Height above sea level varies between 1450 and 1500 meters.

Access to the Deposit

Access to the deposit is relatively easy, since there is a good road with few steep grades from the La Gloria Mountain (2 kilometers to the west of Mendoza) to the mining camp, after a climb of 700 meters.

The Camp

The camp is on the left bank of the Los Papagayos valley; water always is available from a spring which is located somewhat below Puesto Chambón between two alluvial conglomerates, one is poorly cemented, and the other dense one serves as a bottom for the water course. Food resources are adequate.

Geomorphology of the Area

The mining region is characterized by a more or less rugged topography which is similar to a modern Pleistocene terrace. It is cut by a number of faults, which trend to the east and extend from the first pre-Cordilleran slopes to Mendoza. Some hills from 200 to 300 meters high rise from this terrace and their number increases to the west, where they become real mountains dominated by a sharp rise toward the top, such as Alfalfar (2498), Bayo (1816), Aspero, etc., which are correlated with the first slopes of the pre-Cordillera.

Climate

The climate of the region is typical of that of most of the pre-Cordilleran region; it is dry and the variations between summer and winter temperatures are sharp. In the latter season, the average temperature is approximately 6°C.

There are occasional snowfalls in the region, but they are not large enough to affect the mine workings. Rainfall is scarce and reaches a yearly average of 300 millimeters with maximum precipitation during the summer.

Resources of the Region

The region where the "President Perón" deposit occurs is favored by being near consumer centers and adequate roads. Building stone, bentonite, gypsum, and small hematite deposits are being worked in the region.

Of probable importance as energy reserves for the future, let us mention the existence of some outcrops (from a much bigger valley) of bituminous schists, which are visible for quite a distance within the Cacheuta deposits (Norense). In addition to the analysis which is being made to determine the bitumen content of these schists, the required steps also are being taken to determine the amount of uranium and vanadium which they might contain.

Part of these bituminous schists outcrop at Potrerillos, approximately 30 km to the west of these deposits and, at some places, they give a uranium assay of approximately 300–500 grams per ton.

GEOLOGY

In order to gather data on the principal geological characteristics of these uranium-bearing quartz veins (mineralization, structure, genesis), a general geologic map of the region was made first. This was followed by a more detailed one of the local outcrops.

Geological survey (Fig. 2): The principal stratigraphic units recognized in the region are: Tertiary: Miocene; Oligocene; Eocene; Mesozoic: upper Triassic; and Paleozoic: Cambrian.

Cambrian

As one follows the course of the San Isidro River some 600 meters to the west of the farm of the same name, the cross section of the valley reveals the presence of a substantial series of limestones and

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Original language: Spanish.

* Comisión Nacional de la Energía Atómica, Argentina.

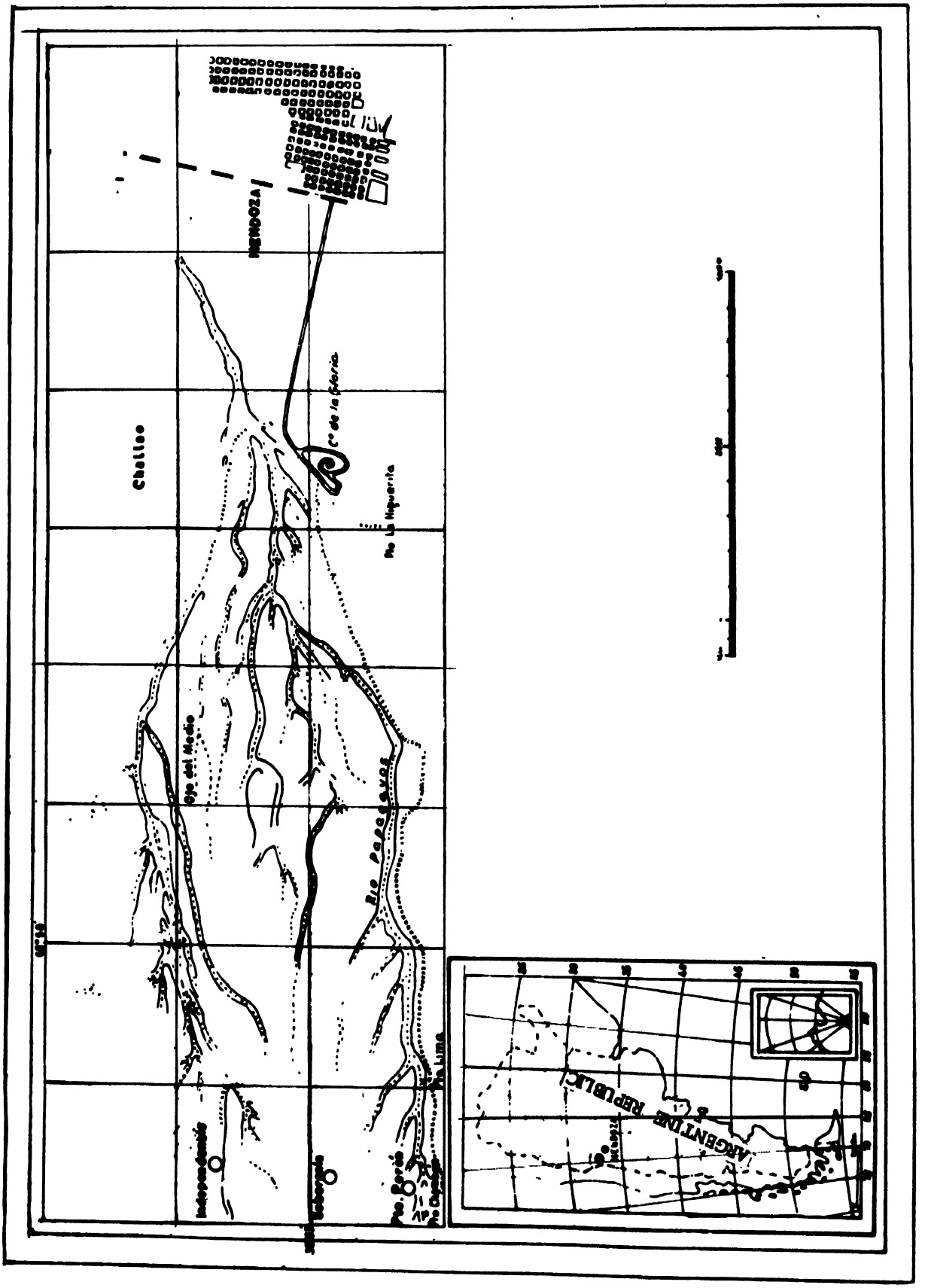


Figure 1. Position of Mendoza uranium deposit (western zone)

calcareous sandstones. These deposits are ascribed to the Cambrian as trilobites are present.

To the east, these deposits unconformably rest on typical sediments of the Retiense (upper Triassic) and to the west they are in abnormal structural contact with Devonian metasediments.

Upper Triassic

The area to the west of Mendoza includes a series of formations which are grouped as follows between the Tertiary and Paleozoic:

Upper Triassic:	
Rhaetic	Río Blanco
Noric	Cacheuta
	Potrerillos
	Cabras
	Fanglomerado
Carnense	Choiyoilitense

The Choiyoilitense (Carnense) is represented by an effusive series (Porphyrites), which rests unconformably on metamorphic rocks which are thought to be Devonian (visible upon entering the Agua de la Falda pass) some eight kilometers to the west of the "President Perón" deposit.

These porphyrites are overlain by a thick series, the base of which is a fanglomerate. This is represented by a mixture of coarse sediments of regular size, which are overlain to the top of the series, by a succession of finer sediments which are composed of sandstones and tuffs of various colors. These formations correspond to deposits at the base of the ancient Pampa de los Nangos.

The finer deposits of this complex are known as the "Serie de las Cabras" and contain typical fossil plants.

Potrerillos Strata

These sediments normally rest above the "Series de las Cabras" and consist of an alternating series of clays, shales, conglomerates and bentonite, which have a thickness of between 200 and 250 meters. Intercalated tuffs and orthoclase porphyries usually are present.

It is possible to recognize in the finer sediments remnants of fossil plants of the Dicroidium type, phylopodic shell fish of the *Estheria* genus, and fish scales (Semionotus). The petrographic and paleontological features warrant the deduction that there has been deposition of various sediments in a valley which has been subjected to various uplifts.

Cacheuta Strata

These consist principally of bituminous schists as well as shales and multi-colored clays with an average total thickness of 60 meters.

The fossil flora and fauna in these sediments is similar to that of the Potrerillos Strata.

These fine grained sediments provide a means of distinguishing them from the older ones, and they indicate a quiet medium for their deposition.

Río Blanco Strata (Victory or Stappenbeck Cretaceous)

A basal conglomerate immediately above the varicolored clays of Cacheuta, indicates the beginning of the Rhaetic deposition which consists of clay, conglomerates, sandstones, and bentonites of various colors which generally are reddish and have a thickness which ranges from 150 to 180 meters. In these deposits which correspond to a terrestrial deposition, probably in an arid climate, no fossils have been identified. Uplifts must have affected these formations and caused the deposition of the associated conglomeratic layers. Upward, these deposits rest unconformably on sediments of the lower Tertiary. The uranium-bearing quartz veins are found in this structural contact.

Tertiary

The lower formations are Eocene sandstones, conglomerates and clays. They are followed in erosional unconformity, by sediments which are assigned to the Oligocene and Miocene.

The following succession of Tertiary sediments is recognized in this zone:

Tertiary:	*Sediments*
Miocene	Mariño Strata
	Interstratified Sandstones
Oligocene	Purplish Conglomerate
Eocene	Variegated Clays
	Anhydrite Zone
	Red Conglomerate
Upper Triassic	

The Eocene deposits are recognized regionally as the "Strata of the Long Divide" and the three lithological units which make up this complex outcrop in the area under study.

Red Conglomerate

This unit is represented here by a dark reddish sandstone, of medium grain and somewhat recrystallized, which contains some kidney-shaped quartz inclusions. Its normal thickness, 35 meters, is reduced in this region to approximately 6 to 8 meters due to the fault which served as a conduit for the solutions responsible for the uranium-bearing quartz veins.

Anhydrite Zone

These deposits consist of medium grained sandstone, Havana cigar brown, with elongated gypsum inclusions. Its thickness varies around 20 meters.

Variegated Clays

With a thickness of approximately 49 meters, these deposits follow in normal succession. They consist of multicolored clays and yellowish-green shales. These clays contain three gypsum veins which are 30 to 40 cm thick.

The variegated clays are followed almost in conformity with the deposits of the Oligocene-Miocene period. This development starts with a purplish conglomerate which here is a well-cemented medium to coarse conglomerate, dark purple, with scattered fragments of quartz-porphyry, and outcrops of the Victor formation (Río Blanco). The thickness varies from 3 to 4 meters.

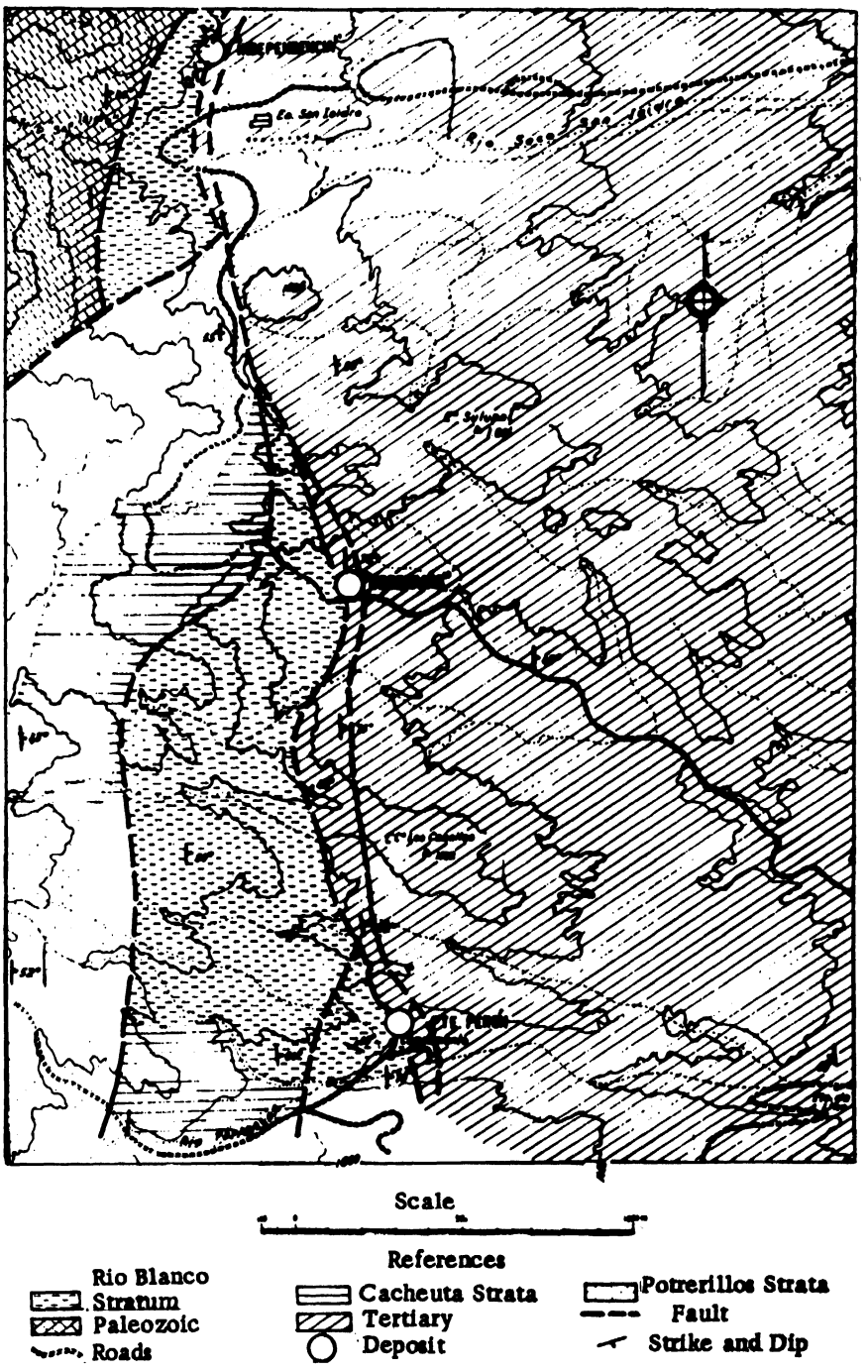


Figure 2. Geological survey of vicinity of the President Perón deposit

Hereafter, in structural contact, we find the interstratified sandstone and the Marino Strata, represented by tuffs, conglomerates and yellowish-red sandstones which make up the succession of Oligocene-Miocene sediments.

Structure

The area where the President Perón deposit occurs, as well as the Soberanía and Independencia deposits, lies on the western flank of a syncline which occupies the area shown on Fig. 3. Tertiary continental sediments of the Oligocene-Miocene lie in the center of this syncline.

The structure is the result of orogenic forces which developed during the upper Tertiary from the Andine geosyncline. The origin and direction of these forces and the possible presence on the eastern side of a crystalline base which would have helped to serve as a support, would account for the axial inclination syncline to the west.

In the accompanying geologic map (Fig. 2) the underlying structure which affected this particular flank of the syncline, is apparent. One of the faults which make up this structural complex was favorable to mineralization, others, on the contrary, not only were unfavorable, but influenced the development of the uranium-bearing quartz veins directly.

In the cross section of this syncline (Fig. 3) these structural factors are indicated as follows:

Fault 1

Brings about abnormal contact between the "Purplish Conglomerate" and the interstratified sandstones (Oligocene).

Fault 2

Brings about structural contact between the "Red Conglomerate" (Eocene) and the sandy sediments of the Río Blanco: it is here that the solutions penetrated and the uranium-bearing quartz was originated.

The breccia-like character of the veins and the slicken sides, which affect the uranium mineralization, suggest movement after deposition of these veins. There is no doubt that these movements must also have been an important influence in the alteration of the mineralization of these quartz veins.

Fault 3

Establishes structural contact between Cacheuta Strata and Río Blanco sediments. It probably is later than Fault 2.

Fault 4

Establishes tectonic contact between the deposits of Cacheuta and Potrerillos.

GEOLOGICAL AND MINING CHARACTERISTICS OF THE DEPOSIT

Position and Geological Age

Geologically, the deposit is in an area of structural contact (locally recognized as the "series of the reddish-green bentonitic clays") between the deposits of the Upper Triassic (Rhaetic) and Lower Tertiary (Eocene).

It can be stated definitely that the "series of the reddish-green bentonitic clays", which look somewhat like a breccia with multiple slicken sides, corresponds to the true breccia of the fault. On both sides of the bentonitic clays, two well recrystallized layers occur. These correspond to the "Crestones del Victor" (Rhaevic) and to the "Red Conglomerate" (Eocene), which not only include and outline this tectonic movement, but also serve as western and eastern boundaries of the mineralization (Fig. 4).

The age ascribed to the fault which affected the "Red Conglomerate" (Eocene) and later served as a conduit for the mineralizing solutions is somewhere between middle and upper Tertiary. On the basis of this evidence, we conclude that this deposit belongs to the third uranium metallogenic period, as defined by Everhardt and Wright, and corresponds to the mineralization period of the upper Mesozoic and Tertiary, and to an upper Tertiary age.

Description of the Quartz Veins

The deposit is considered as being a mineralized layer which consists of two to four quartz veins which dip between 50 and 70 degrees to the E and NE. There is a complicated quartz-like "stockwork" which penetrates the wall rock and is made up of clay, bentonitic clays, and sandstones.

The quartz veins, a few decimeters thick, are white. They are generally massive—occasionally with some small cavities, extremely cataclastic, and somewhat breccia-like in appearance. At some places in the veins, the presence of silica as opal is striking. Calcite and gypsum in small quantities occur in the gangue.

The quartz-like "stockwork" on both sides of the veins corresponds to branches of these veins which have developed from small fissures in the wall rock. These smaller branches have the same characteristics as the vein.

Microscopic study of a thin section shows that "quartz occupies most of the sample. It is subangular, of varying sizes, very shattered in parts, shows many extinction and jagged margins. In some zones, the quartz is cemented by opal which cuts the quartz veins in long thin stringers. Between these, there are anhedral sections of calcite and gypsum, the distribution of which, as that of opal, is very irregular."

Extremely plastic clays, partly bentonitic, reddish-green, somewhat breccia-like in appearance, and with many slicken sides, together with a white sandstone, which is medium grained and uniformly compact, form the wall rock of the uranium-bearing quartz veins.

The only evidence of alteration by the mineralizing solutions occurs on both sides of the veins, as seen by a zone of 2 to 3 centimeters in which the host clays assume a dark orange-like color, and give the impression of having been altered.

Linear and Vertical Development of the Deposit—Structural Correlation

The study of the uranium-bearing quartz veins along a line which connects the President Perón, Soberanía, and Independencia deposits shows a definite irregularity in the longitudinal development of what has been designated as a mineralized strip. In fact, one may observe along this development successive enrichments and depletions, so that the mineralization occurs as pockets of varying sizes which are separated by barren zones.

Many factors can be considered as causes of this irregularity, among these we shall mention three, in order of their importance.

It is obvious that the main concentrations of uranium are in the places where solutions circulated through the straighter and more open parts of the fault. (One section of President Perón and Soberanía, on the contrary, decreases and at times is barren in the parts where the veins show considerable opening between zones two and three of President Perón.)

The more or less diaclasic nature of the quartz veins must have influenced, as a permeability factor, the passage of the descending mineralizing solutions (meteoric zone).

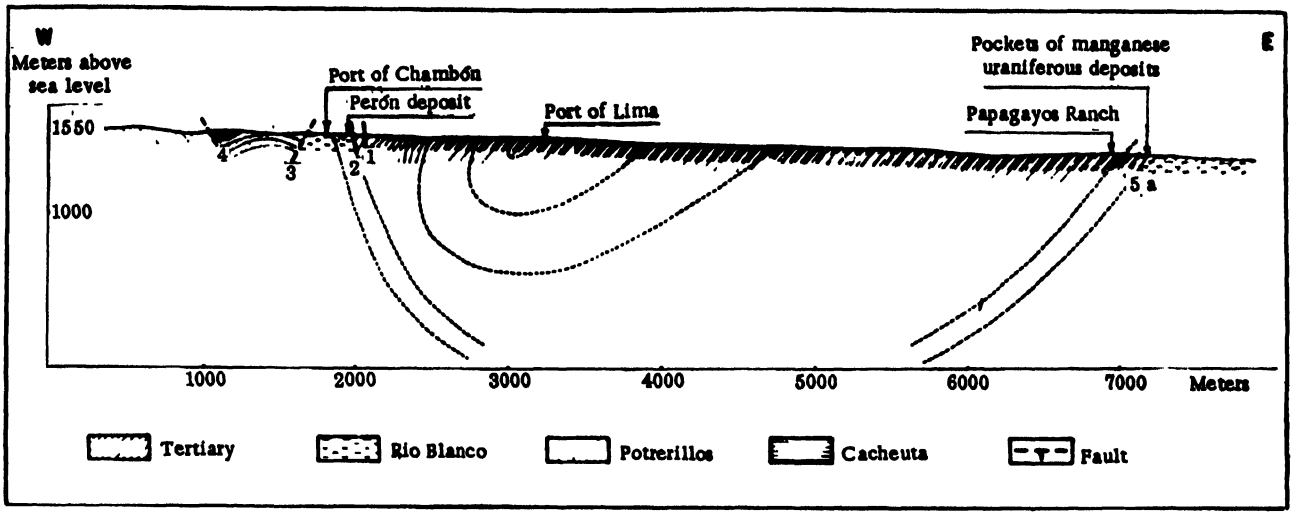


Figure 3. Cross section of syncline west of Mendoza on Río Papagayos

The deformation which occurred after mineralization must also have been important in this irregularity. In fact, these actions, which have preferentially developed in the straight parts of the veins, also have affected the accompanying clays which formed seals for the pockets which already were mineralized. Thus, the passage of the waters was obstructed and could have caused the leaching of the uranium deposited in the veins.

One piece of evidence in support of this hypothesis is the presence of low humidity in the deep workings of the mineralized sections, in contrast with the permeability seen in the exploratory drifts in the barren sectors.

It can be inferred, from the above, that the structure, the permeability, and subsequent impermeability of the veins may have been decisive factors in the unevenness of the mineralization.

The vertical development, on the contrary, shows definite regularity in the mineralized zones as evidenced by secondary mineralization close to the surface and a primary zone at depth, somewhere between 15 and 20 meters.

MINERALIZATION

Mineral Association

From the study of the uranium-bearing quartz veins, both in the supergene zone and at depth, the existence of a simple mineralization is shown with a predominance of uranium minerals. The other minerals which are recognized microscopically in order of importance are: manganese oxide, magnetite, pyrite, hematite, azurite and malachite.

The existence of a primary copper and tin mineral is very likely, as well as that of galena, in very small quantities. The manganese oxide and probably hydroxide form small dendrites in the upper zone; and at depth, their concentration increases markedly and they appear as patinas or black films on the diaclases of the quartz veins.

Magnetite appears in very low percentages, from a depth of 10 meters.

Pyrite was observed as small crystals, and in very small amounts in some diaclases of the veins explored in Mine II.

The hematite, as a product of alteration, partly colors the oxidized zone of the veins red.

Azurite and malachite appear in very small amounts, and are usually found in association with uranium minerals of the supergene zone, particularly with schroekingerite.

Uranium Minerals

Macroscopically, the uranium minerals appear in the sides and diaclases of the quartz veins, as patinas, rosettes or nodules of a yellowish-green color in the secondary zone, and as a patina or a black bitumin in the primary zone. This mineralization also is found in the stockwork and in the veins, and sometimes in the clays and sandstones of the wall rock. In these, mineralization has been effected by the circulation of leaching waters; this occurred before the deformation which affected the vein and opposed the passage of these weathering waters.

In the slicken sides of the primary rock and veins, which were caused by these movements, one will note "dragging patinas" of the uranium minerals. This confirms the theory that these mineralized pockets were made by these movements for, had it not been so, these patinas would have been the first to disappear, in view of their position in planes of easy circulation for the leaching waters.

The uranium minerals identified are:

Pitchblende

Below 15 meters this shows in the dark areas of the breccia-like and diaclased zone of the veins, and also microscopically in dendritic form, where it replaces the quartz, at other times in botyroidal form where it surrounds quartz and calcite, which remain in the darkish mass. It also occurs as spherulites inside the quartz, or finally as veins in the quartz.

In the same thin section, we could identify along with the pitchblende, a yellowish dark mineral of

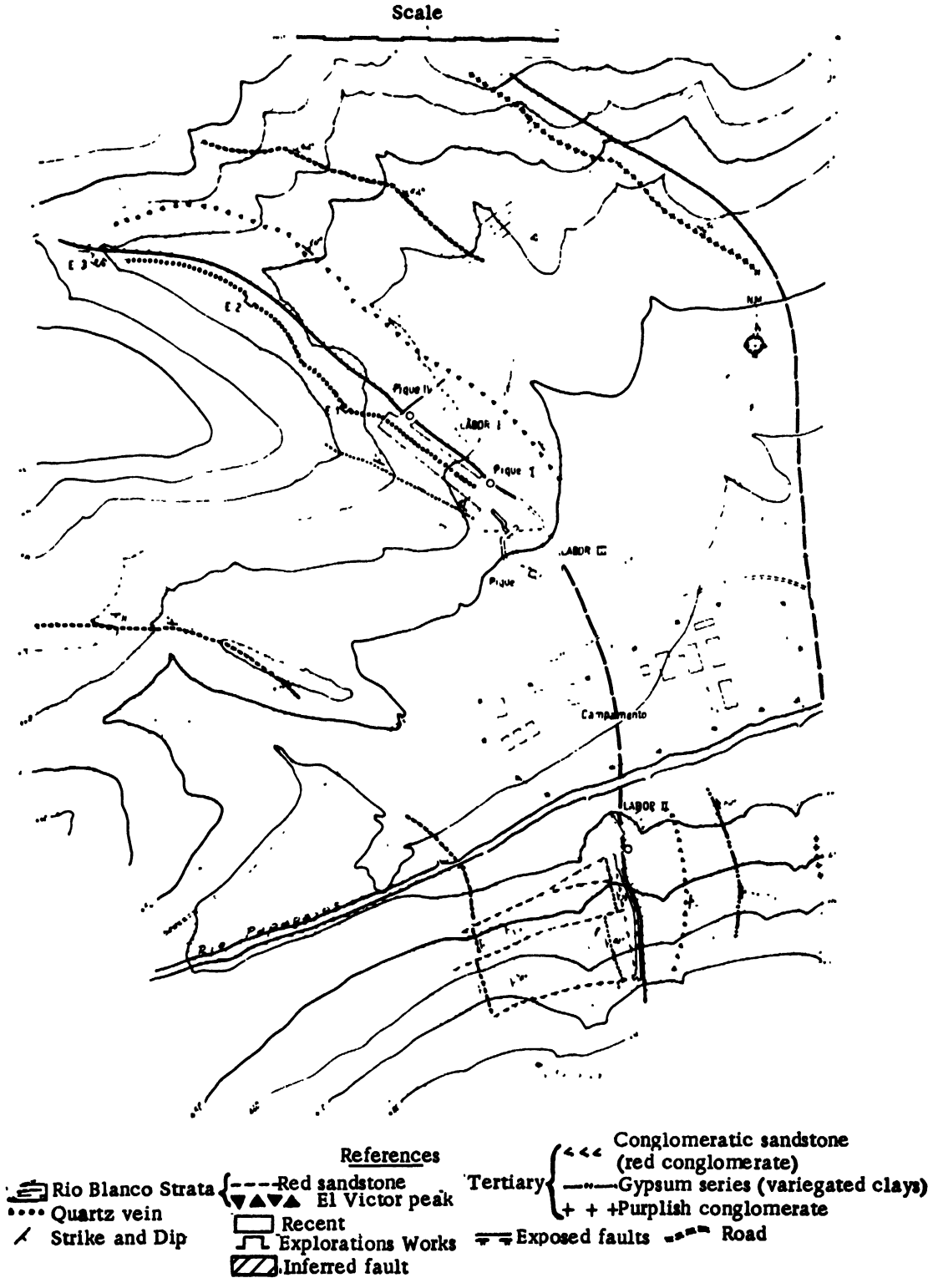


Figure 4. Topographic, geologic and mine map of President Perón deposit

radiating-concentric structure, in the form of bands in the light and dark parts. At times, we observed a dark nucleus, which also appears as a fine penetration between the concentric radial fibers, always normal to the sides. These areas, which are slightly anisotropic, are considered as altered primary mineral which is a transition stage toward the secondary minerals which are observed in the thin section (gummite?).

The secondary mineral in the thin section was recognized as *uranophane,* which is present in a finely fibrous form. It occupies the margins of the opal veins, but generally occurs in very small fibrous radial aggregates. The anomalous birefringence is evident, either between or included in the quartz grains. A spherulitic arrangement is present, although it does not develop into fibers. This material surrounds quartz, calcite, etc. Macroscopically, the color is canary yellow, with a dull luster.

The quantitative analysis of this sample shows 0.75%.

Schroekingerite

This forms films and tabular crystals 0.5 to 5 mm in diameter which are arranged as rosettes; they penetrate the walls or the faults and at times appear as small druses in the quartz. They also are found in small quantities in the clay and sandstone wall rock.

This material is very fluorescent with a quartz lamp and its micaceous appearance is interesting, as well as its brilliant green color.

Meta-autunite

This yellow uranium mineral was recognized in a clay-like nodule which is soft, light brown in color, and associated with azurite.

Phosphuranylite

The spectrographic study of a concentrate of oxidized mineral made it possible to identify phosphuranylite, another phosphate of uranium and lead which shows the same optical and chemical properties as renardite.

Spectrographic Analysis

Spectrographic analysis of separate samples taken close to the surface reveal traces of: U, Si, P, Al, Ca, Fe, Mo, Na, K, Mg, Cu, and Ba.

Spectrographic analysis of separate samples taken at depth indicate the presence of: U, Si, Ca, Mn, Fe, Pb, Cu, Ag, V, Mo, Mg, Al, P, Ti, Sn, Sb, Ni, and Na. The sample is largely U, Si, Fe and Sn.

The uranium concentration varies between 0.30% and 0.70% if the supergene and deeper mineralizations are combined.

GENESIS

On the basis of this evidence, the genesis is summarized as follows:

Fault 2 (Fig. 3) of the middle upper Tertiary, which brought the upper Triassic and the lower Tertiary in structural contact, caused the fissure through which, probably during upper Tertiary, residual hydrothermal solutions were able to ascend.

These hydrothermal solutions can be correlated, either with an effusive rock of the upper Tertiary, or with deeper seated rocks of the same age. This possibility must be considered since rocks of this type are not visible in the area.

In view of the characteristics and paragenesis of the deposit, it is possible to ascribe an epithermal character to the solution coming from the veins.

As indicated previously, the ascent of the mineralization in the veins formed from these epithermal solutions was influenced by the structure and the straight parts of the fault are the zones which are more favorable to mineralization.

From the epithermal solution, according to the microscopic data, the following paragenesis probably occurred: quartz, opal, calcite, pitchblende.

After mineralization, strong pressure produced intense fracturing of the veins.

Undoubtedly, this cataclastic, and at times breccia-like nature of the veins, made it possible for the meteoric waters to circulate. They brought about, in the first place, the oxidation of the primary uranium minerals close to the surface, and thereafter their concentration in the breccia-like parts of the veins, as well even, as in the wall rock. This is the form in which the impregnations of uranophane, schroekingerite, meta-autunite, etc., occur.

The presence, at depth, of uranium-rich black patinas containing an appreciable amount of manganese, which coat particularly the diaclases and margins of the quartz veins, enables us to surmise that the origin is due possibly to descending solutions which contained a certain percentage of manganese oxides and hydroxides. Manganese, in this condition, has the capacity to form adsorption compounds, making it possible, in this case, to concentrate a certain percentage of uranium in the solution. Logically, deposition occurs in the zones where circulation is easier as represented by the diaclases and margins of the veins. It has not been established as yet in what form uranium occurs in such cases. As an illustration, let us mention the presence in the eastern flank of the syncline of this zone, and in the same structural relation between lower Tertiary and upper Triassic, a series of "blocks" of manganese with a high uranium content deposited from meteoric waters.

After the secondary deposition, new movements reactivated Fault 2, and completed the breccia-like character of the veins. This caused the formation of typical "dragged-out patinas" of uranium minerals, which are visible in the slicken sides of the veins and wall rock.

These movements are those which also must have sealed the mineralized masses and made it impossible at a later date for the meteoric waters to circulate.

REFERENCES

1. Bracaccini, O. I., *Acerca de los movimientos intertriásicos en Mendoza Norte,* Prim. Reun. Comun. IPIMIGEO, Sec. Arg. Buenos Aires (1945).

2. Frenguelli, J., *Estratigrafía y edad del llamado "Rético" en la Argentina,* Soc. Arg. Est. Geogr. GAEA, VIII, Buenos Aires (1948).
3. Groeber, P. F. C. and Stipanicic, P. N., *Triásico, en Groeber et al., Mesozoico,* Geografía de la República Argentina, GAEA, Buenos Aires (1952).
4. Pandolfi, C. L., de, *Estudio microscópico del mineral primario del yacimiento Presidente Perón,* Direc. Nac. Energ. Atóm., Buenos Aires Inédito (1954).
5. Truempy, E., *Probable extensión de la cuenca Rética de Mendoza,* Y.P.F. (1943).
6. Varese, F. and Tabacchi, M. A., *Informe geológico-minero de la mina "Soberanía",* Dpto. Las Heras. Prov. de Mendoza. Direc. Gral. Fab. Mil. Buenos Aires Inédito (1948).

The Natural Occurrence of Uranium and Thorium in Australia

By the Department of National Development, Commonwealth of Australia

Uranium minerals have been reported from the six Australian States and also from the Northern Territory. In the Northern Territory and in South Australia, uranium deposits are being mined and treated for the recovery of uranium oxide. In Western Queensland one prospect that may prove to be important is being tested. In New South Wales, Western Australia and Tasmania, prospects have been found and are being tested. In Victoria a few prospects have been found but are either of no economic importance or are still being tested.

The most important source of thorium is the monazite contained in the beach sands and dunes along the southern part of the Queensland coast and the northern part of the New South Wales coast.

This paper will be restricted to a discussion of the more important sources or potential sources of uranium and thorium. Paragraphs 4 to 24 deal with uranium and 25 and 26 with thorium.

NORTHERN TERRITORY

The deposits and prospects are confined almost entirely to the Darwin-Katherine region.

At Rum Jungle, Northern Territory, where uranium oxide is being produced, uranium minerals occur in carbonaceous shale which has been folded, sheared and dragged by faulting. The ore-bodies are close to the margin of granite, intruding Pre-Cambrian sediments, and also close to a major fault which displaces the southern part of the granite 3¾ miles to the southwest. The two most important deposits are White's and Dyson's. At White's and adjacent prospects, pyrite and chalcopyrite are associated with the uranium. Fine-grained disseminated lead and cobalt minerals are also present in the vicinity. The primary uranium minerals is uraninite but secondary minerals occur to shallow depths below the surface. At Dyson's deposit the uranium mineral is principally saleeite. Although most geologists regard these deposits as hydrothermal replacement type there is a distinct possibility that all the minerals, or all except the chalcopyrite, were included in the sediments at the time of deposition.

In the South Alligator River area of the Northern Territory many relatively high grade prospects of secondary uranium minerals have been found along a belt which parallels a major fault zone. The prospects are generally found close to a Pre-Cambrian limestone reef breccia. These deposits have been little investigated except at the Sleisbeck prospect where an orebody has been indicated by drilling. It is likely that the uranium was deposited with the sediments and concentrated during sedimentation or by later tectonic processes.

At the ABC Prospect, near Katherine, Northern Territory, secondary uranium minerals are found mainly in an acid sill intrusive into a basic volcanic sequence. The deposit is close to a major fault and the volcanics have been very much altered. The uranium may have been introduced hydrothermally at the time of alteration of the basic volcanics, deposited as volcanic ejectmenta derived from underlying rocks, or deposited from surface or underground water.

Other prospects, in the Darwin-Katherine region include Coronation Hill, Brock's Creek, Adelaide River and George Creek and are still being tested; small amounts of ore have been produced from the last three prospects, but largely if not wholly from development ore. Prospects of no commercial importance occur in granitic rocks at Edith River and Ferguson River. Uranium and thorium minerals occur in the pegmatites at Harts Range.

SOUTH AUSTRALIA

At Radium Hill, near Olary, uranium ore is being mined and concentrated and the concentrates sent for treatment to Port Pirie. The uranium deposits consist of several parallel lodes occupying fissures in Pre-Cambrian gneiss. The lodes contain quartz, black and bronze biotite and ilmenite and the uranium mineral is davidite. Coatings of carnotite occurred near the surface.

At Mount Painter, uranium minerals occur in crushed granite and pegmatite. In the upper parts of the prospect the most plentiful mineral was torbernite and uraninite was reported to be the primary mineral. Much testing was carried out during 1944–48.

At Crocker's Well near Olary coarse disseminations of absite occur in granitic rocks. Davidite is also present in the area and at Mt. Victoria ore has been proved in sufficient quantity to justify another mining operation which will supplement the production from Radium Hill.

Throughout the State, the Department of Mines is actively engaged on geological, geophysical, drilling and prospecting work generally connected with evaluation of uranium discoveries. Amongst those being currently tested are Myponga, Port Lincoln, Ardrossan and Kadina.

QUEENSLAND

The prospects are confined mainly to the Cloncurry-Mt. Isa region in north-western Queensland.

In the Mt. Isa-Cloncurry region many uranium prospects have been found, but only one, on "Mary Kathleen" lease, at present shows promise of being of economic size. The Mary Kathleen deposit is a skarn rock consisting mainly of allanite, garnet and apatite, and containing uraninite and rare earths. A new mineral (a barosilicate of cerium, etc.) has been reported and the name "stillwellite" has been proposed for it. The uranium mineral is uraninite and it occurs as inclusions in the allanite and stillwellite. The deposit is in a calc-silicate sequence of metamorphosed sedimentary rocks but its structural relationships and origin are not known.

The "Counter" deposit in the Mt. Isa-Cloncurry region consists of disseminated davidite-like mineral in hard greywacke, alongside major faults.

Deposits 20 miles north of Mt. Isa have brannerite disseminated in carbonate beds and lenses, and a group of deposits about 10 miles north-west of Mt. Isa has a davidite-like mineral disseminated in fine and coarse-grained amphibolite and fine-grained hornfels. A davidite-like mineral has also been found in pegmatite and in calc-silicate metamorphosed sedimentary rocks.

There is no obvious relationship to granite in any of the deposits of the Mt. Isa district but there are many granitic intrusions into the sediments containing the deposits and granite may be present at shallow depth almost anywhere in the district. Although the origin of the uranium in this district is virtually unknown and is mainly thought to be hydrothermal in origin, there is a distinct possibility that in many of the deposits the uranium was deposited by the sediments, but it may have been later concentrated by tectonic and/or metamorphic processes.

NEW SOUTH WALES

In the Broken Hill District, the primary mineral davidite occurs in one area and in other parts of the district secondary uranium minerals occur in copper, lead and other prospects.

In the New England District, secondary uranium minerals occur in shears and fissures in granitic rocks, associated with tin, tungsten, lead and other prospects, and in one case with beryllium minerals.

At Carcoar, uraninite and secondary uranium minerals are in association with cobalt, molybdenum and copper; some testing is still in progress. Near Condobolin, pitchblende and secondary uranium minerals occur in zinc, lead and copper in a fissure in granite. Near Pambula, traces of uraninite and secondary minerals are present in molybdenum-bismuth pipes within granite.

WESTERN AUSTRALIA

Attention has recently been drawn to the Hall's Creek-Wyndham region. Aerial scintillograph surveys have revealed radioactive anomalies and ground prospecting has found some uranium prospects. Prospecting and testing are in progress.

Uranium minerals have been found in pegmatites in the Pilbara area.

TASMANIA

Torbernite occurs in tin-bearing formations in the old Royal George Mine near Avoca in the north-eastern district.

VICTORIA

Small amounts of torbernite have been found in granitic rocks in eastern Victoria and radioactivity at other places.

THORIUM

Thorium (in monazite) is found in the beach sands and dunes of the east coast of Australia from the mouth of the Clarence River in New South Wales to Stradbroke Island in Queensland. These sands are probably derived from the Palaeozoic granites of the adjoining areas. Alluvial and eluvial sands containing monazite, rarely in workable quantities, are common around granite masses.

A thorium mineral in a very finely disseminated form was found in quartzites and grits of pre-Cambrian age near Darwin but the type of mineralization in the deposit has not been determined. The mineral is not monazite.

Natural Occurrence of Uranium and Thorium

Austria

Austria does not possess any technically exploitable uranium or thorium deposits. It must be pointed out definitely that the very few deposits of radioactive minerals detected up to now do not consist of technically exploitable quantities, but represent at best scientifically interesting traces. On the research carried out in this respect the following scientific papers have been published:

1. Mache & Bamberger: "Über die Radioaktivitität der Gesteine and Quellen des Tauerntunnels und über die Gasteiner Therme", published in the Report 123 of the Academy of Sciences, Vol. 1914.
2. Dittler & Abrahamczik: "Über die mineralischen Absätze der Gasteiner Thermen", published in the Central Journal for Mineralogy, 1938.
3. Haberlandt-Hernegger-Schemintzky: "Fluoreszenzspektren von Uran-Mineralien im filtrierten ultra-violetten Licht", published in Vol. 4 of the Spectro-Chimica-Acta, 1950.
4. Haberlandt-Schinner: "Die Mineral- und Elementvergesellschaftung des Zentralgneisgebietes von Bad Gastein", published in Vol. 2 of the Czermak-Mineralogisch-Petrographischen Mitteilungen, 1951.
5. Exner & Pohl: Yearbook of the Geological Federal Institute, Vol. 94, Part 2, 1949-51, "Granosyenitischer Gneis und Gesteinsradioaktivität bei Bad Gastein".

In the course of the years a very great many spring water analyses have been carried out and all of them show only very slight traces of radioactive minerals. The large numbers of tests that have been carried out may well be regarded as a proof that throughout Austria no exploitable quantities of radioactive minerals are likely to be found.

The Shinkolobwe Uranium Deposit: Current Status of Our Geological and Metallogenic Knowledge

By J. J. Derriks* and J. F. Vaes,* Belgium

CHAPTER I. GENERAL

1. One would not propose in this study to review all of the observations made since the discovery of the Shinkolobwe deposit. Few ore deposits have been subjected to such close observation nor, probably, have remaining so many geological problems.

2. In their adherence to the facts, the authors have tried to be scrupulously objective, regardless of the risk of upsetting several accepted theories, including the very ones they propose to submit. The selection made from the mass of documents available has been so conducted as to give as accurate a picture as possible of our present knowledge of the deposit.

3. The conclusions represent the current opinion of the authors. While they have met with no major objections on the part of their colleagues, the fact still remains that they are not definitive.

Geographical Position

4. The Shinkolobwe deposit is located 20 km to the west of Jadotville and 20 km to the south of Kambove, in the heart of the Katanga synclinorium (Fig. 1). In common with the majority of the metal deposits found in the province, the outcrop area is at an elevation of about 1400 m above sea-level and thus somewhat higher than the surrounding country. It is one of several deposits, copper-bearing as a rule, but of small importance as such, and is the most westerly of the group (Fig. 4).

Historical Summary

5. The Shinkolobwe group was prospected as early as the beginning of this century by the Tanganyika Concessions Ltd., but some of the smaller copper deposits had been worked at an earlier date by the aborigines. In 1915, uranium was discovered on the deposit now worked by Major Sharp. The geological studies were first undertaken in 1921, at which time operations were begun for the purpose of producing radium.

6. Mining was suspended in 1936. During this initial 15-year period, the deposit yielded from open cut and underground workings, some 100,000 tons of radioactive minerals derived from about 500,000 cubic meters of excavated materials. The major part of the production was held in reserve, only the very rich materials being sent to the radium refinery at Oolen.

7. When mining was suspended, in 1936, the open cut had reached level 57 m† while the underground workings extended to level 79 m. Exploration of level 114 m had been started, and the water pumps had been installed at level 150 m.

8. From the standpoint of our early knowledge of the deposit, nothing could be added to the study of Messrs. Thoreau and du Trieu, published in 1933.‡

9. Open cut operations started again in 1944, and underground extraction in 1945. Since then, mining has been carried on continuously. The ore held in reserve began to move as early as 1943, but uranium, rather than radium, was the metal now produced.

10. Geological research has been actively pushed during the last decade. This has involved a substantial portion of the activity of the Geological Department of the Union Minière. We propose methodically to review the results obtained to date.

CHAPTER II. STRATIGRAPHY

General Stratigraphy of the Katanga

11. In order to consider the problem in correct perspective, it seems essential to briefly outline our current understanding of the Katanga stratigraphy. The subdivision into systems is based on lithologic considerations, and a common group is made up of the whole, in order to allow for tectonic unity.

Kalahari	Sands and Sandstone	For reference
Katanga Group		
Kundelungu System		
Upper	Feldspar sandstone	
	Basal conglomerate	
Middle	Sandstone schist of calcoschist	500 to 1500 m
	Calcareous sandstone	
	Schist or argillaceous calcoschist	
	Pink calcareous rock	
	Petit conglomerate (Marine facies)	
	Petit conglomerate (Tillite facies)	
Lower	Calcareous sandstone	300 to 1000 m
	Schist	
	Feldspar sandstone	
	Poorly stratified schist with vacuoles	
	Kakontwe calcareous massif (lenticular)	

Original language: French.

* Geological engineers, Union Minière du Haut-Katanga.

† Levels are indicated under 1404 reference.

‡ J. Thoreau and R. du Trieu de Terdonck, Le Gite d'Uranium de Shinkolobwe-Kasolo, Mémoires de l'Institut Colonial Belge, Tome 1 fasc. 8.

Grand Conglomerate and Mwashya Systems

Grand conglomerate		300 to 600 m
Feldspar quartzite Banded or platey calcoschist Mwashya conglomerate Dolomite and schist Oolite, jasper, iron		250 to 400 m

Schist-Dolomite System

*Roan System**—Mine Series

Mofya (ancient Mwashya dolomite, other dolomite), schist or sandstone		over 45 m
Dipeta (R.G.S.)	Dolomite and psammite Sandstone and schist	150 to 250 m
C.M.N.	Various dolomites	100 to 400 m
S.D.	Alternate dolomitic and graphitic schist	50 to 100 m
R.S.C.	Siliceous dolomite, often with collenia	15 to 25 m
R.S.F.	Siliceous dolomite in layers	3 to 9 m
D. Strat.	Stratified and nodular dolomite	2 to 5 m
R.A.T. Gr.	Sandstone dolomitic schist	3 to 15 m
R.A.T.	Various schists and dolomites	more than 200 m

Unconformity

Kibara Group — For reference

This outline enables us to bring the stratigraphy of Shinkolobwe into focus.

Regional Stratigraphy of Shinkolobwe

12. The stratigraphic column is fairly well defined as a result of patient research made difficult by the lack of Kundelungu outcrops and lateral variation of the Mine Series facies. Between the lower half of the middle Kundelungu and the top of the R.A.T. all formations are represented. However, some uncertainties exist between the top of the C.M.N. and the iron of the Mwashya.

Kundelungu System

Middle

I C Argillaceous schists, at times slightly sandy, micaceous and pyritiferous. Various shales of yellow, brown, massive. In general, poorly stratified, but locally finely stratified. Interstratified massive bluish-gray siliceous sandstone	?
Siliceous basal sandstone.	Several meters
I B Silicified dirty brown banded or massive correlated with the pink calcareous rock	Several meters
I A Petit conglomerate. Bluish-gray calcareous, argillaceous to varying degrees. Light-colored calcareous, often limonitic, quartz fragments rare	60 m

Lower

IV D Massive or well stratified siliceous sandstone, bluish-gray or greenish IV C Gray argillaceous or argillaceous-sandy schist fine-grained, thinly stratified, or massive, in plates or slabs. Ripple-marks, silica concretions, cross-bedded. IV B Argillaceous or argillaceous-sandy schist, light in color, well stratified, with ripple-marks IV A Not observed Feldspar sandstones	1650 m
III Gray argillaceous schist, lilac pink or red, poorly stratified. Intraformational conglomerate	900 m
II B Kakontwe calcareous rocks and dolomites A (Not differentiated)	Lenticular
I Argillaceous gray-green schist, well stratified platey	60 m

Grand Conglomerate and Mwashya Systems

Grand conglomerate	Not described	
Upper Mwashya	Not differentiated: Conglomerate	More than 120 m
Lower Mwashya	Not observed. Poorly represented	

Schist-Dolomite System

Roan System—Mine Series

Mofya	G	Not differentiated from the Lower Mwashya
Dipeta	F	Not identified. Probably very thin

G.M.N.

E 2 Underlying the sandy dolomite:		
Greenish dolomite with fine-grained sand	?	
Crystalline magnesium-rich dolomite	2 m	
Argillaceous dolomitic quartzite, fine-grained, greenish	1 m	
Crystalline magnesium-rich dolomite	13 m	
Talcose dolomite, more or less stratified	3 m	
White high magnesium dolomite, with crystalloblasts	3 m	
Crystalline pink dolomite	6 m	
Gray dolomitic chloritic schist	2 m	
Brecciated silicified dolomite	3 m	
Light bluish-gray silicified dolomite, slightly stratified	5 m	More than 75 m
Silicified sandstone conglomerate, light colored, irregularly stratified dolomite	1 m	
Argillaceous talcose schist, dark gray with roundish magnesite crystalloblasts	1 m	
Dolomitic quartzite	2 m	
Gray dolomitic sandstone, poorly sorted	1 m	
Siliceous dolomite, light bluish-gray, stratified	4 m	
Argillaceous, sandy gray dolomite	1 m	
Dolomitic quartzite, grayish beige, sometimes banded	5 m	
Grayish beige dolomite, sometimes stratified	9 m	
Argillaceous sandy dolomite, grayish beige	2 m	
E 1 c Siliceous-talcose dolomite horizon:		
Light gray banded dolomite	1 m	
Light gray stylolitic crystalline dolomite	11 m	
Talcose dolomitic quartzite, lilac, pink stratified, sometimes with silica nodules	7 m	60 m
Dolomitic argillaceous to sandy chert purplish, with pseudo-oolitic dolomite crystalloblasts	20 m	
Talcose dolomite, more or less well stratified, with lenticular chert	18 m	

* Position of the Mine Series, in the Roan System, remains open for conjecture. Transition of the Roan System to the Grand Conglomerate and the Mwashya Systems is not defined as yet.

E 1 b Magnesite horizon:		
Grayish crystalline magnesite, little stratification	28 m	130 m
Granular white magnesite	45 m	
Siliceous light-gray magnesite, irregularly stratified, with blackish joints	35 m	
Stratified micaceous gray magnesite	7 m	
E 1 a Acicular dolomite horizon:		
Magnesium-rich stratified dolomite, gray-beige	4 m	25 m
Crystalline magnesium-rich dolomite, stratified with muscovite	4 m	
Magnesium-rich dolomite interbedded with black needles of magnetite and micaceous gray schists	5 m	
Stylolitic magnsium-rich dolomite, beige-gray dolomite, with silica concretions	10 m	
S.D.		
D 3 b		30 m
Dark gray micaceous schist	4 m	
a		
Dolomitic micaceous schist, light-gray	7 m	
D 2 b		
Dolomitic micaceous schist, dark gray	3 m	
a		
Light gray micaceous schist, with pyrite lenses	5 m	
D 1 b		
Dolomitic schist, finely micaceous, dark gray	2 m	
a		
Crystalline magnesium-rich dolomite, gray, stratified	10 m	
R.S.C.		
C		0 to 20 m
Siliceous dolomite, with collenia		
Siliceous dolomite, without collenia		
R.S.F.—D. Strat.		
B 2		9 m
Fine-grained magnesite, well stratified, clear or stratified with chert	5 m	
B 1 b		
Nodular, quartz-bearing, stratified, gray, magnesite, or stratified siliceous dolomite	2 m	
Blackish phanerloblastic magnesite or siliceous dolomite	2 m	
R.A.T. Gr.		
A		10 m
Sandy dolomitic schists		
R.A.T.		
Schist and various dolomites		?

13. The Grand Conglomerate and Mwashya System generally is poorly represented in the Shinkolobwe region, except in the Tantara sector, which has not been studied stratigraphically. However, this inadequacy in our knowledge probably will be remedied in the near future.

14. It is noted that the C.M.N. is very extensive, and is comparable with the Kambove. One has the impression therefore that this development has opposed the deposition of the immediately overlying beds, namely the R.G.S. The findings to date are not adequate to form a final opinion on the latter point. However, in the deposit itself, attention is given to a substantial mass of laminated schistose dolomite, which is wedged between the Mine Series and the Kundelungu. If no correlation can be established between these formations and the C.M.N., they must doubtless be assigned to the Dipeta or Mofya.

15. As is characteristic of the Mine Series, the sequence is lost at depth in argillaceous-talcose rocks (R.A.T.), which are more or less mylonitized. Nevertheless, various borings have penetrated at depth a mass of coarse gray sandstone and conglomeratic pink arkose, which previously was unknown in the mines of Upper Katanga. No stratigraphic correlation could be made, but inclusion in the lower Roan is a possibility.

16. In conclusion, it should be noted that the granite intrusive outcrops only 150 km from Shinkolobwe (Haute Kabombo) and that no basic intrusions (dolerites) are observed within 20 km (Kilembe, Sambwa) (Fig. 1). However, during the last few years attention has been focused in the vicinity of the mines to a plainly intrusive series which is so intensely altered that it is impossible to identify. One has the impression, however, that they are trachyte.

CHAPTER III. STRUCTURE

Regional Geology

17. A geological survey of the Shinkolobwe region has been carried out on a scale of 1:5000, and mapped at 1:20,000. A 1:100,000 plot of this map is shown in Fig. 2.

18. The area surveyed is divided in half by a great fault which extends from Tantara, in the west, to Shomberwa, in the east. Farther to the north, in the valley of the Mura, a similar fault occurs, but it has a rather marked curve to the south-east.

19. Aside from the marginal complications in the southern part, the beds of the Lower and Upper Kundelungu form a fairly regular double syncline, the northerly limb of which overlies the Shinkolobwe fault. The dips show that the folds are sharply overturned to the north.

20. Between Shinkolobwe and the Mura, another Kundelungu type syncline occurs. This one is very regular, and its northern limb also overlies the Mura fault.

21. Beyond this river the same formations recur and form, in order, a syncline overturned to the north, an anticline which exposes the Mwashya and a syncline, the center of which consists of the calcareous Kakontwe-Kisanga (Kombove) mass.

22. The repetition of this harmonious tectonic structure, and the agreement of the overturned beds in the vicinity of the faults, makes it fairly easy to draw the important cross section which passes through Shinkolobwe and Kisanga (Fig. 3). This gives a series of folds overturned to the north, stretched out in fold-faults and, on occasion, in small overthrusts of the first kind. A section through Djambelwa would show additional complications, but their interpretation clearly does not come within the scope of this paper.

23. The Shinkolobwe fault is important in the interpretation of the geology of the deposit. This tec-

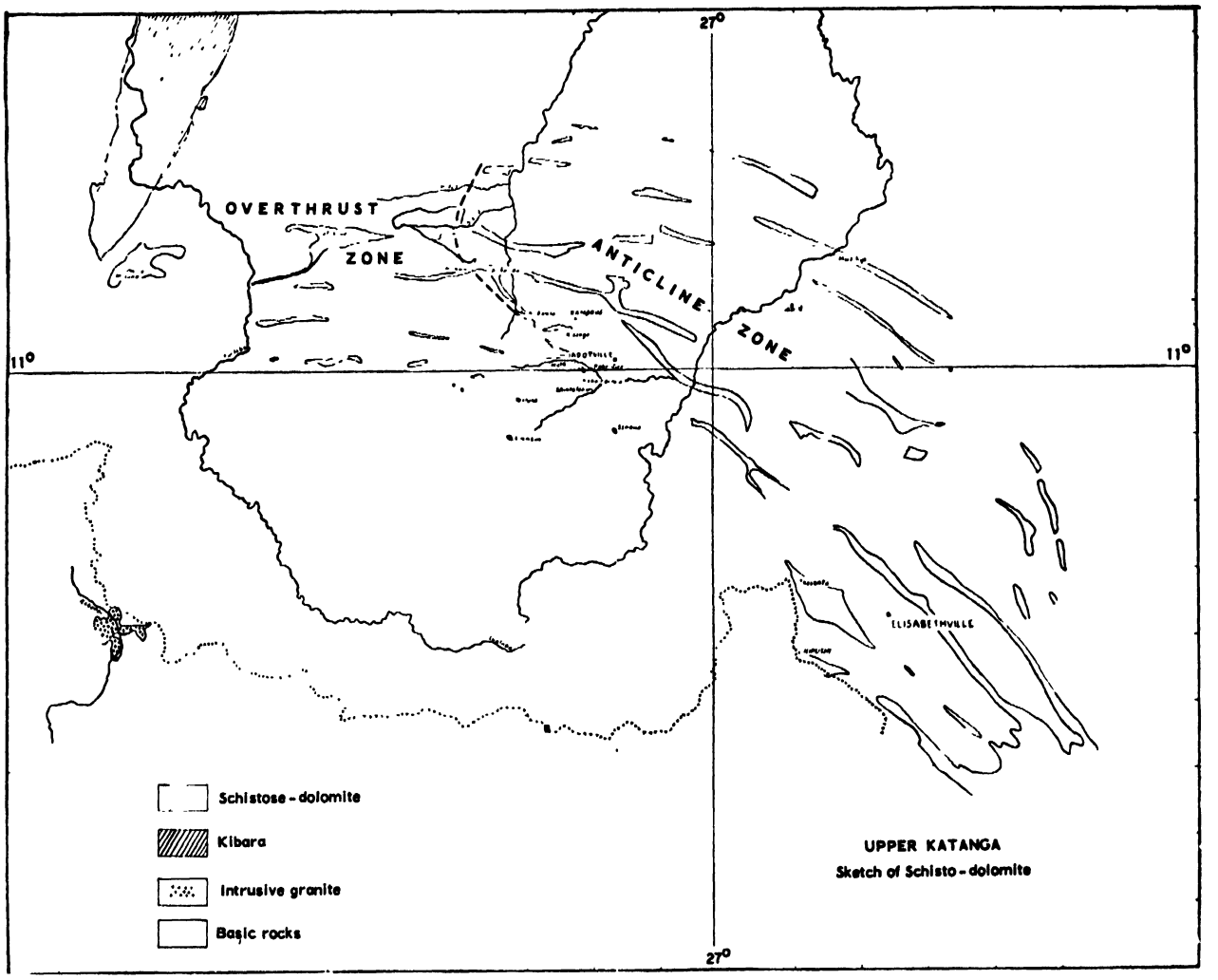


Figure 1. Upper Katanga — Sketch of Schistose-Dolomite

tonic feature is intermediate between the fold-fault and the overthrust of the first kind. However, in the overfolding of the Kapare syncline on that of Kanguluwe, a fairly sizable Middle Kundelungu outlier§ remains. The beds of the Mine Series remain wedged under it and, in part, folded before it.

Correlation of Shinkolobwe with Haut Katanga

24. The Shinkolobwe group is found immediately to the southwest of the Kakanda-Elisabethville schistose-dolomite (Fig. 1). In the system of the Katanga folds it lies at the top of the Kasonta opening or of the Kipushi anticline. If the eastern part of the entire series is considered as far as the Fungurume, it will be observed that the southern folds have a straight axis, whereas the northern ones form an arc, the center of which is some 250 km to the southwest. On the other hand, on the west all folds follow the curve started in the east.

25. Shinkolobwe is precisely at the hinge of this change of direction which is beautifully illustrated by the outcrops of the schistose-dolomitic valley of the Mura, and along the Tantara-Shomberwa axis (Fig. 2).

26. It is well known that, under the influence of pressure from the south, the Katanga basin was compressed, and that the spur of the Lualaba in the underlying masses of the Kibari, accounts for the curve of the Katanga mass. In our opinion, the influence of this spur has been underestimated, and we think it accounts for the structural differences between the eastern and western parts of the depression. While the eastern part could be compressed greatly, and not assume a curved aspect except at the north at the end of the movement, the western zone remained wedged against the spur. The continuous southerly pressure finally brought about a horizontal shearing of the fold of the western zone, thereby giving it the type of fold-fault of the Musoni, Kalukundi and Fungurume polygons.

27. We divide the copper area therefore into two sectors: that of the westerly overthrusts and that of the anticlines which are more or less elongated to the east. The line of demarcation may be capricious; we currently consider it to pass through Fungurume, Mukondo, and Kabolela. We feel that the differ-

§ This spur is called the "Shinkolobwe balcony."

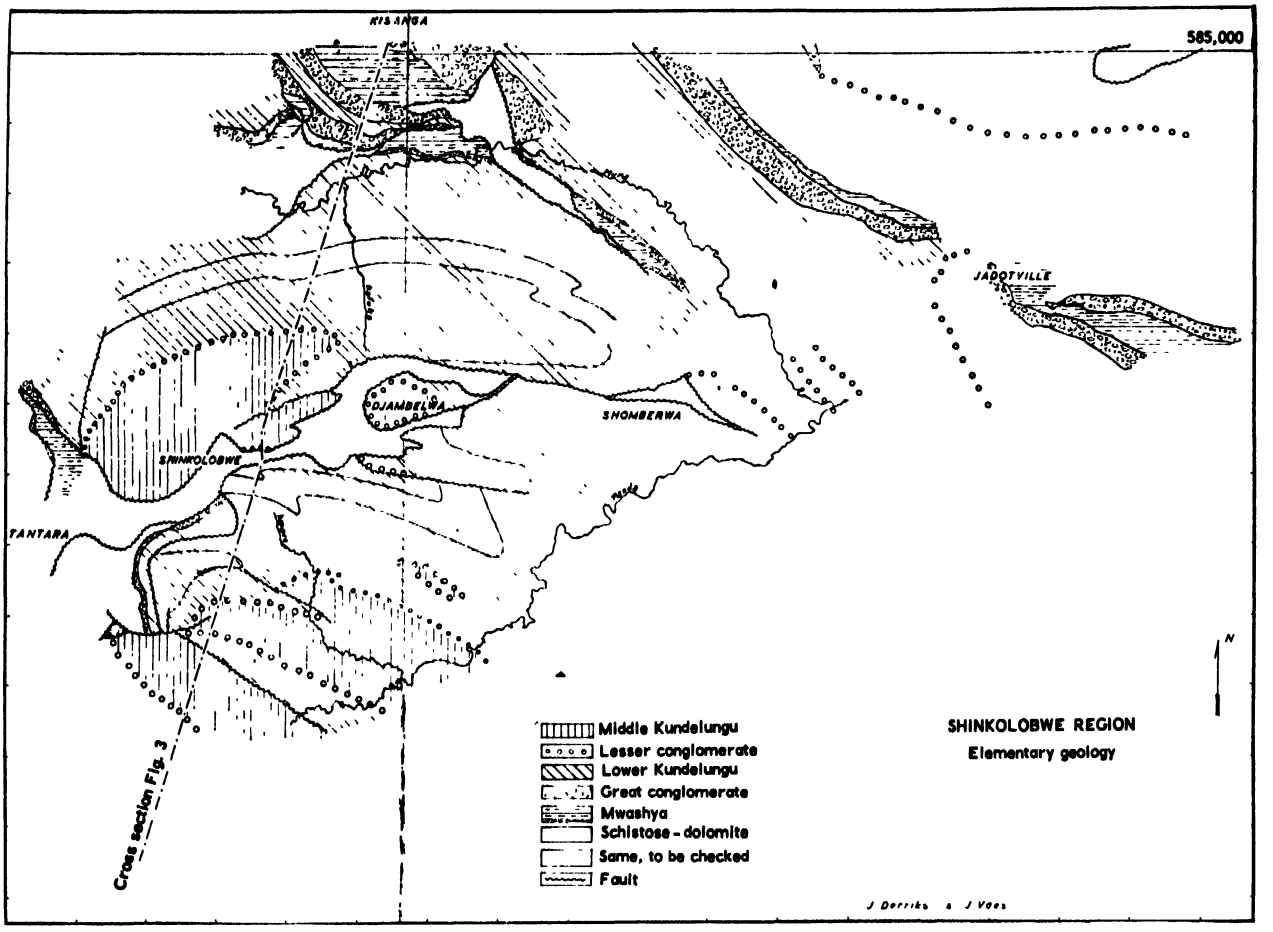


Figure 2. Shinkolobwe Region — Elementary geology

entiation in appearances is buried in the Shinkolobwe country.

28. Let us add, without ascribing too much importance to the argument, that the topography shows higher elevations in the western than the eastern sector. This agrees with our theory that the main overthrust is located only on the side of the Kibari spur.

29. It is understood that overthrusts may occur in the sector, but their amplitude would be relatively small (i.e., Kambove).

30. This digression into the general geology of the Upper Katanga has no purpose other than to make our interpretation of the structure between Shinkolobwe and Kisanga agree with that of the eastern sector, and to show the influence of the study at Shinkolobwe on the structural problem as a whole.

31. It may be stated that the series of fold-faults, such as we have outlined will fit into an overthrust type of structure. It would then form the upper flank of a nappe, the front of which would be the north, beyond Kambove. We object to the theory that the existence of a nappe of this size would have to show tangible manifestations in the region at either end of it. Until such evidence appears, it is logical to hold to the simplest interpretation.

CHAPTER IV. DESCRIPTION OF THE DEPOSIT

32. The following observations are based on careful research. At the surface, where it was necessary, holes were drilled at distances of 25 metres apart. Underground, in the deposit, the drifts through the beds are 15 metres apart, and the workings are 18 metres apart.

This close spacing increases the reliability of these surveys.

For the purpose of reading the plates which show the detailed geology, it would be well to refer to the captions under Fig. 5.

Areal Survey (Fig. 6)

33. As explained above (Paragraphs 18 to 23), the schistose-dolomite of Shinkolobwe appears between two contacts of the Kundelungu. The northern contact, made up of a strip belonging to the Kapare formation, is outlined by the small conglomerate; it is complicated by slight faulting to the south, 200 m to the east of the 0 transverse coordinate. The outcrops of the dolomitic schists also are bounded to the north by Faults A–B (p: 60°N), B–C (p: 30–40°E), and C–D (p: 90°).

The southern contact is marked by a fairly regular fault, which dips to the south.

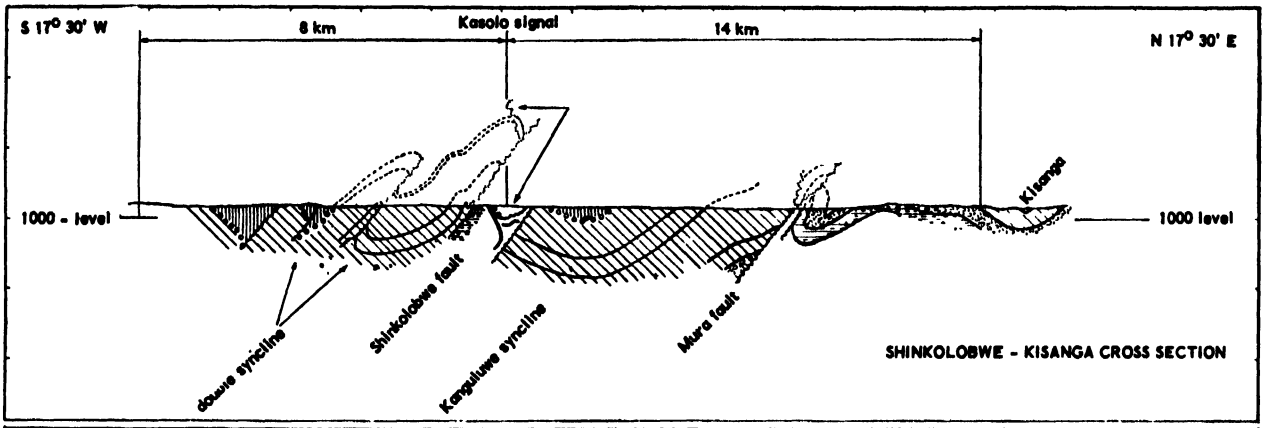


Figure 3 (above). Shinkolobwe — Kisanga cross section

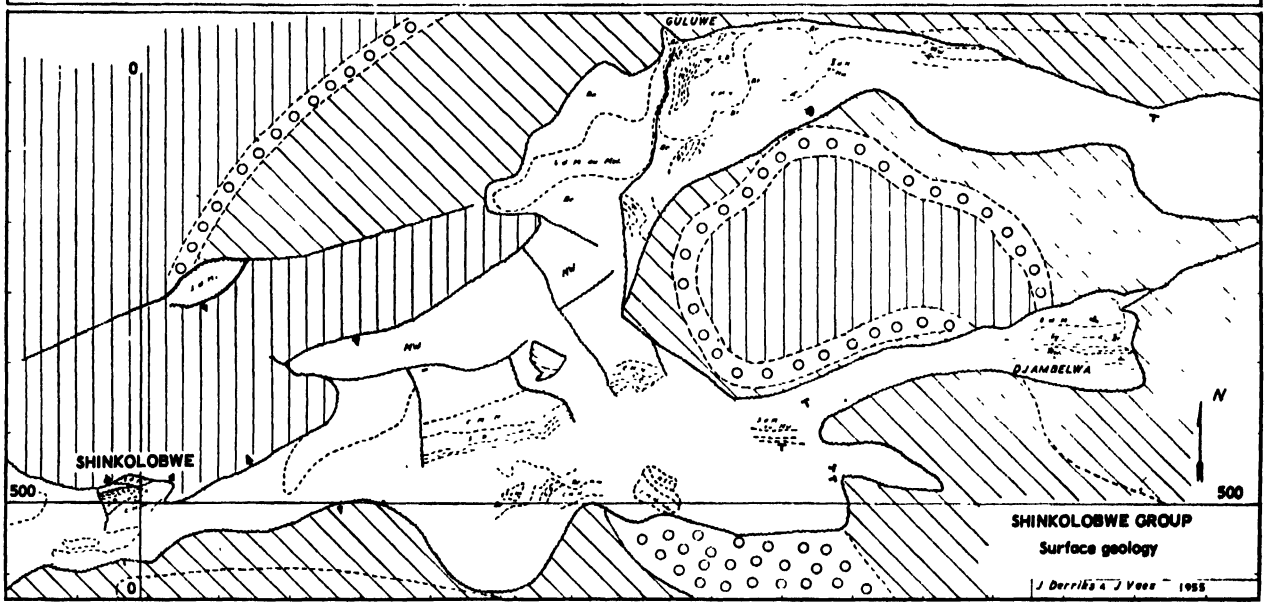


Figure 4 (below). Shinkolobwe group — Surface geology

34. In the Mine Series, three spurs can be distinguished: the first, I,¶ lies along fault A–B, the second, II, along B–C, and the third and most important slips into the angle formed by the first two. All three have an east-west orientation, and they are stratigraphically reversed, with an average dip of 60°N.

35. At the point where the three spurs appear to overlap, there is an area of a breccia with a brown clay matrix and various elements of the Schistose-dolomite and the Kundelungu. It is a Brèche de Remplissage (filled breccia); its edges are vertical.

36. The main spur is bounded to the south by a C–E breccia, which is clay-like and lilac in color. It appears to be similar to the R.A.T. This breccia occurs in the prolongation of the C–D fault. The direction D–E thus is a displacement, the influence of which will be noted at depth. To the south of this, are found various remnants of the Schistose-dolomite, which are extremely difficult to locate stratigraphically, but not a part of the metalliferous deposit.

37. The western limit of the deposit is not clearly exposed on the surface. The A–E fault marks the end of the outcrops. The whole western area is crushed.

38. Between Spur II and Fault A–B, as in the extension of Fault C–D, there occurs a remnant of a sandy and talcose formation which recurs at depth mylonitized shistose dolomite. Until now, we have not been able to locate these rocks stratigraphically, even though they lie between the C.M.N. E 1 b and the lower Mwashya. It is on these that we have focused attention in Paragraph 14. They form what we call l'Assise (base) de Kasolo.

39. At the surface, the uranium mineralization was mostly concentrated in the S.D. of Spurs I and II. It occurs here as veins which follow the stratification and the various dips. These many veins have but little continuity and give the appearance of a stockwork to the whole system. In fact, mineralization extends into fissures, along the bedding planes, into the cavities, and along some secondary faults. It is interesting to note that there is no mineralization in the main faults: these are generally marked by a clay-talc breccia.

¶ Spur I is known as the Kasolo spur, the former name of Shinkolobwe, which is used again in mineralogical terminology as the name "Kasolite."

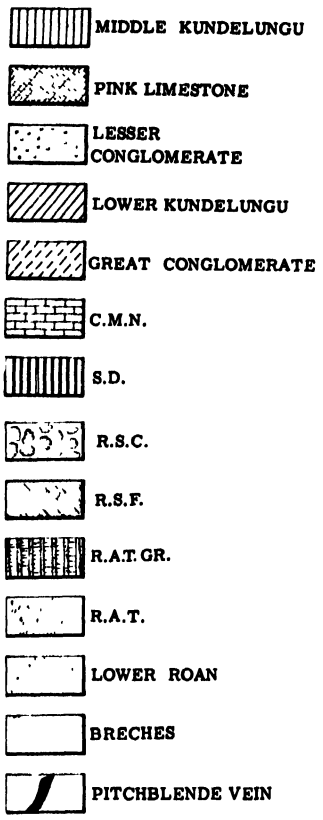


Figure 5. Shinkolobwe — Keys for details of geology

40. At the center of the veins some pitchblende with an aureole of gummite, sklodowskite and torbernite occurs. This is associated with cobalt and nickel oxide minerals. The secondary minerals, such as kasolite and torbernite, can be quite distant from the primary mineralization. A definite preference for some types of rocks is noted: kasolite occurs in flakes which lie between the strata of the S.D.; torbernite accumulated in the cavities of the R.S.C.

Thus the R.S.F., R.S.C., and lower S.D. may be considered as favorable beds for mineralization.

Level 57 (Fig. 7)

41. The continuation of the northern edge of the Kundelungu remains the same as at the surface, and the dip of the faults is maintained. Spur I slips to the East and becomes less important. Spur II is parallel with Spur III, and only the Brèche de Remplissage breaks the continuity of the layers. There now appears a large mass of III and II. The Mine Series always abuts to the east against the Kundelungu and its extent increases with the retreat of the fault in that direction. L'Assise de Kasolo is always present. All formations are altered except for the dolomitic part of the R.S.C. of Spur II.

42. While the beds in general slope to the north in keeping with the 60° dip as measured on the outcrops,. the outline of the Brèche de Remplissage at depth follows almost exactly that noted at the surface. Thus, we are faced with a sort of natural pit which is filled with material derived from the surrounding formations or from those which formerly were overlying having been deposited between the surface and the level 57. One even observes lumps of ore in this breccia.

43. The mineralization of Spur I disappears nearly completely: one finds only some nickel and cobalt oxides in the R.S.F.

The R.S.C. of Spur II are rather rich, and the mineralization overlaps the R.S.F. and the basal S.D. It appears as veinlets of pitchblende, more or less fresh, and impregnations of uranium minerals and Ni and Co oxides.

The thickness of the R.S.C. is extremely variable in Spur III, where the base appears to form a series. The pitchblende veins (uraninite) are particularly abundant between transverse coordinates 0 and 45, at the top of a narrowing in the R.S.C. Uranium always is associated with cobalt and nickel, but, in addition, it contains appreciable quantities of gold and palladium. These precious metals are relatively common in very small quantities throughout the deposit. Concentrations occasionally are found in uraninite, and from level 57 to level 114 they occur in a narrow layer of chloritic rock which laminated at the contact of the R.A.T. and R.S.F. (Fig. 16).

Level 114 (Fig. 8)

44. Spur I is completely wedged against the Kundelungu; it is no longer represented by anything other than a small tongue of C.M.N. The Brèche de Remplissage always occurs in the sector between transverse coordinate 45 and longitudinal coordinate 500; it rests nearly entirely in the dolomite of C.M.N. Spurs III and II, which appear to meet at level 57, are again separated, this time by a broad band of R.A.T.

45. There is another displacement: between levels 57 and 114 the R.S.F. and R.S.C. are interrupted and the down dip side is overturned to the south; the R.A.T. of the upper part slides into the hiatus, and comes against the S.D. of the wall (Fig. 12). Longitudinally, this intrusion affects the whole Mine Series, between the F–G and B–C faults, and slopes toward the east (Fig. 15). R.A.T. intrusions are frequent in the Mine Series, and the intrusion at Shinkolobwe is interesting because of its size and influence on mineralization.

46. Immediately below level 114, at the level of transverse coordinate 45, the R.A.T. nappe forms a dome which due to its imperviousness forms a barrier for mineralization. Under this dome, the R.S.F., R.S.C. and S.D. are faulted, and the countless cracks and fissures are host to an abundant mineralization of uraninite, sulphide and selenium-sulphides, dense monazite, molybdenite, etc. At level 114, all of Spur III which is trapped in the R.A.T. is mineralized. In the course of mining, a detailed examination of the top indicates the total imperviousness of the R.A.T. nappe. This observation must be remembered as the genesis of the deposit is being studied.

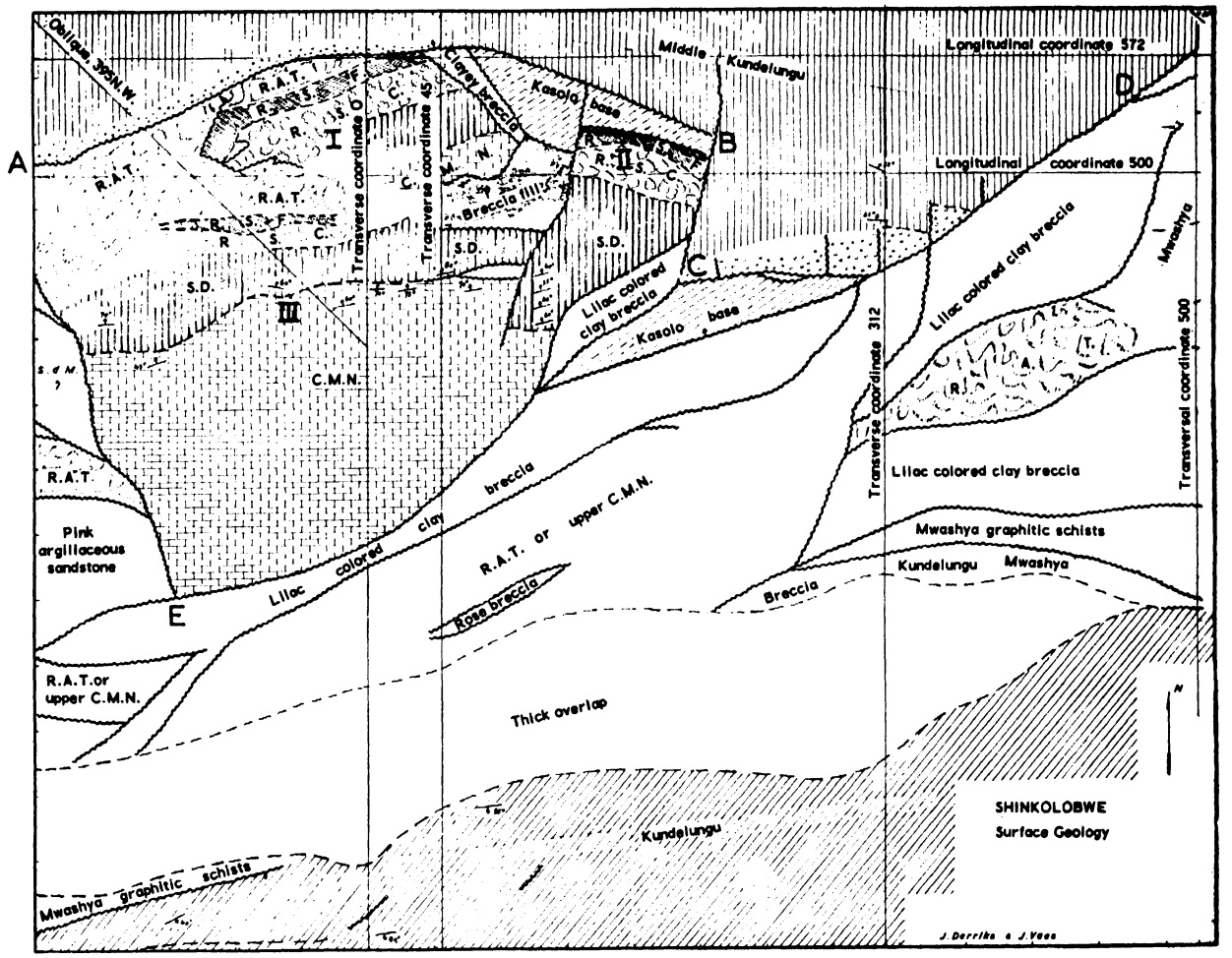


Figure 6. Shinkolobwe — Surface geology

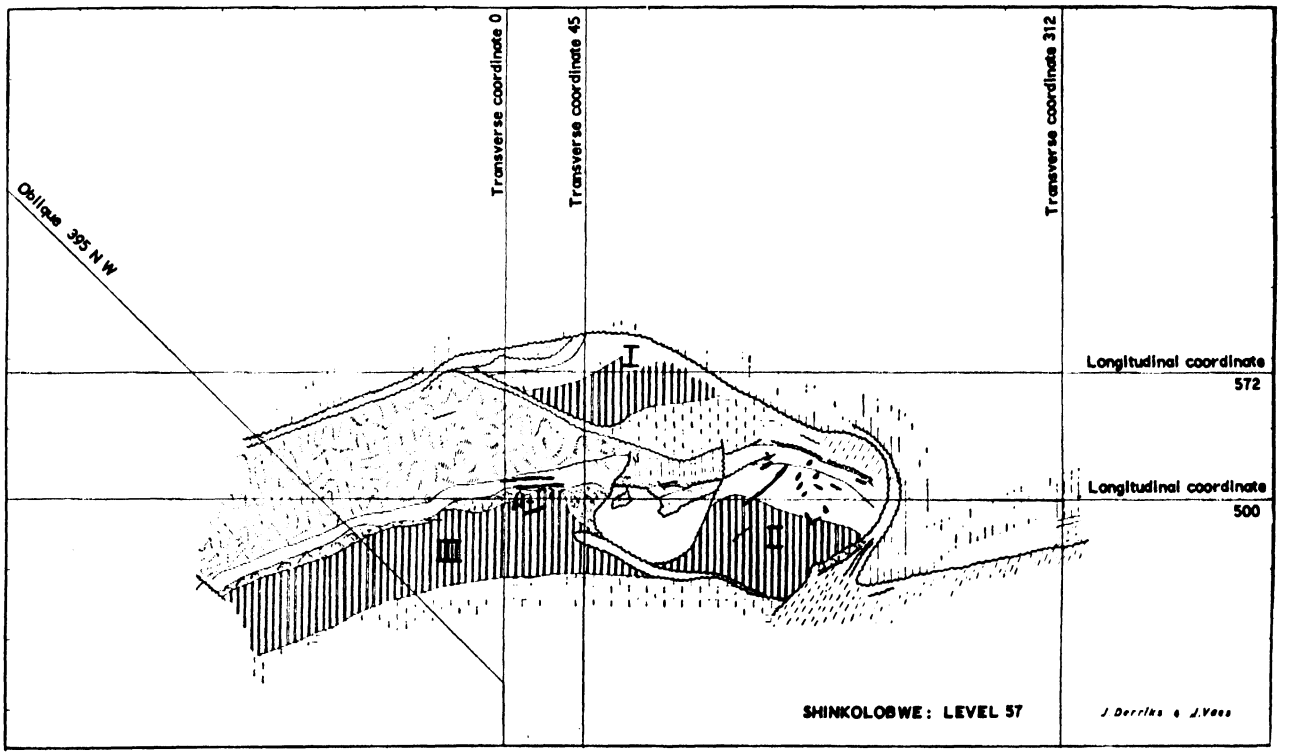


Figure 7. Shinkolobwe — Level 57

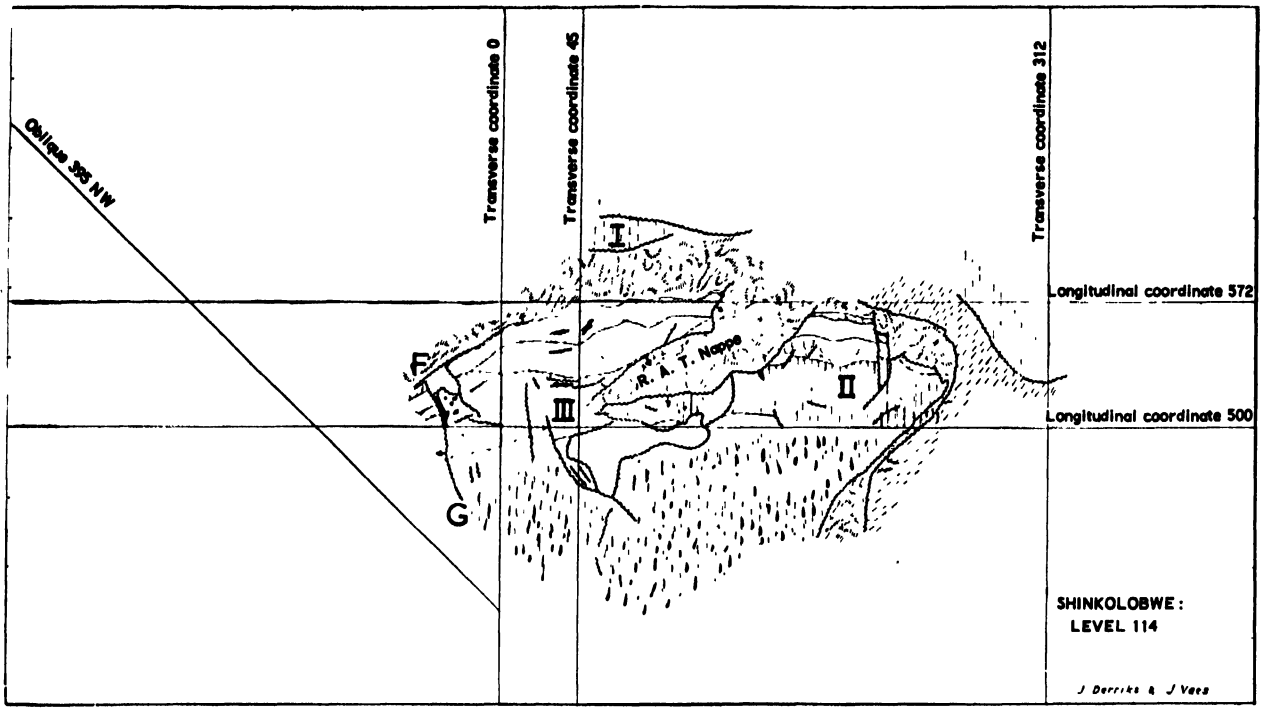


Figure 8. Shinkolobwe — Level 114

47. The transverse F–G fault, which affects the deposit from level 79 to level 255 with a dip of 50° W, does not cause any important breaks in the beds of the Mine Series. From levels 70 to 132 east of this fault, the R.S.F. and R.S.C. are replaced by a dolomite breccia, which ends at the contact with the R.A.T. nappe.

The width of the F–G fault sometimes exceeds 3 m at longitudinal coordinate 500; between the wall rocks which are distinctly cut, there occurs a fine vein of uraninite associated with nickel and cobalt sulphides. To the west, the envelope rock is disturbed little, and only a few small apophyses occur. To the east the S.D. is fractured and strongly mineralized with some selenium-sulphides which are not conspicuous in the so-called vein. An excerpt from one of the working plans of this zone is shown (Fig. 16).

Below level 132, the wall rock closes, the strata of the Mine Series is intact, and there are only occasional traces of the beautiful mineralization which the fault shows at the upper levels.

48. Beyond the uranium-bearing zone, the S.D. and the base of the C.M.N. are regularly mineralized with cobalt and nickel sulphides. These minerals (vaesite, siegenite, cattierite), are concentrated either as veins, or disseminations in nodules or specks, in the rock. This mineralization occurs in the upper levels, but, because it is oxidized, it has not been specifically prospected. It is interesting to note that nickel is predominant in the vicinity of the uranium, and that it decreases progressively away from the uranium. The ratio of 3 nickel to 1 cobalt, in the uranium zone, shifts to 1 nickel to 3 cobalt at the S.D./C.M.N. contact. If the wall is penetrated further, one finds that cobalt sulphide as cattierite is the only dominant mineral.

49. It is also noted that in the neighborhood of the Brèche de Remplissage the dolomite of the C.M.N. shows an abnormal magnesium enrichment.

Level 150 (Fig. 9)

50. The Mine Series is now continuous except for minor displacements; the R.A.T. nappe reunites the B–C fault above level 150. The F–G fault always is clearly marked by a slip. To the west of the fault, and therefore above it, the rocks are deeply altered, whereas to the east, they become dolomitic at depth. The Brèche de Remplissage always occurs in the same topographic position, this time in the C.M.N.

51. At the top of this breccia, to the east and west, the layers of the C.M.N. are replaced by a crystalline, white, very pure, magnesite. This phenomenon, of which the first indication was noted in connection with level 114 (Paragraph 49) becomes more conspicuous at depth. It is felt that this is a magnesium enrichment of the vein which is directly related to the cavity that is the origin of the Brèche de Remplissage.

52. In the western part of the deposit (starting from Fault F–G), there is no uranium mineralization, and we find only oxidized cobalt and nickel. However, between the 0 and 45 transverse coordinates, at a point where the R.S.C. narrows, there occurs in the R.S.F. and S.D. a network of veinlets which form a stockwork that is well mineralized with uraninite and such associated minerals as vaesite and molybdenite, as well as precious metals. There is no direct connection with the corresponding mineralization of level 114; on the contrary, lower level of 132 is practically barren. Farther to the east, and all the way to the end of the deposit, very few concentra-

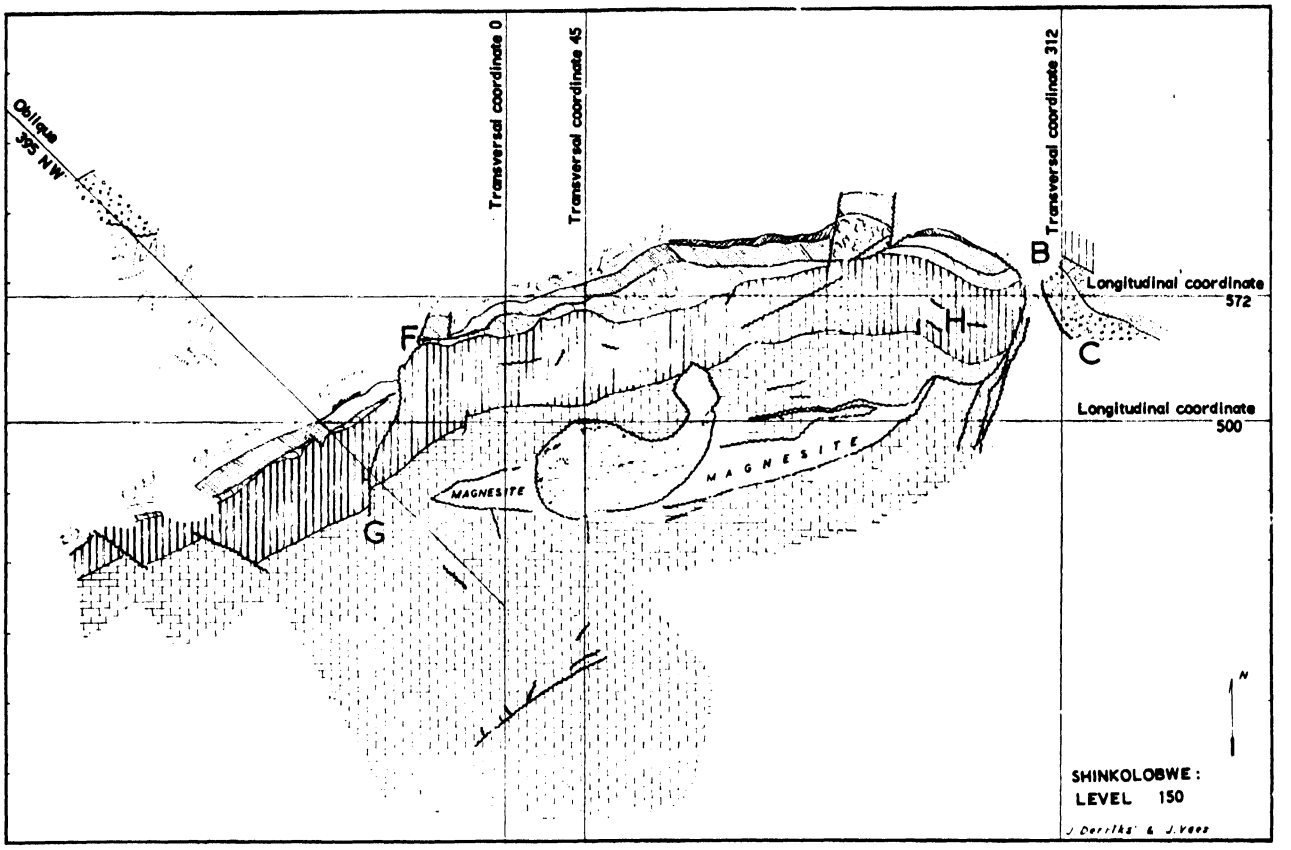


Figure 9. Shinkolobwe — Level 150

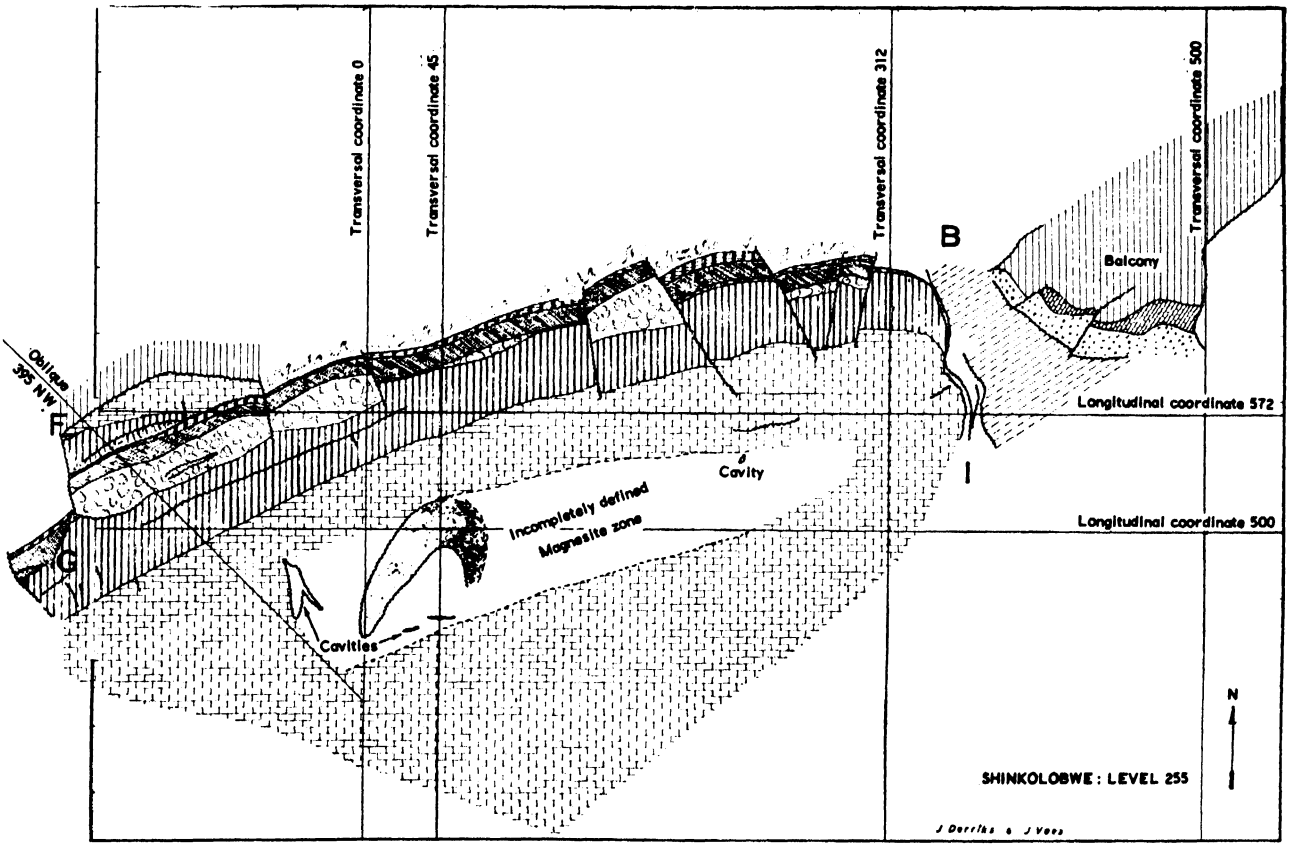


Figure 10. Shinkolobwe — Level 255

tions are observed, but rather, a dissemination of pitchblende and sulphides occur in the R.S.F. and S.D. There is a definite tendency for the uranium to be displaced toward S.D./C.M.N. contact.

A fine vein of uraninite which occurs at level 132, also can be seen at level 150 in the small longitudinal faults of point H. There is no doubt that this occurrence is related to the displacement B–1 which separates the Mine Series from the Kasolo layer. A similar type of mineralization has been mined open face at level 79.

Level 255 (Fig. 10)

53. At present level 255 is the deepest to be developed by underground workings.

The lower beds of the Mine Series, frequently cut by transverse faults, have a very regular contact with the C.M.N. mass. Fault B–C always slips away in a northeasterly direction, and the Kundelungu terrace becomes less distinct. Fault F–G, as it flattens out, rapidly disappears to the west.

In general, the Series is dolomitic, except, of course, for some alteration near the displacements.

The breccia-filling has a more varied outline, and tends to thin out; at the same time we note many nearby cavities, which at times are very large. The magnesite zone, parallel with the beds becomes quite thick, but at present its outline is poorly defined; at any rate, it surrounds the whole breccia-filling zone. We can only marvel at the continuity of this natural shaft for a depth of 250 m and believe that we are nearing its bottom.

54. The nickel-cobalt mineralization persists throughout level 255, although it is less intense, particularly as far as nickel is concerned. There is no more uranium localization, and the weak traces of the metal which can still be observed are somewhat more intense in the vicinity of Faults F–G and B–C. Drilling prior to the development of level 255 indicates the depletion of uranium deposition in the main mass, from level 220. Systematic prospecting by underground workings indicates that we must look elsewhere for the extension of the ore, and this is what the study of these sections will show.

Oblique Section 395 NW (Fig. 11)

55. To the west of the F–G fault, starting from level 150, the beds curve to the southwest. The formations situated above the fault are altered and have never shown uranium mineralization. The F–G fault itself is well mineralized between levels 79 and 132 where it cuts the lower beds of the Mine Series; interesting mineral content is followed to level 185. Traces of this mineralization persist to level 255.

We know by experience that these deposits of uranium are discontinuous at Shinkolobwe and, since it is not ruled out that Fault F–G is one of the mineralizing faults, a drilling program was carried out to the west below level 255 and Fault F–G.

Transverse Section 45 (Fig. 12)

56. On this section we can note the reversed layers of the Mine Series, which are parallel with the margin A–B of the Kundelungu section. The overturning of the R.S.F. and the crumpling of the R.S.C., under the intrusion of the R.A.T. nappe are found at the top of level 114. It can be assumed therefore that this displacement is due to the presence of Spur I, which is interposed between the Kundelungu and the Massif Principal.

The breccia filled natural opening is well shown on the cross section; between the surface and level 79, it curves slightly to the west, and leaves as shown in the figure.

Longitudinal Section 572 (Fig. 15)

57. This section must be studied before transverses 312 and 500; essentially, it is presented in order to show the continuation of the beds to the east beneath the Kundelungu terrace B–C_1–C–D. Let us observe, however, in passing, the position of Spur I against Fault A–B, and the appearance of the R.A.T. nappe which cuts the Massif Principal horizontally to the south.

58. From the beginning, the attention of geologists has been drawn by the fact that the Mine Series appears to slip at depth beneath the Kundelungu, because of dislocation by Fault B–C (Fig. 6). As a consequence, drilling was undertaken and the easterly extension of the deposit up to the displacements B–C_1–I was known well in advance of the development by underground working. Favorable indications of uranium have been noted, particularly in the vicinity of the C_1–I fault, in the S.D. and in the lower C.M.N. This stratigraphic position of the mineralization corresponds to a crumpling of the lower members (R.S.C. and R.S.F.) cut by the fault. From this, we conclude that the mineralization is related to the Fault C_1–I which we attempted to follow. In progressing to the east, it is observed that the lower Kasolo continues to be intercalated with the Kundelungu and the underlying formations. At the same time, a fragment of piece, L, of the C.M.N., appears above Fault C_1–I. Starting from this point, and progressing north, one finally discovers Spur IV, which is represented on Fig. 14.

59. Furthermore, it is observed that the new spur and l'Assise de Kasolo rest discordantly (I–M) on a mass of coarse sandstone, the existence of which was indicated in Paragraph 15. The nature of this formation, some layers of which are plainly conglomeratic, reminds one of the characteristics of the Lower Roan, but at present there is no definite stratigraphic evidence.

Cross Section 312 (Fig. 13)

60. This cross section shows that the Mine Series underlies the Kundelungu Terrace and l'Assise de Kasolo. The C_1–I fault marks the discordance. The Mine Series retains its average dip of 60° N, but has a tendency to vertical straightening below level 255.

Cross Section 500 (Fig. 14)

61. As indicated in the description of cross section 572, Spur IV penetrates the Assise de Kasolo

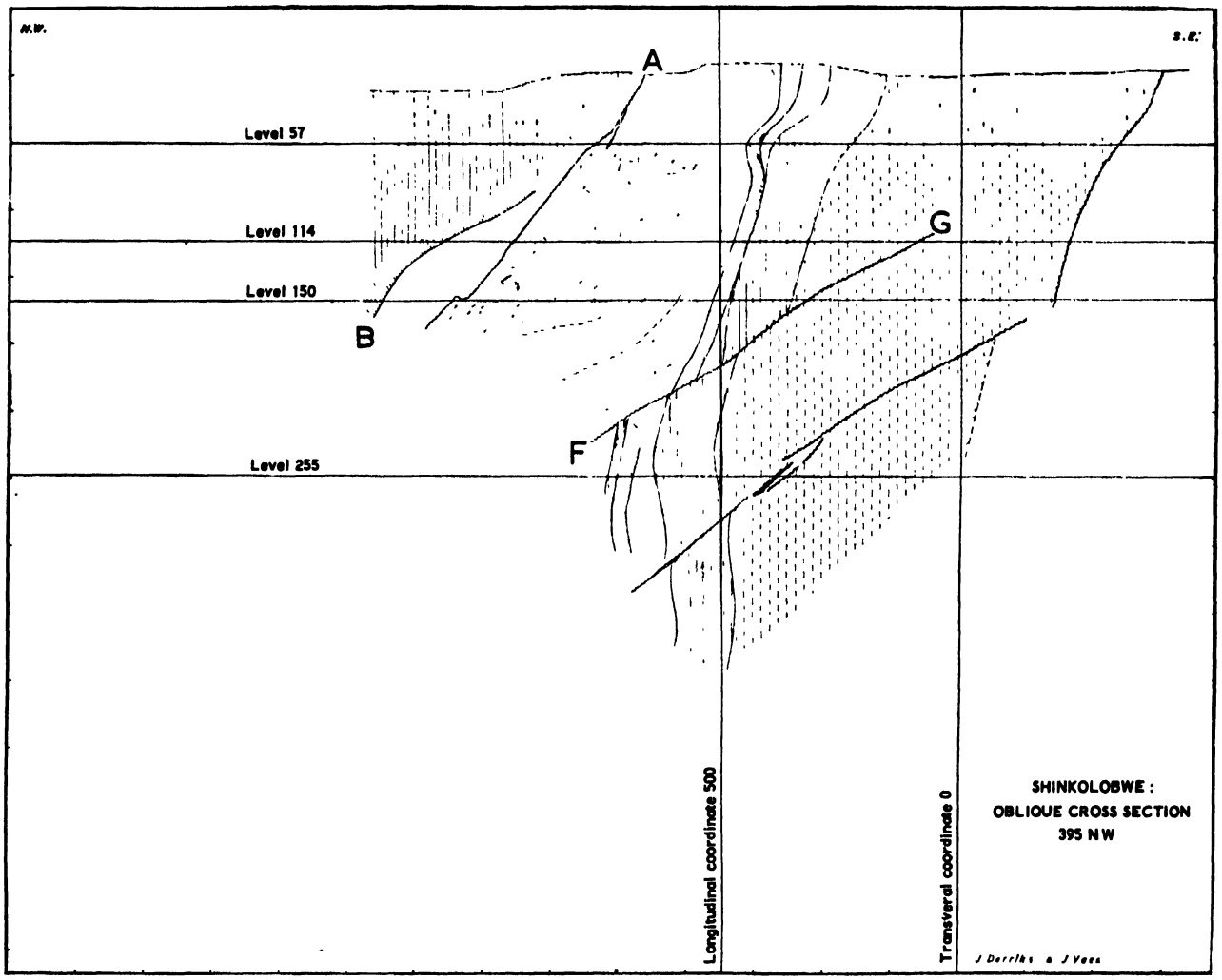


Figure 11. Shinkolobwe — Oblique cross section 395 NW

and the lower sandstone. The new spur, located below level 300, currently is being prospected by drilling. Due to the lack of sufficient evidence, these results are not summarized. Let us merely state that here, we should see the continuation at depth of the Shinkolobwe deposit, that uranium is always accompanied by nickel and cobalt, and that the continuity of the Mine Series to the northeast is recognized.

CHAPTER V. DESCRIPTION OF THE MINERALS

General

Based on the description of the minerals presented in the study by Messrs. Thoreau and du Trieu (Paragraph 8), we have assembled a great deal of information on the mineralization of the deposit. We have in effect passed from the upper oxidation zone at level 57 to the deep zone which is known down to level 255.

The secondary uranium minerals, which are so numerous toward the surface, rapidly disappear at depth, and the brightly colored (due to alteration) uranium-bearing veins pass into black masses of uraninite. The rocks themselves, which above are silicified and cavernous, assume their natural composition of compact dolomite. Here and there, we still find, along the faults, a small band of altered rock, which is accompanied by secondary uranium minerals.

Fortunately, the discovery of the sulphides has created renewed interest in mineralogical studies which, until now, have been concentrated on the oxidized minerals.

The first fine sulphide-bearing vein was visible at level 79. At depth, the veins and the masses increase; the principal minerals found here are cattierite (CoS_2), vaesite (NiS_2), and siegenite (nickle-linnaeite). Locally, selenium (up to 19%) gives selenium-vaesite and selenium-siegenite.

The dome formed by the R.A.T. nappe above level 114 served as an actual dam for the mineralization (monazite, molybdenite, selenium-sulphides) which generally is disseminated below. The schist-dolomite gangue, strongly crushed, has been affected by the mineralizing solutions and metamorphosed to a chloritic rock.

Uranium Minerals

63. Among the approximately 30 minerals which have been identified in the deposit, only five have

been described. Many of the new species have been identified later in other parts of the world; some occur only at Katanga. The list includes:

	Color	Associated Element
Oxides		
Uraninite	Black	
*Ianthinite	Purple	
*Becquerelite	Amber	
*Schoepite	Yellow	
Uraninites		
*Curite	Red	Lead
*Fourmarierite	Red	Lead
*Masuyte	Red	Lead
*Vandendriesschéite	Orange	Lead
*Richetite	Brown-Black	Lead
* ? (new)	Red	Lead
*Lead-bearing Becquerelite	Amber	Lead
*Billietite	Amber	Barium
*Vandenbrandeite or Uranolepidite	Dark Green	Copper
Urano-silicates		
*Kasolite	Brown	Lead
*Soddyite	Yellow	
*Sklodowskite	Yellow	Magnesium
*Cuprosklodowskite	Light Green	
Uranophane	Yellow, Greenish-Yellow, or Brownish	
Urano-phosphates		
*Dewindtite	Yellow	Lead
*Dumontite	Yellow	Lead
*Renardite	Yellow	Lead
*Parsonsite	Brown inclusions (The mineral is yellow)	Lead
*Saleite	Yellow	Magnesium
Torbernite	Green	Copper
Metatorbernite	Green	Copper
Urano-carbonates		
Rutherfordine	Yellow and Brown	
*Sharpite	Gray-Yellow	
*Studtite	Very light Yellow	
*Diderichite	Gray-Yellowish	
Urano-Molybdenite		
Being studied	Dark Purple	Magnesium

Sulphides and Selenides

64. Primary Minerals: *cattierite, CoS_2; *vaesite, NiS_2; *nickel-cattierite, $(CoNi)S_2$; *cobalt-vaesite, $(NiCo)S_2$, (probably partially secondary); siegenite, linnaeite with nickel; *selenium-vaesite, selenium-bearing vaesite; *selenium-siegenite, nickel-bearing siegenite; molybdenite, MoS_2; pyrite; chalcopyrite; umangite, Cu_3S_2; white selenite, ?; light-blue selenite, ?; and whitish-grey grains, palladium, possibly sulphide.

Secondary Minerals: millerite, bornite, blue chalcocite (digenite), covellite, white mineral associated with digenite, melonite, $NiTe_2$; galena, and siegenite.

Native Metals

65. Copper and gold.

Miscellaneous

66. Primary Minerals: chlorite, magnesite, monazite, quartz, dolomite, and calcite.

* Mineral which was found for the first time at Shinkolobwe.

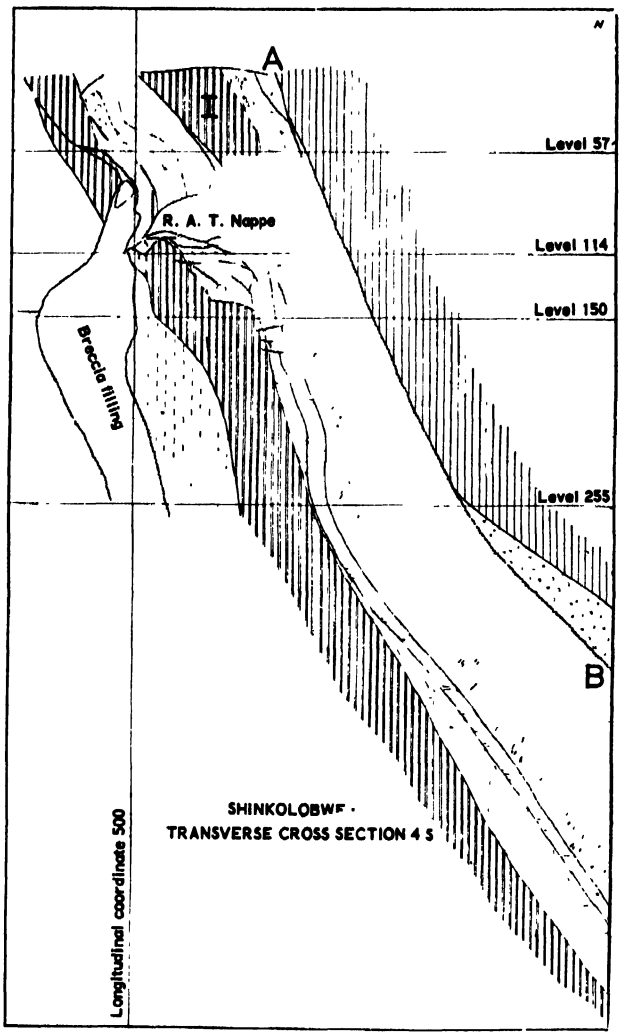


Figure 12. Shinkolobwe — Oblique cross section 45

Secondary Minerals: wulfenite, quartz, pink dolomite (cobalt-bearing), aragonite, heterogenite, asbolite, palladium-bearing black oxide, and garnierite.

Description of the Uranium Minerals

67. The uranium minerals occur in masses, veins and veinlets in fissures, diaclases, and joints of the lower beds of the Mine Series. At times, they are disseminated in the beds.

At depth, the deposits consist partly of massive uraninite and partly of uraninite which is associated with nickel and cobalt sulphides. The uraninite always is crystalline. We never have observed at Shinkolobwe the colloform type which occurs at Great Bear Lake and St. Joachimsthal. Where crystals could develop, uraninite always appears as cubes, often passing to the hextetrahedral form. These cubes are fairly common, and occur in the open fissures of the massive veins or in the wall rock. Perfectly cubic crystals occur surrounded by massive vaesite (and siegenite) (Figs. 18 and 19), as well as in monazite and veinlets of calcium and magnesium carbonate. In general, the sides of these cubes do not exceed one cm, but occasional crystals which are 4 cm on a side have been found.

68. In the uraninite veins, there are few associated minerals. Occasionally, in polished surfaces small specks of sulphide are seen between the single crystals of the uranium mineral. Several veins contain native gold (Figs. 20, 21, and 22). One veinlet contains a nickel telluride, probably melonite (Fig. 23). The mixed veins consist of uraninite, cobalt and nickel sulphides (vaesite and siegenite) (Figs. 24 and 25). They are associated with various minerals which will be discussed in the section on sulphides.

69. Toward the surface, the uraninite is altered and replaced by a number of oxidized minerals. The majority of these secondary minerals occur only as replacements of the uraninite *in situ*. Only some have been displaced from the veins to cavities in the altered rock. These usually are metatorbernite and torbenite. The other minerals which are precipitated from circulating solutions are: kasolite, renardite, saléite, sklodowskite, uranophane, and in smaller amounts, soddyite.

The alteration *in situ* has formed compact yellow, orange or red masses, mixtures of microscopic crystals of various secondary uranium minerals.

70. Below level 57, we collected several new minerals which have not been found near the surface. These include particularly, billietite, vandendriesscheite, masuyite, richetite, studtite, and diderichite, as well as lead uranate and magnesium urano-molybdate always in very small quantities. We also found rutherfordine, which was hitherto unknown in this deposit. On the other hand, dewindtite, dumontite, parsonite and sklodowskite have not been observed at depth.

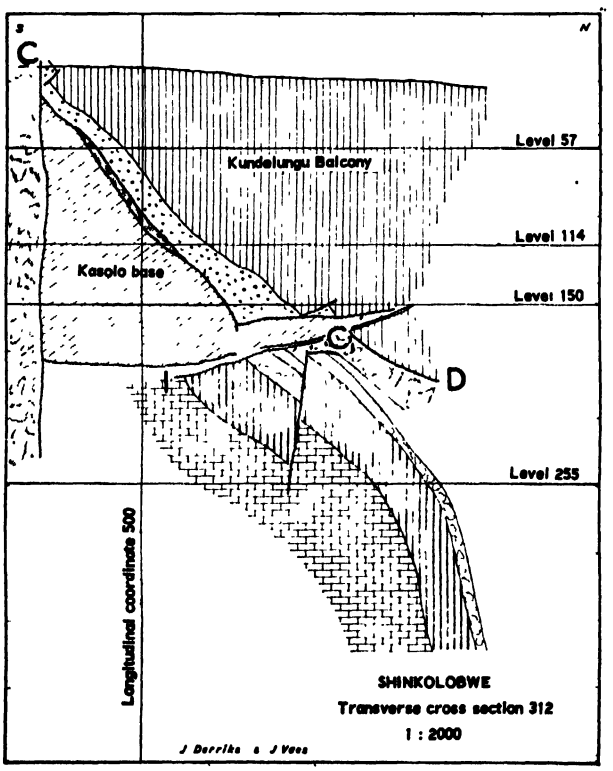


Figure 13. Shinkolobwe — Transverse cross section 312

71. The first publications on the Shinkolobwe minerals describe sklodowskite (magnesium uranium silicate), but do not draw attention to uranophane (calcium uranium silicate). However, later Messrs. Thoreau and du Trieu noted presence of these two minerals. In depth, we have never found sklodowskite, whereas uranophane is one of the most widespread oxidized minerals.

It will be noted with interest that saléite (magnesium uranium phosphate) is associated with sklodowskite as well as uranophane, but we never have found any autunite (calcium uranium phosphate).

Primary Sulphides and Selenides

Cattierite

72. This cobalt sulphide very often is found in an unaltered zone of the mine, but it is always some distance from the uranium mineralization. Particularly in the lower C.M.N., strong impregnations of this mineral have been found. It occurs in fine disseminations, in masses, and sometimes in veins. The disseminations may take the form of idiomorphic crystals in the dolomite.

Cattierite has the theoretical composition CoS_2 (48% Co, 52% S), but it always contains as much as 3 or 4% Ni and approximately 0.5% Cu. The mineral crystallizes as tobacco-brown cubes. In polished surface, it is somewhat more pink than siegenite, and has higher relief when the polishing is fine enough. The cleavage is perfect along the cube faces.

73. Cattierite is associated with pyrite; below level 57, it is fairly often partially replaced by siegenite (Fig. 26). The fact that cattierite is not mentioned in the older publications gives us reason to believe that this mineral was entirely replaced by siegenite in the upper parts of the deposit. We find it difficult to believe that this sulphide could have passed unnoticed since its typical brown color is very different from that of the other lighter colored sulphides.

Rarely, small quantities of chalcopyrite are associated with cattierite, but it never occurs as an inclusion in the cattierite itself (Fig. 27).

Uraninite never has been found in the cattierite veins. The gangue which accompanies the masses of this mineral always consists of carbonate, usually magnesite rather than dolomite.

Vaesite

74. Vaesite is a nickel sulphide which has the composition NiS_2. It appears either as disseminations in the lower Mine Series, or in well defined veins. Although there will, at times, be vaesite in the parts of the mine which are away from the uranium-bearing region, it is a particularly characteristic mineral of the uraninite zone. The first sulphide vein was encountered at level 79 along the important F–G fault. The transition from uraninite to vaesite is rather abrupt. Since then, we have found several veins of massive vaesite, which contain little or no uranium.

Vaesite is gray-black (light gray on polished sections). The few rare crystals which have been found are octahedrons. The cleavage, which is parallel with

the cube faces, is almost as perfect as that of galena. Just as cattierite contains a little Ni and Cu, vaesite may contain as much as 3.5% Co and 0.3% Cu.

75. In the masses and veins of this sulphide, one again finds pyrite (Figs. 29 and 30), siegenite (Figs. 31 and 32), and small quantities of chalcopyrite which are associated with diegenite, covellite or bornite (Figs. 33, 34 and 35).

In the vaesite and uraninite veins, one often notices the presence of molybdenite. Some small particles of gold have been observed on several polished sections of the massive vaesite.

Some of the polished surfaces clearly show that, in many cases, the veins which contain vaesite have been crushed. This sulphide has been broken or crushed, and the fissures are filled with dolomite, siegenite, and to a smaller extent, chalcopyrite.

Let attention be drawn to the fact that, within the large single vaesite crystals, one will at times observe idiomorphic crystals of quartz, monazite or chlorite.

Nickel-Cattierite and Cobalt-Vaesite

76. In the eastern part of the deposit, between levels 114 and 150, some veins occur, the southernmost of which is composed of a sulphide which resembles cattierite but is a darker color. This mineral is not so hard, and in polished surfaces, it is less pink. Analysis shows that this sulphide contains 15% Ni rather than the 3.5% found in the typical cattierite (Fig. 36).

Two other veins in this area contain vaesite which is cobalt-rich: 9.5% and 12.5% Co.

Therefore, between cattierite and vaesite we find a series of intermediate compositions: this is why vaesite and cattierite have never been found in the same vein. The accompanying minerals do not change (Fig. 37).

Siegenite (Figs. 38, 39 and 40)

77. Siegenite (nickel-bearing linnaeite) is found, both in the cattierite zone as well as the part of the deposit which is mineralized with vaesite. Massive vaesite is rarely found without siegenite; on the other hand, polished surfaces of cattierite, without any trace of siegenite, are found more frequently. In both cases, there is no doubt that the two primary sulphides are being replaced by siegenite. In the case of vaesite, the fissures of which are being filled by dolomite and chalcopyrite, both the dolomite and chalcopyrite, as well as the vaesite, are being replaced by siegenite. Figure 38 gives a good example of this replacement; one notes a mass of vaesite (dark gray) which is being replaced by siegenite (light gray). A veinlet of chalcopyrite which occurred first was in the vaesite, also is replaced by siegenite. In the lower right corner of the same picture, another small vein of chalcopyrite will be seen. It is not yet replaced by siegenite, but already has been attacked on the edges.

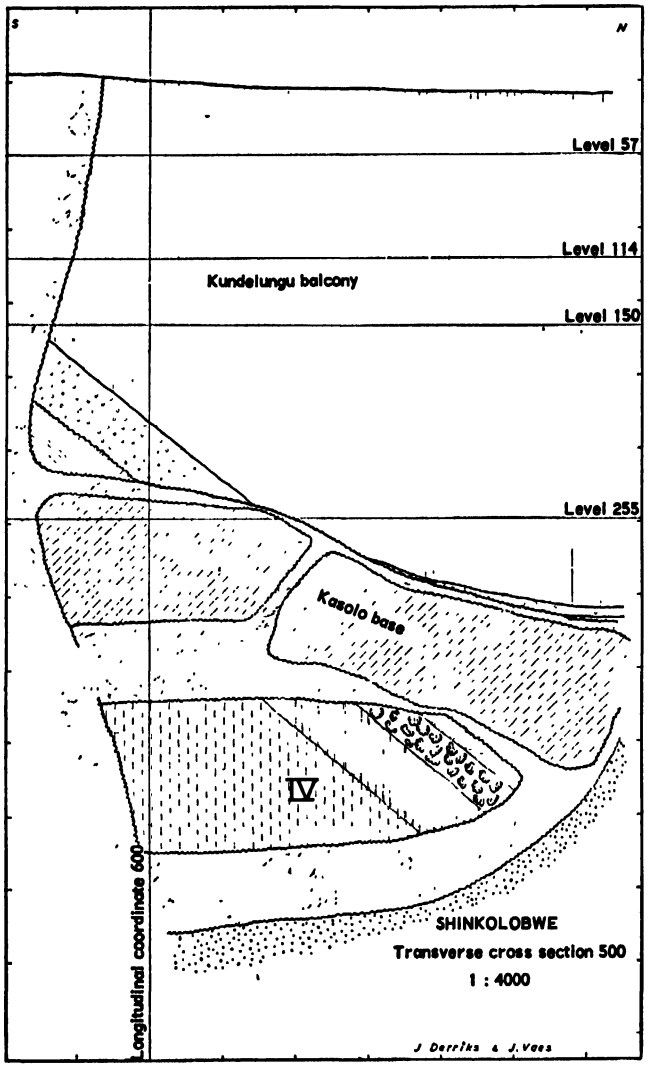


Figure 14. Shinkolobwe — Transverse cross section 500

Where siegenite occurs in massive veins, there is probably complete replacement of earlier vaesite veins; indeed, one may find, in these veins, small patches of vaesite which are surrounded by gangue. We assume that this gangue protected the vaesite from replacement.

The only accessory mineral which resisted replacement is pyrite.

78. Carrollite is extremely scarce at Shinkolobwe. Its presence is mentioned by Professor Thoreau, but analysis reveals the presence of nickel, selenium, and molybdenum, which therefore replace certain of the cobalt, iron and sulphur molecules.

Selenio-Vaesite, Selenio-Siegenite, and Other Selenides

79. Messrs. Thoreau and du Trieu have mentioned the presence of selenium in certain sulphides above level 57, but without giving the sample locations. Various samples which we took above level 114 do not contain selenium, or only very small quantities of it. Only below the dome of the R.A.T. nappe, do we find sulphides high in selenium. They are very similar to vaesite and siegenite.

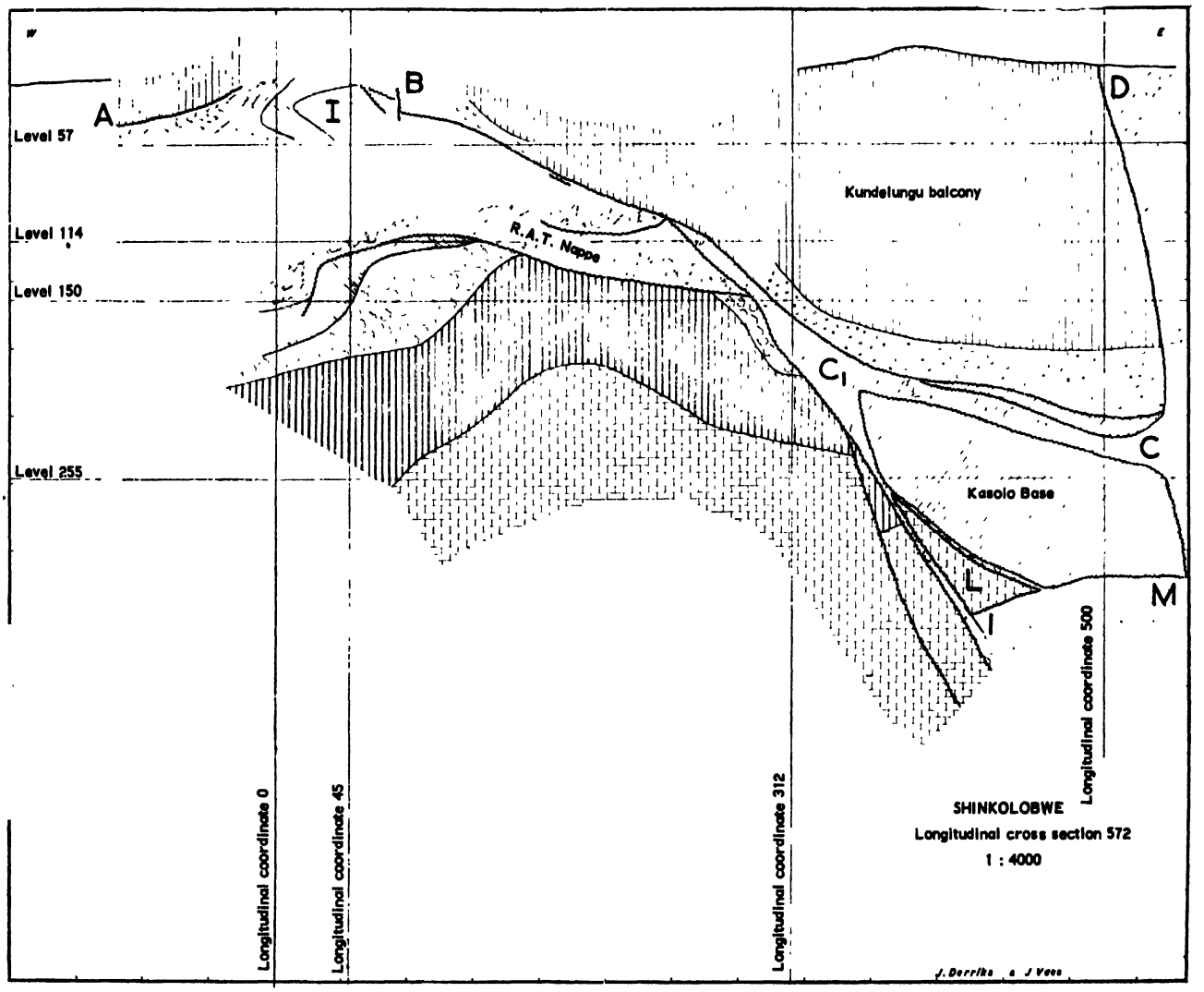


Figure 15. Shinkolobwe — Longitudinal cross section 572

Analyses carried out on selected samples from the massive sulphide veins gave results which are similar to the compositions of vaesite and siegenite; with this difference, in the gray mineral 19% of the sulfur is replaced by selenium (selenio-vaesite), and in the white sulphide 11% selenium replaces an equal amount of sulfur (selenio-siegenite).

80. The veins of selenium free Ni and Co sulfides have a fairly simple mineralogical composition; whereas the selenio-sulphide veins have a greater number of minerals.

At first sight, on certain polished surfaces, one finds two main minerals which are distinguished by their different gray colors. Both probably have (NiCo) (SeS_2) for their composition, the difference between the two being in an unequal proportion of the component elements (Fig. 41).

The usual accessory minerals are molybdenite, pyrite, and chalcopyrite, the latter often accompanied by bornite, digenite and covellite. Gold is fairly common, contrary to the situation in the non-selenium bearing veins. The particular complication in this selenium-bearing zone is the presence of three other minerals: (*a*) The first is strongly anisotropic. It is pleochroic with a color which varies from that of "tarnished bornite" to a light blue-gray. We think it is related to umangite (Fig. 42). (*b*) The other two minerals as yet have not been identified. However, after etching by the Hiller test, they are covered by a film of a red dust. They are, therefore, selenides. One of these two minerals is white. It is anisotropic, and occurs as small masses in the selenio-vaesite as well as in the selenio-siegenite (Fig. 43). The second mineral is isotropic. It is a light blue, and occurs occasionally as small masses, but usually it occurs as thin veinlets in the selenio-vaesite.

We have seen how, in the midst of vaesite, veinlets of chalcopyrite come in contact with masses of siegenite. Likewise, here the veinlets of the latter selenide, in the midst of selenio-vaesite, comes in contact with selenio-siegenite masses. At this contact, the veinlet of selenide enlarges to form a small mass (Figs. 44 and 45). The selenium is always accompanied by small amounts of tellurium.

Molybdenite and Selenio-Molybdenite (?)

81. Molybdenite is widespread in small amounts throughout the deposit. It is particularly associated

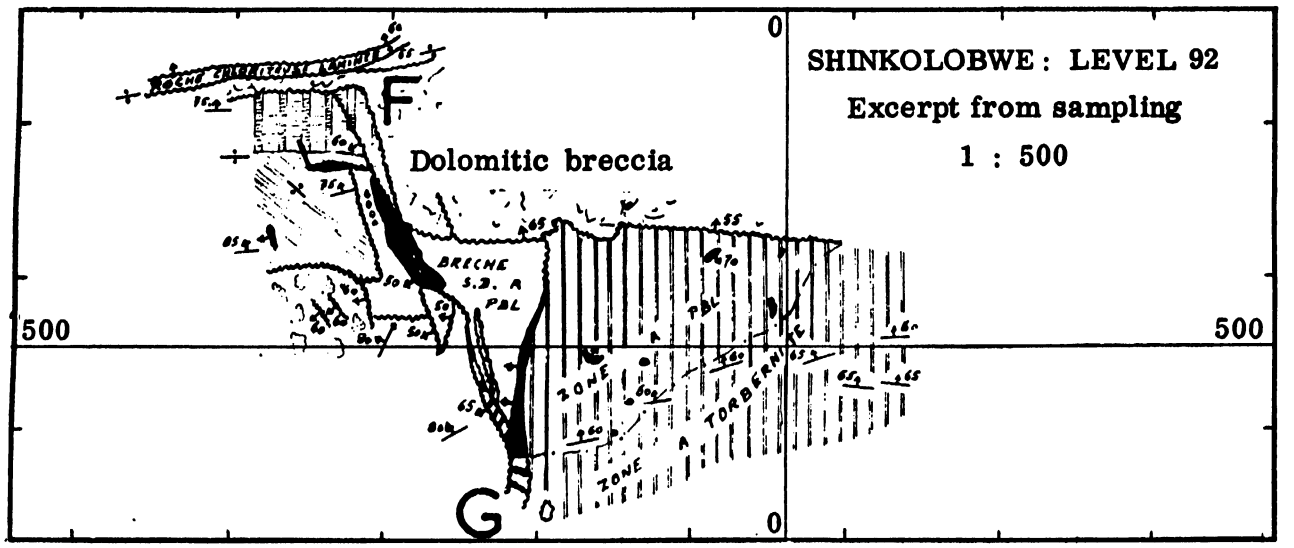


Figure 16. Shinkolobwe — Level 92 — Excerpt from sampling

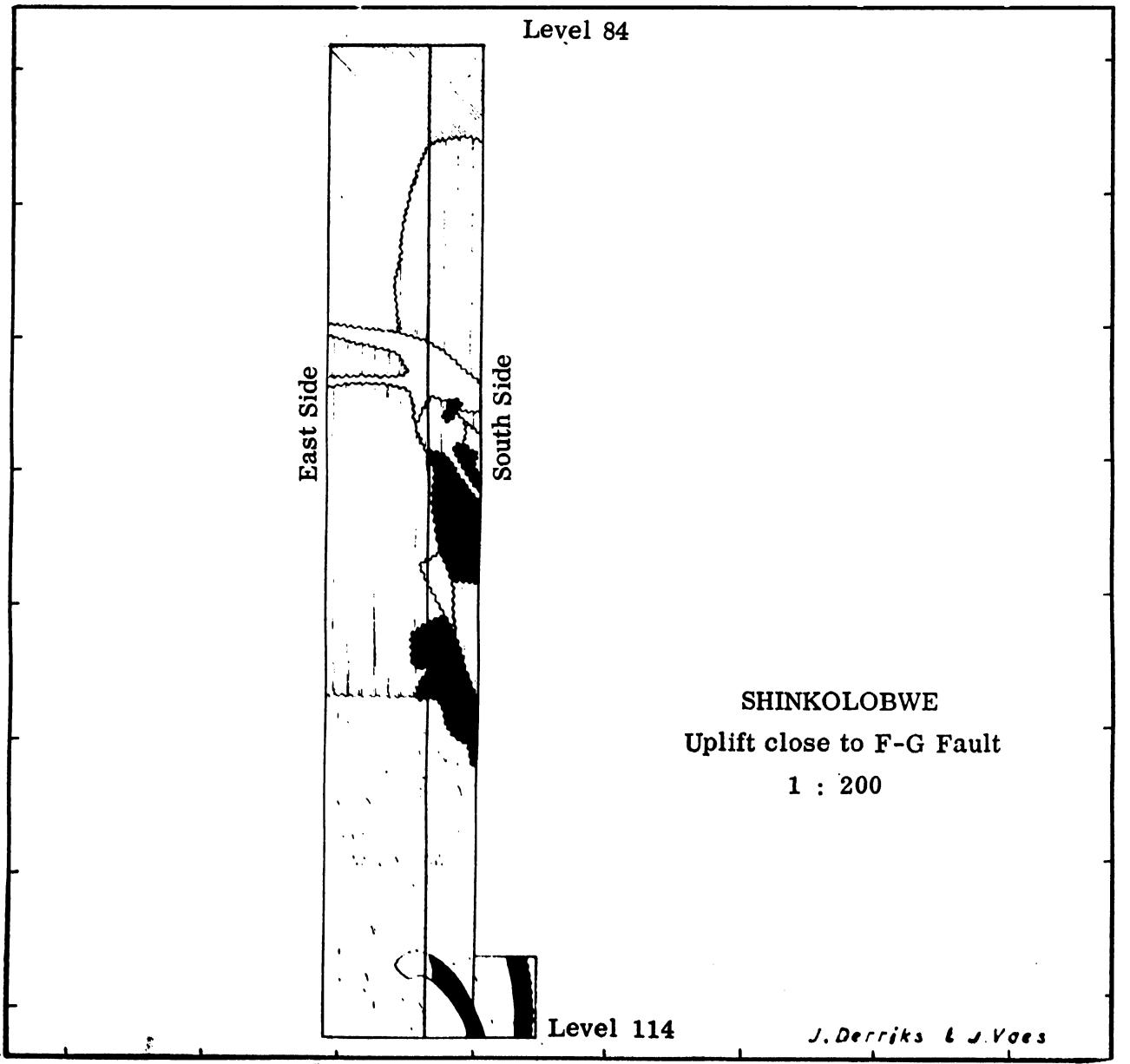


Figure 17. Shinkolobwe — Uplift close to F-G fault

with uraninite. Usually, it occurs as a coating or as small fibrous balls; less commonly, as fibers without orientation or preference included in the (selenio)-vaesite, (selenio)-siegenite or gangue (Figs. 46, 47).

At some places in the mine large deposits of molybdenite occur. At level 96, east of the large uraniferous vein which is related to the F–G fault, the S.D. is impregnated with molybdenite for a distance of some 20 m from the fault. In the brecciated formations of level 114, strong mineralization occurs of a mineral which is almost identical with molybdenite. It is intimately associated with the selenium sulphides, and we have not been able to isolate it. Chemical analysis gives only a little information as to its composition (Fig. 48). This mineral (being studied) gives a strong Se reaction by the Hiller test. In polished section, it is lighter and does not tarnish like molybdenite. Temporarily, we shall consider it as a variety of selenium molybdenite.

A third deposit of molybdenite occurs at level 150. Here, it is associated with uraninite and, by alteration, has formed a magnesium urano-molybdate which appears as elongated purplish-black lamellae.

82. In the selenio-sulphides, molybdenite often occurs as a thin coating which has a dendritic pattern. The molybdenite must have been deposited on a crystal of unknown composition which was completely replaced by selenio-vaesite (Figs. 50, 51, 52).

83. Molybdenite often corrodes uraninite (Figs. 53, 54, 55) and it has also been observed attacking pyrite crystals (Figs. 56 and 57). No replacement of molybdenite by nickel and cobalt sulphides has been found. The attack by digenite and covellite is very rare (Fig. 58).

84. Molybdenite, in fibrous concretions forms small balls, the nuclei of which often seem to be replaced by selenio-siegenite; sometimes, on the contrary, by gangue (Fig. 59). It is likely that this gangue has been replaced by siegenite, but it is also possible that these small balls were originally occupied by the mineral with the "dendritic pattern".

Pyrite

85. This sulphide is found throughout the deposit. It is associated with cattierite and vaesite as well as the selenio-sulphides. In C.M.N. masses of pyrite have at times been found in the absence of any other sulphides.

The pyrite crystals always are corroded by the sulphides of Co and Ni, and occasionally by molybdenite (see preceding pictures of these sulphides).

Chalcopyrite, Bornite, Digenite and Covellite

86. Although macroscopic examination suggests that copper sulphides are rare, the examination in polished section shows that they are nearly always present in the zone of uranium mineralization; whereas, in the cattierite zone, they are rarely found.

Chalcopyrite is probably the only early sulphide of copper, the other three being hypogene. One also finds a mineral which is very white on the polished surface and intimately associated with covellite. It is not a white chalcocite, because the mineral turns gray after attack by acid, instead of blue as does chalcocite: it is not identified (Figs. 60 and 61).

Digenite occasionally is light blue; sometimes very dark. Bornite is more rare than digenite and covellite. These minerals occur in small masses in the nickel sulphides and in the gangue; they occur also in small masses and thin veinlets in (selenio) vaesite and in far smaller amounts in the (selenio) siegenite (Figs. 33, 34, 35, 62 and 63). In the cattierite zone, chalcopyrite occurs only in the gangue (Fig. 27).

Umangite and Two Unidentified Selenides

87. See Paragraph 80.

Palladium

88. We examined a sample which was very rich in palladium that came from the stockpile. Palladium occurs as whitish-gray metallic particles which are insoluble even in aqua regia. Chemical analysis reveals the presence of sulfur in this mineral.

Secondary Sulfides

Millerite

89. Clusters of millerite needles occur occasionally in cavities in the dolomite of the Mine Series.

Bornite, Digenite and Covellite

90. See Paragraph 86.

Melonite and Galena

91. These two minerals occur as thin films in cracks in the uraninite. Melonite has been observed only in one vein where it replaces gold (Fig. 23).

Siegenite

92. Some of the siegenite probably is supergene, as in the description of cattierite (Paragraph 73).

Native Metals

Copper

93. In its native state, copper is very rare at Shinkolobwe, and has been found only exceptionally as minute particles in the fissures of the Ni and Co sulphides.

Gold

94. Native gold is frequently found in the uraninite and sulphides of the central part of the mine.

In uraninite, this precious metal occurs as thin coatings and rods. Its colors are nearly submicroscopic (Figs. 20, 21 and 22). Gold often replaces vaesite veinlites. In one vein, it is partly replaced by melonite (Fig. 23).

Occasionally, small gold particles occur in the sulphides, but it is especially in the selenio-sulfides of the 114 level that it is relatively abundant.

95. In the upper parts of the mine, this metal is found in the panning concentrates of the lower Mine Series and in a chlorite layer at the contact of the R.S.F. (Paragraph 43). This schistose layer is completely metamorphosed to chlorite, and is considered as a regional metamorphic formation which is related to the localization of the Mine Series. However, identical chloritic schists are found below

the R.A.T. nappe, and they are hydrothermal in origin.

Miscellaneous Primary Minerals

Chlorite

96. Chlorite sometimes occurs as inclusions in the vaesite. Also, it is the principal mineral in the metamorphic schists mentioned above (Paragraph 95).

Magnesite

97. This mineral is very abundant in the deposit. In the C.M.N. it forms a vein which, at level 255, reaches a thickness of 50 to 60 meters. Furthermore, it is found everywhere in the rocks of the Mine Series, from the R.S.F. to the upper S.M.N. Magnesite replaces dolomite where it forms crystals in rocks: acicular crystals in the R.S.F., R.S.C., S.D. and lower C.M.N., and rounded white crystals in the upper C.M.N.

In the large vein perfectly white granular magnesite occurs. Sometimes this material is coarsely crystalline.

Magnesite often forms the gangue of veins and sulphide masses, particularly those of cattierite; in the latter case, a small quantity of cobalt is located in its structure, and the crystals are lilac. It also occurs as a coating in the brecciated zone of level 114.

Monazite

98. The presence of monazite in the deposit has been known for a long time. It is abundant in the panning concentrates where it occurs as small brilliant honey-yellow crystals. These crystals come from disseminations in the R.S.F., R.S.C. and S.D. of the uranium-bearing zone.

99. In the brecciated zone of level 114, below the R.A.T. nappe, veins, masses, layers, and veinlets have been found, which consist solely of small aggregates of monazite crystals, identical to those found in the concentrates. These compact masses cover the magnesite crystals which were deposited on the breccia (Fig. 64).

Monazite veinlets penetrate and surround the uraninite crystals (Fig. 65).

In the masses of cerium phosphate microscopic sulphide particles, which are comparable to the dissemination in the schists have been observed.

This strong monazite mineralization is very localized; it is limited to the north by a selenio-siegenite vein, and to the south by a fault which separates it from a breccia zone which is mineralized with uraninite and molybdenite.

Quartz

100. Quartz crystals, often smoky and bipyramidal, occur in cavities and fissures in the rock; often, they are attached to crusts of magnesite crystals. They are found rarely as inclusions in the masses of nickel and cobalt sulphides.

Hydrothermal quartz is not abundant at Shinkolobwe.

Dolomite

101. Dolomite often forms the gangue which accompanies the nickel and cobalt sulphides. After the latter are crushed, this carbonate cements the break.

Dolomite crystals occur throughout the dolomite of the Mine Series. These crystals must be partly hydrothermal as some of them contain sulphide inclusions, particularly pyrite, but also vaesite.

Miscellaneous Secondary Minerals

Wulfenite

102. This mineral, the alteration product of molybdenite, occurs in the upper part of the mine where there is a Mo sulphide.

It occurs in several different crystal forms. On the compact masses of oxidized uranium minerals, wulfenite is deposited as small gray obelisks which are rectangular or square at the base. On the uranophane crusts, found in small cavities in massive uraninite at level 79, wulfenite resembles phonograph needles and is blackish-brown. In the fissures of the schistose rocks, wulfenite occurs as bipyramidal crystals which are orange and often accompanied by flakes of torbernite. Wulfenite also occurs in rectangular crystals which vary from beige-gray to light brown, and in dendritic spear-shaped twin crystals on torbernite masses.

Quartz

103. Quartz is widespread in the upper zone. The dolomite of the Mine Series, as everywhere in Katanga, is silicified completely.

According to the older publications, the dolomitic gangue which occurs at depth is transformed entirely into quartz near the surface.

Dolomite

104. Secondary dolomite generally is not distinguished from hydrothermal dolomite. The dolomite crystals which are colored pink by cobalt, may be considered as being secondary.

Aragonite

105. Aragonite is rare: it has been found as masses of acicular crystals in the uraninite cavities.

Black Oxides

106. The black oxides which are alteration products of cobalt and nickel sulphides are common in the upper part of the deposit; in the deeper part they are more rare and developed only in the altered zone along the faults.

The composition varies from place to place from cobalt oxide with a small amount of nickel and copper (heterogenite), to manganese oxide which contains only a little cobalt, nickel and copper (asbolite).

The chloritic layer near the R.S.F. (pseudo-regional metamorphism) contains a palladium-rich black oxide.

Garnierite

107. This nickel silicate is found in small amounts disseminated in the altered part of the deposit, near faults. Its composition varies from nickel silicate to magnesium silicate which is very low in nickel.

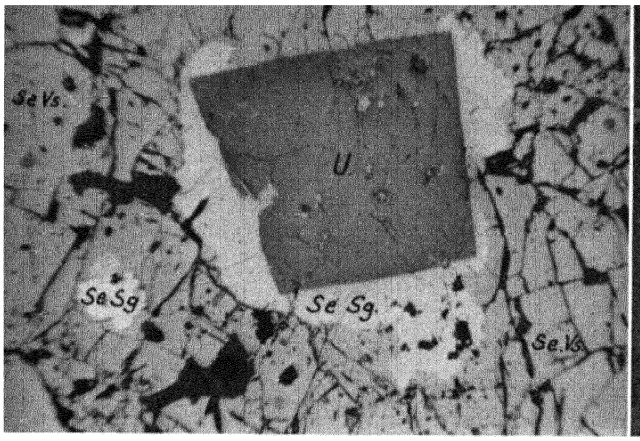


Figure 18. 47 × linear. Cubic uraninite crystal (U) embedded in selenio-vaesite (Se.Vs). Around the uraninite, observe the beginning of the replacement of the selenio-vaesite (Se.Vs) by the selenio-siegenite (Se.Sg)

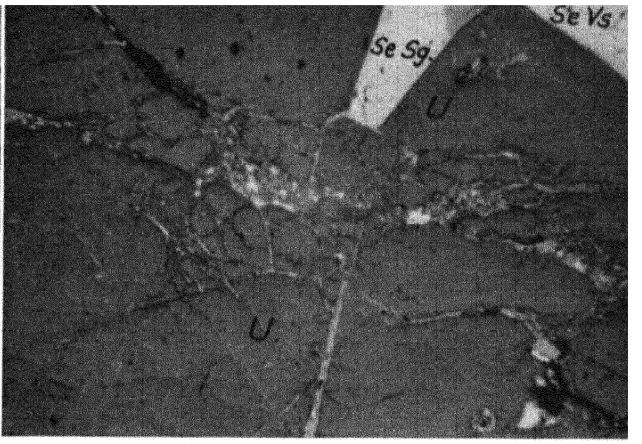


Figure 19. 80 ×. Same. Selenio-siegenite is deposited in the uraninite cracks

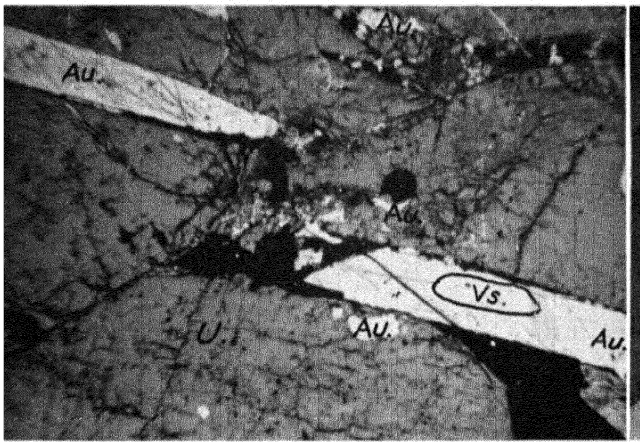


Figure 20. 47 ×. Small vein and dissemination of gold in uraninite. In the small vein of gold, there remains a small amount of vaesite replaced by gold

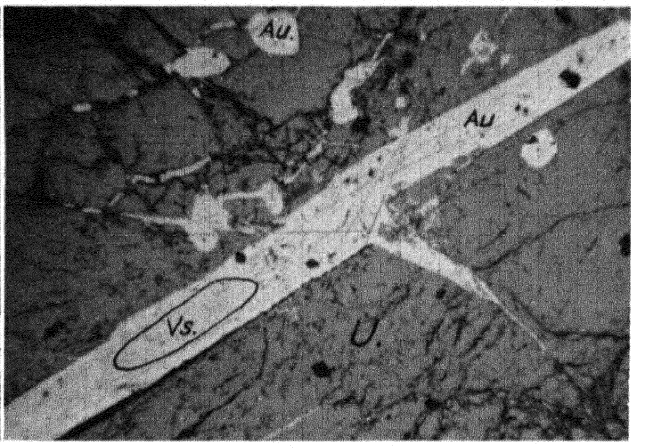


Figure 21. 47 ×. Same

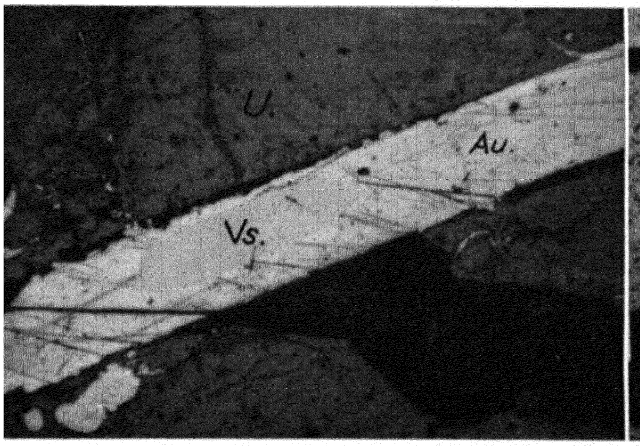


Figure 22. 80 ×. Same

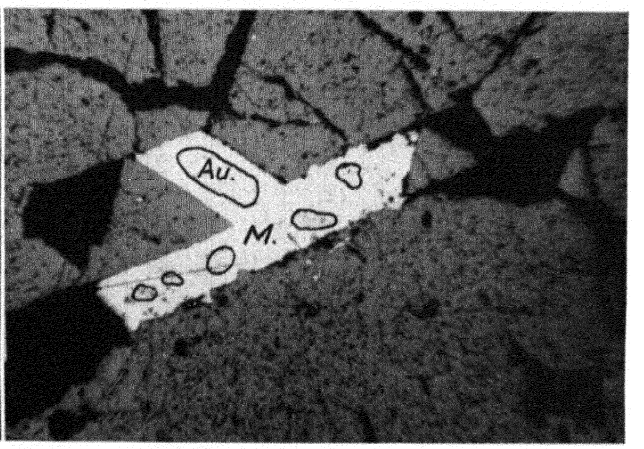


Figure 23. 47 ×. Small vein of melonite (M) and gold (Au) in uraninite. The melonite replaces the gold

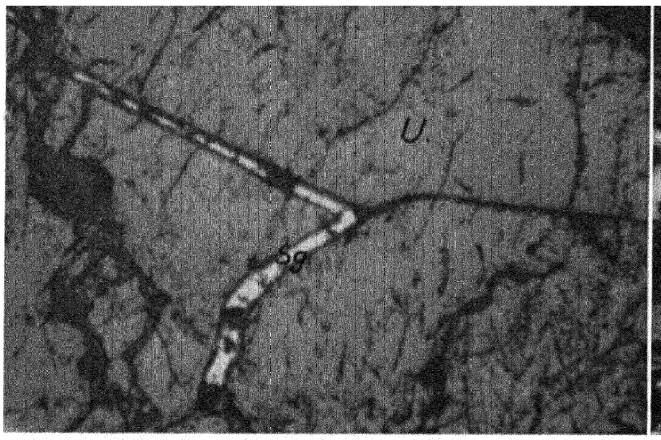


Figure 24. 80 ×. Siegenite between uraninite crystals

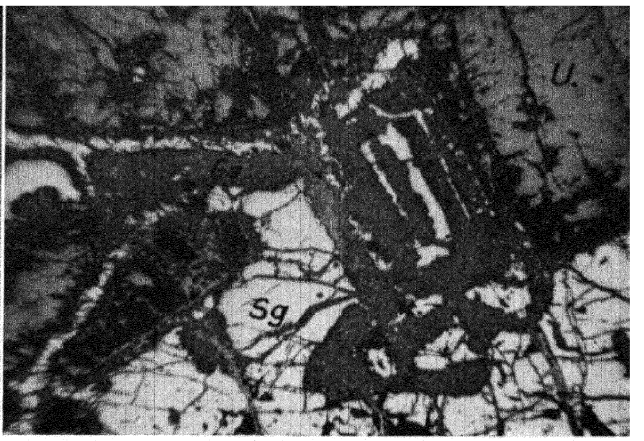


Figure 25. 47 ×. Uraninite and siegenite. Sample taken from a vei

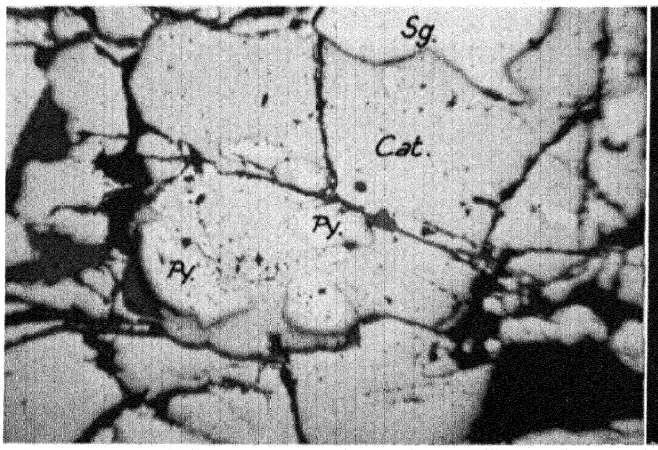


Figure 26. 47 ×. Cattierite (Cat) partly replaced by siegenite (Sg). Small crystals of pyrite (Py) are corroded

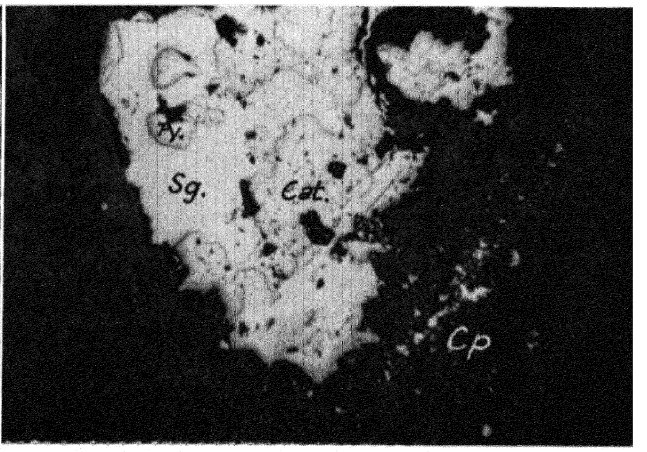


Figure 27. 80 ×. Mass of cattierite in a dolomitic gangue. Cattierit is largely replaced by siegenite. The numerous and very small spot in the gangue are chalcopyrite

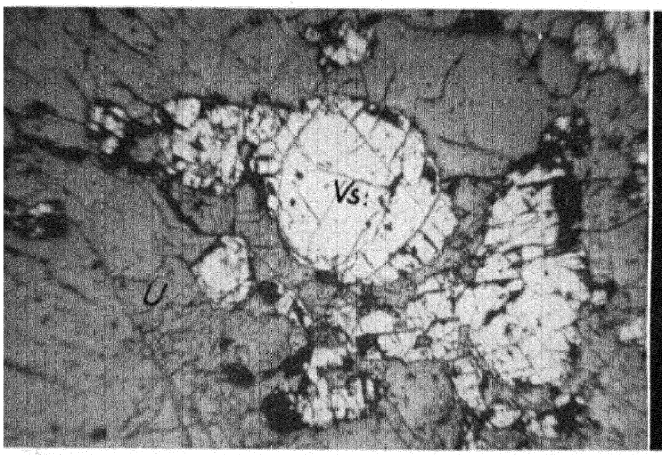


Figure 28. 47 ×. Vaesite in uraninite, from the first uraninite-vaesite vein, found at level 79

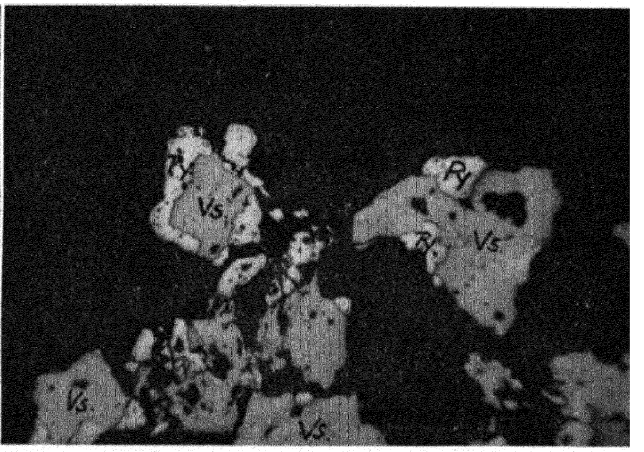


Figure 29. 47 ×. Vaesite, which corrodes pyrite

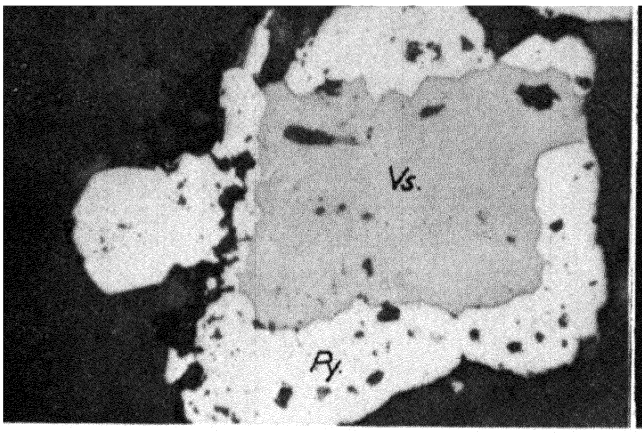


Figure 30. 170 ×. Detail of Fig. 29

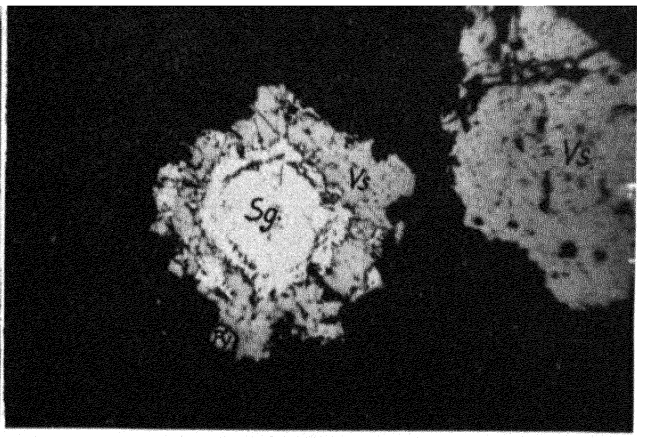


Figure 31. 47 ×. Vaesite in a dolomitic gangue, partly replaced at the center by siegenite

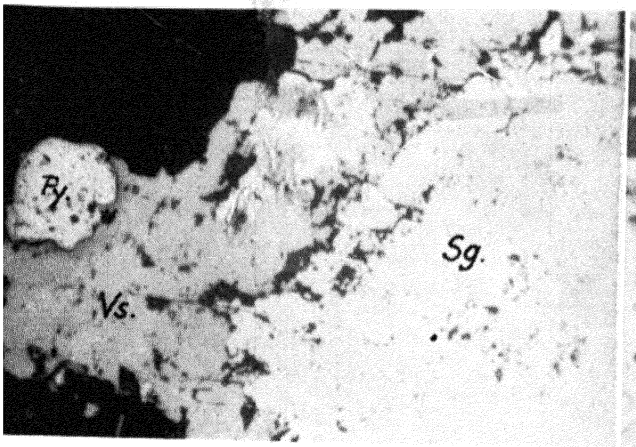


Figure 32. 170 ×. Detail of Fig. 31

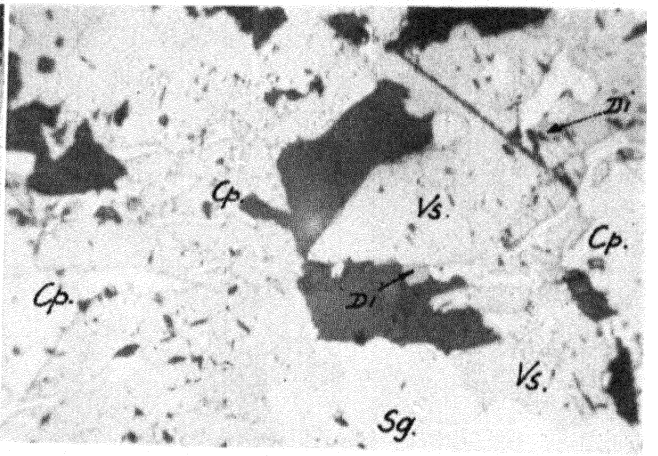
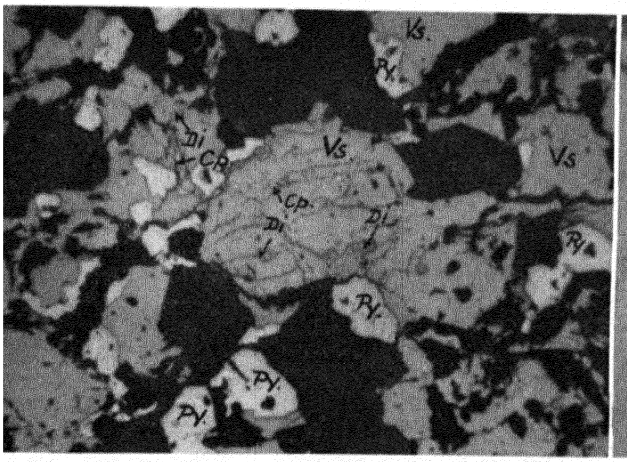


Figure 33. 170 ×. Small veins of chalcopyrite (Cp) in vaesite (Vs). Some small masses of digenite (Di) in the small veins. Bottom of picture, vaesite is shown replaced by siegenite



ure 34. 80 ×. Small veins of digenite (Di), dark grey, in vaesite, lighter grey. Several pyrite crystals (Py) corroded by vaesite

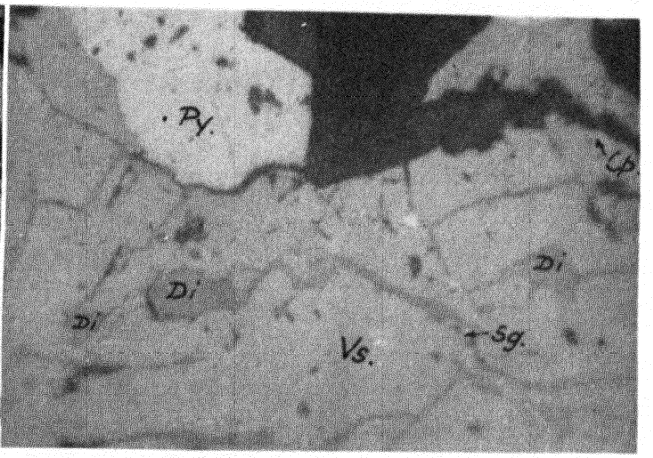


Figure 35. 290 ×. Detail of Fig. 34

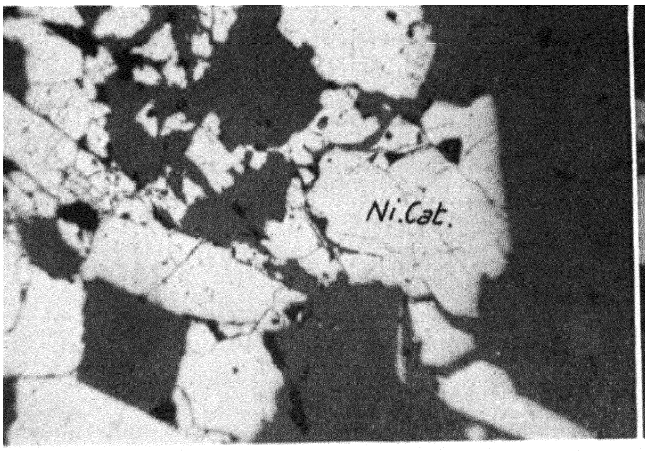


Figure 36. 47 ×. Nickel-cattierite in dolomitic gangue

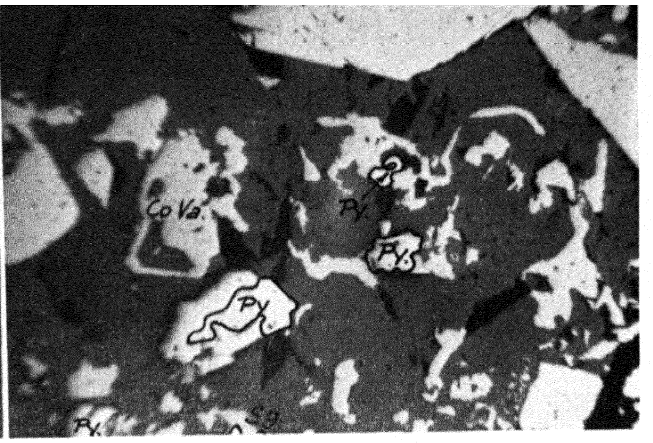
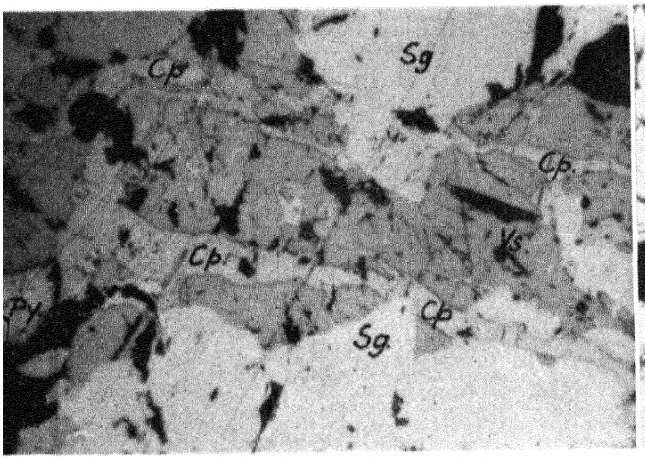


Figure 37. 47 ×. Cobalt-vaesite in dolomitic gangue. Crystals of pyrite, corroded by cobalt-vaesite



igure 38. 170 ×. Vaesite (Vs), partially replaced by siegenite. A einlet of chalcopyrite (Cp) in the vaesite is corroded by the siege- ite. Toward the bottom of the picture, note that another veinlet is partially attacked by the siegenite (Sg)

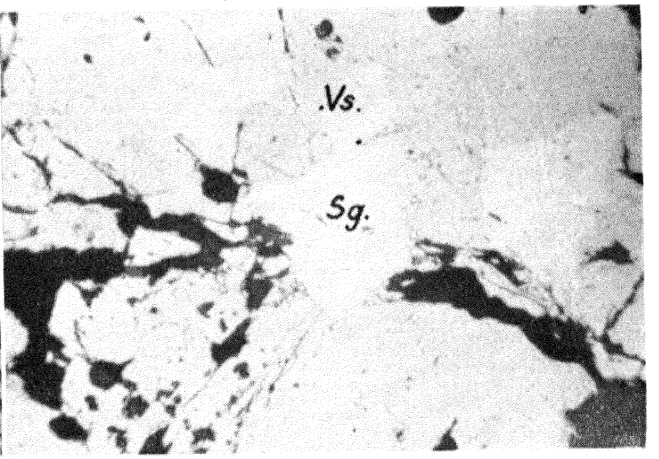


Figure 39. 80 ×. Siegenite replacing vaesite and cutting a fissured area in this mineral. (Polishing has enlarged the cracks)

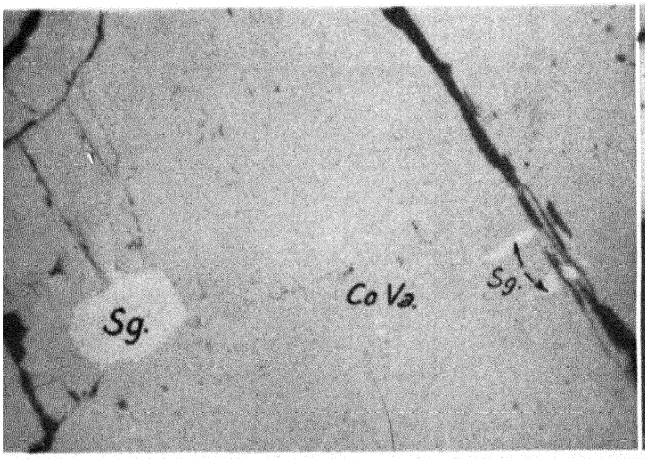


Figure 40. 170 ×. Beginning of the replacement of the cobalt-vaesite by the siegenite. It starts from the cleavage plane of the earlier mineral

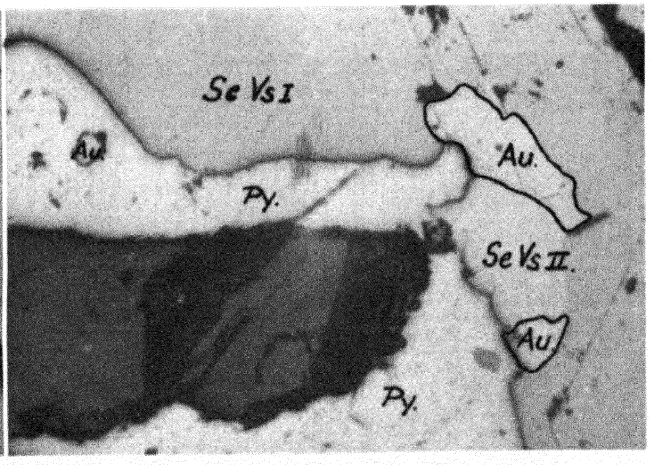


Figure 41. 170 ×. Selenio-vaesite (Se.Vs.I), and probably a selenio-vaesite rich in cobalt because it is harder (Se.Vs.II). Corroded pyrite. Native gold (Au) along the Se.Vs.I and Se.Vs.II contact. A small grain of gold apparently included in the pyrite.

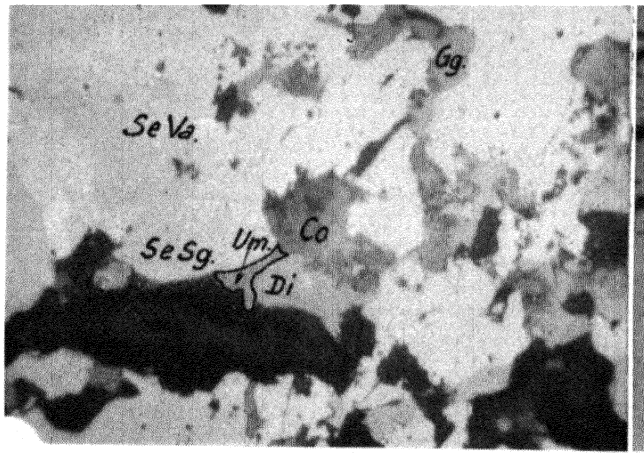


Figure 42. 290 ×. Umangite (Um), in contact with a layer of digenite (Di) and covellite (Cov), in a sample of selenio-vaesite (Se.Vs) and selenio-siegenite (Se.Sg)

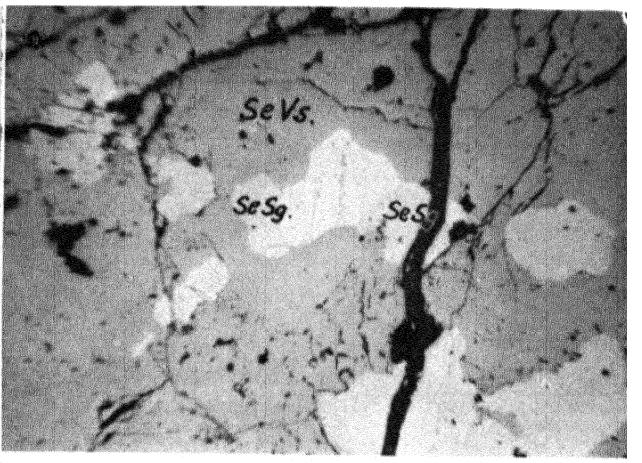


Figure 43. 47 ×. Small mass of a white selenide (Sel) between tw spurs of selenio-siegenite, in selenio-vaesite

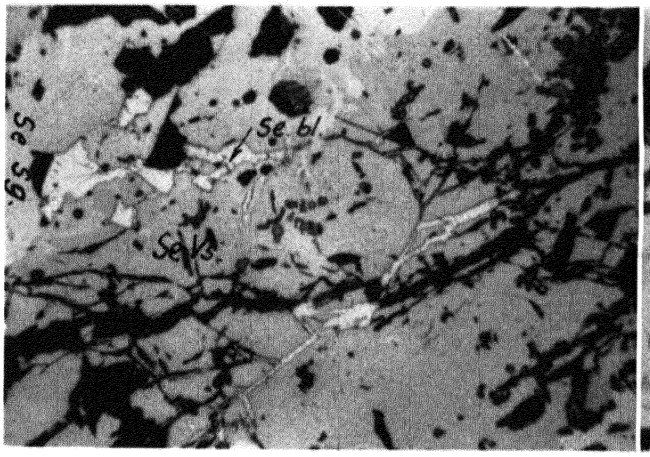


Figure 44. 80 ×. Selenio-vaesite cut by veinlet of a light blue selenide (Se.bl). The veinlet widens at the place where it comes in contact with selenio-siegenite

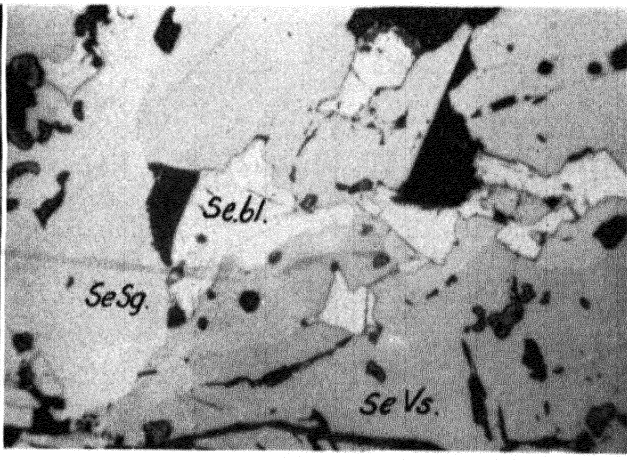
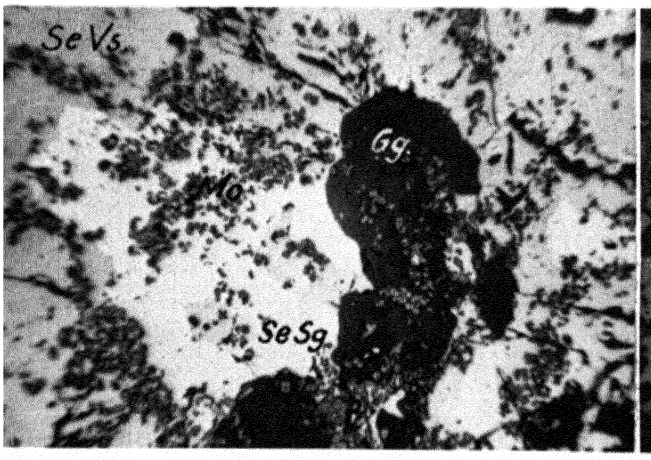
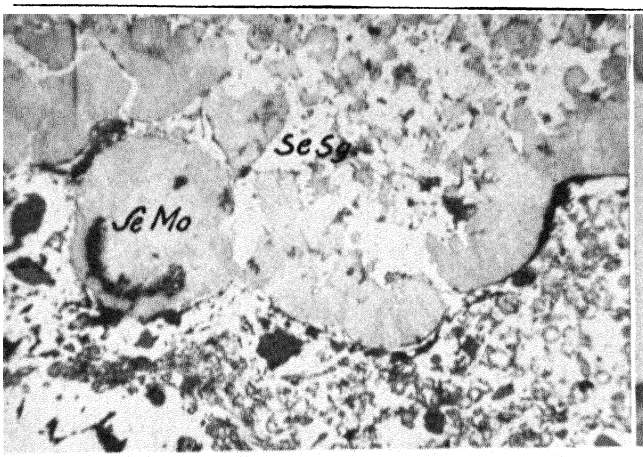


Figure 45. 170 ×. Detail of Fig. 44



igure 46. 47 ×. Small fibrous, radial flakes of molybdenite, with nclusions, as well as selenio-vaesite and selenio-siegenite as in the gangue

Figure 47. 80 ×. Elongated mass of molybdenite (Mo) broken in the selenio-vaesite, near a mass of dolomitic gangue



igure 48. 80 ×. The new mineral, temporarily considered as a elenio-molybdenite. Relicts of a fibrous-radial coating embedded in selenio-siegenite

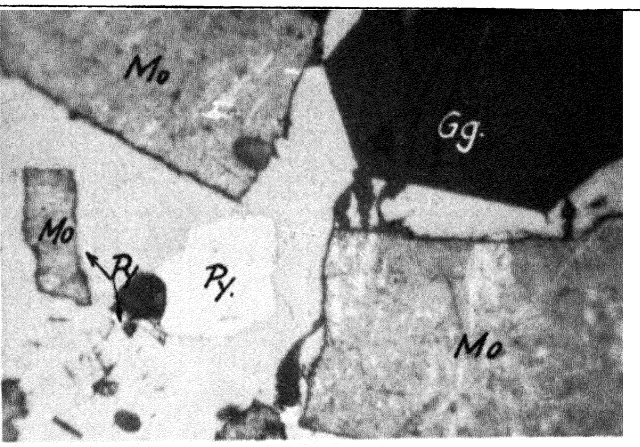
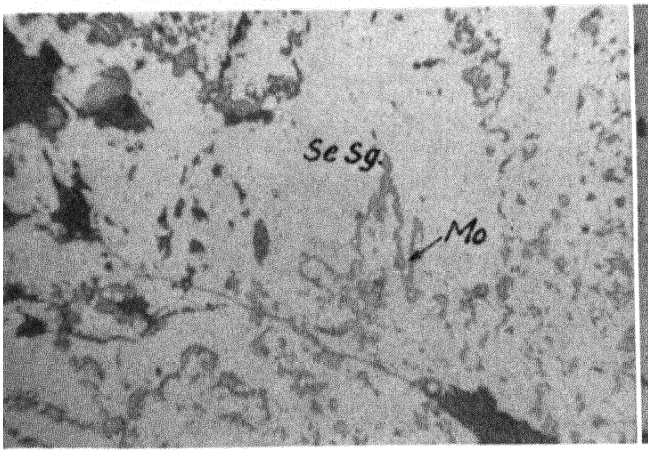


Figure 49. 290 ×. Detail of Fig. 47



igure 50. 47 ×. Molybdenite (darker gray), in thin ribbons, forming jagged patterns in the selenio-siegenite (lighter gray)

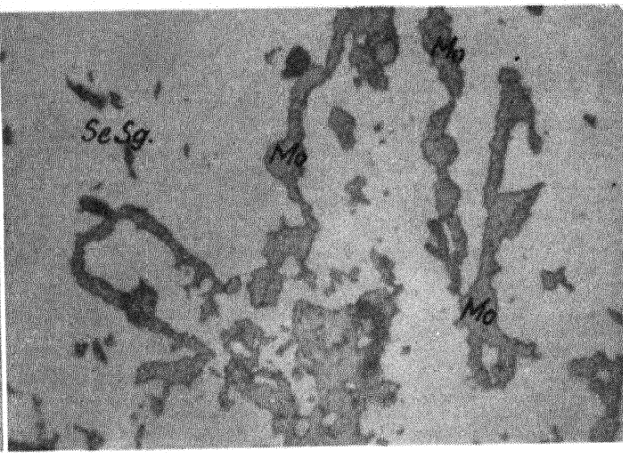


Figure 51. 170 ×. Detail of Fig. 50

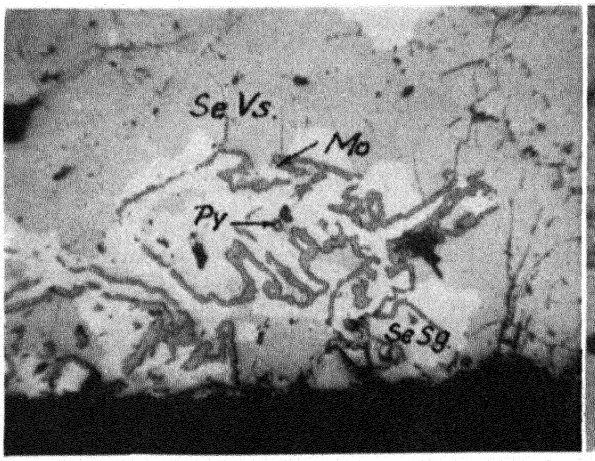


Figure 52. 47 ×. Thin ribbons of molybdenite; they follow the form of a dendritic crystal. The ribbons disappear in selenio-siegenite, which replaces the selenio-vaesite

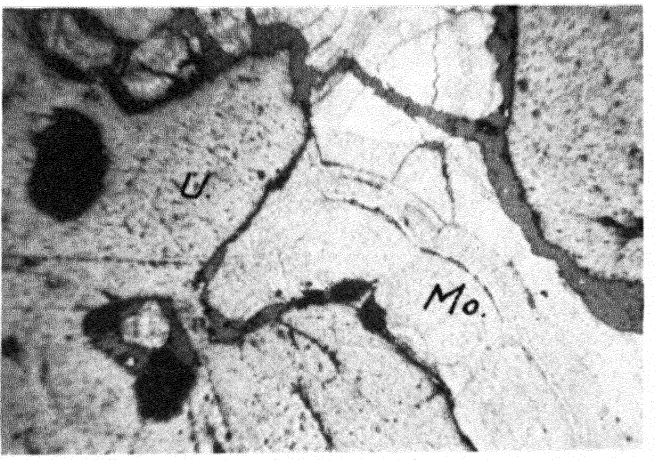


Figure 53. 47 ×. Uraninite (U) corroded by molybdenite (Mo

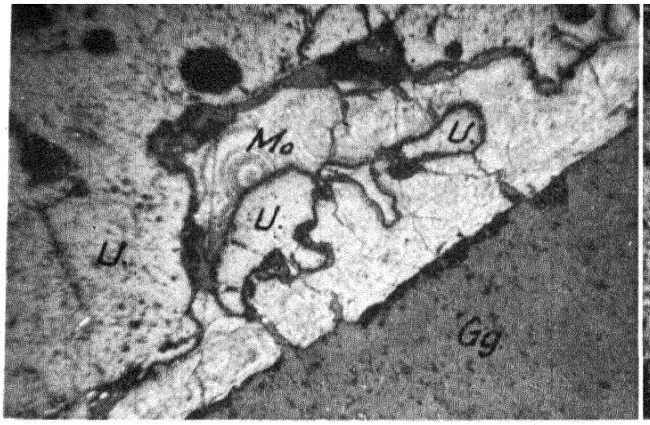


Figure 54. 47 ×. Same. Molybdenite between the gangue and face of the uraninite cube which is corroded

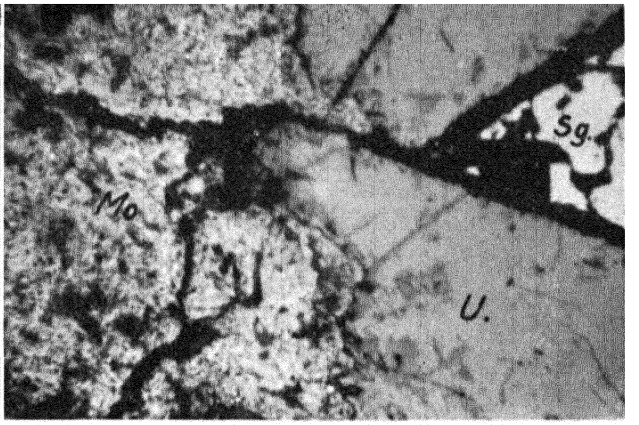


Figure 55. 80 ×. Uraninite corroded by molybdenite. The molybdenite fibers are randomly oriented

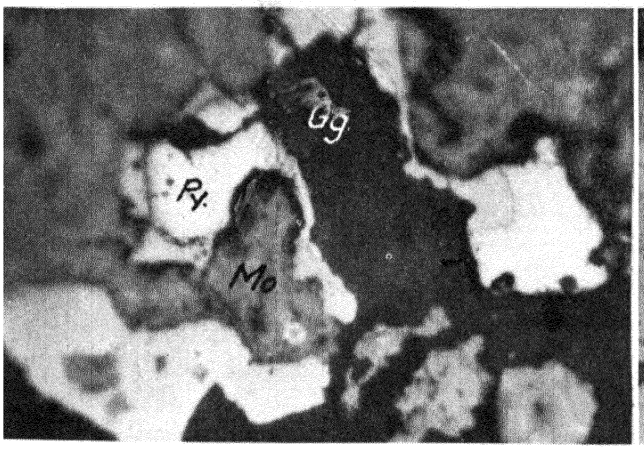


Figure 56. 290 ×. Pyrite crystal corroded by a small molybdenite concretion

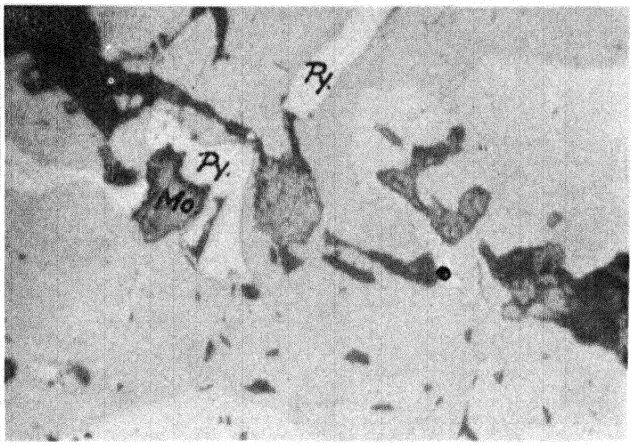


Figure 57. 290 ×. Same

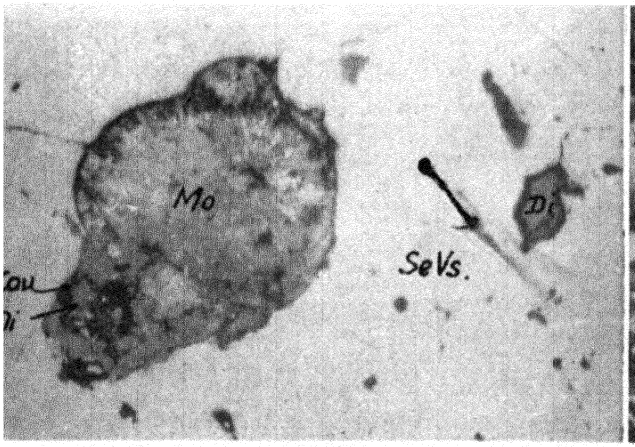


Figure 58. 290 ×. Small radial-fibrous concretion of molybdenite (Mo), with local replacement by digenite (Di), with covellite (Cov)

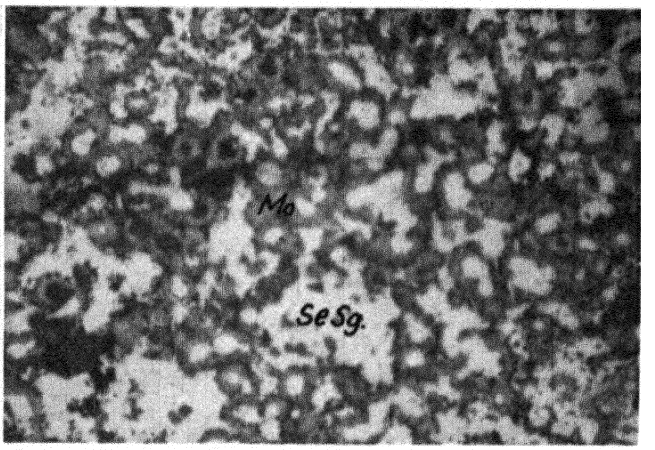
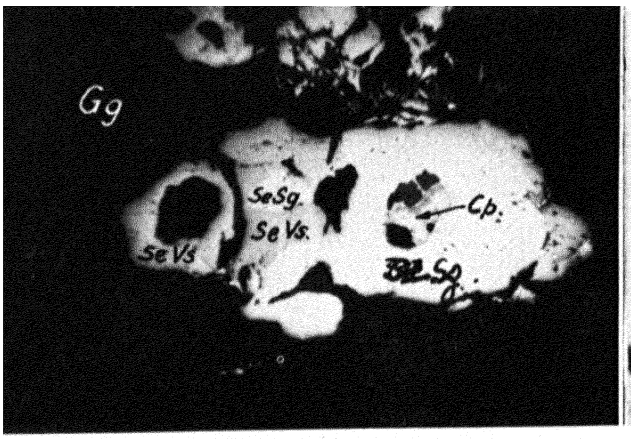


Figure 59. 170 ×. Radial-fibrous molybdenite rings (gray) around white nuclei of selenio-siegenite or around gangue nuclei (black-gray)



igure 60. 47 ×. Mass of selenio-siegenite which would seem to enlose some chalcopyrite which is partly replaced by covellite (Cov), and a white mineral (Min.bl.) unidentified

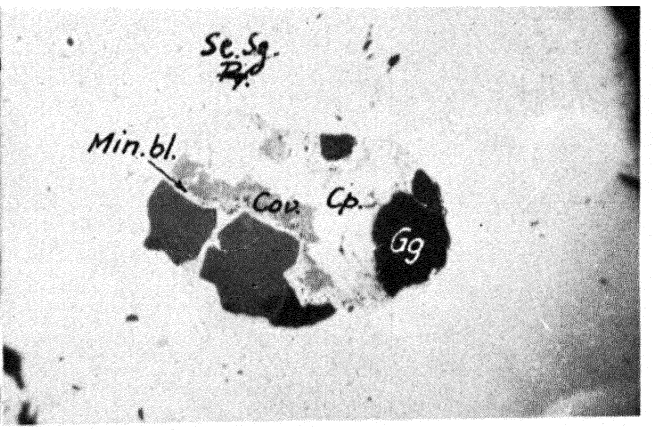


Figure 61. 170 ×. Detail of Fig. 60. Note that the white mineral separates covellite or chalcopyrite from the gangue. The picture does not show that the transition of the white minerals to the covellite is diffuse

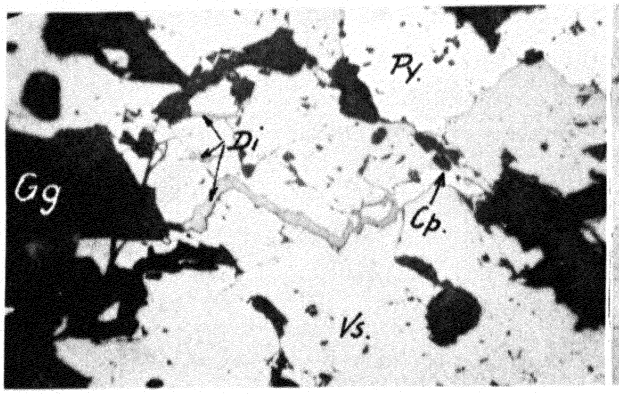


Figure 62. 170 ×. A break in the vaesite (light gray) filled by chalcopyrite (white) which is largely replaced by digenite (Di) (darker gray)

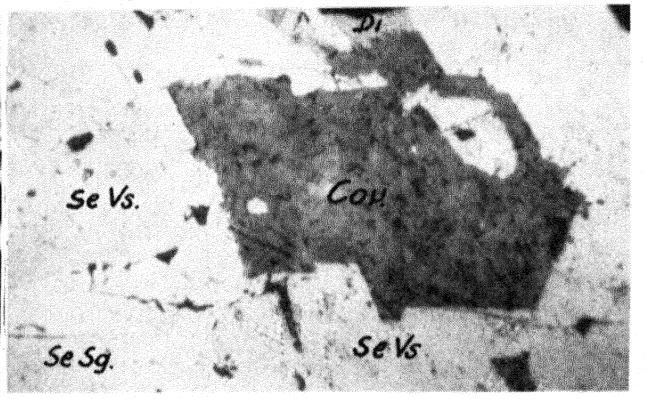


Figure 63. 290 ×. A polygonal shaped section made up of covellite, probably the product of the alteration of chalcopyrite, which seems to have replaced the rhombohedra by a carbonate

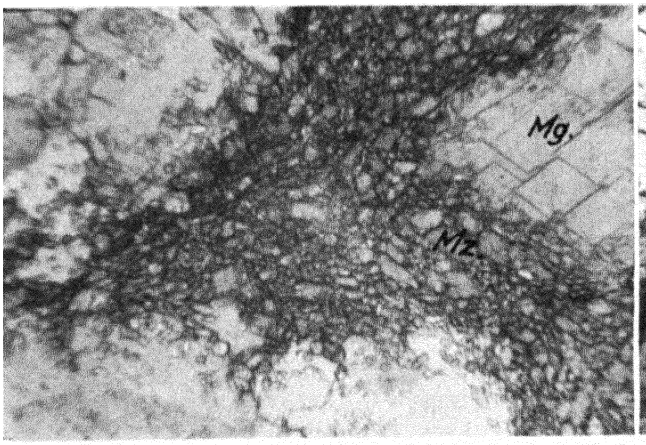


Figure 64. 47 ×. Thin section. Mass of small monazite (Mz) crystals which flowed between rhombohedral crystals of magnesite (Mg) and corroded them

Figure 65. 47 ×. Polished surface. The same phenomenon, namely the fluid flow of small monazite crystals between the uraninite crystals. Uraninite is in the process of altering to a mixture of various uranium minerals

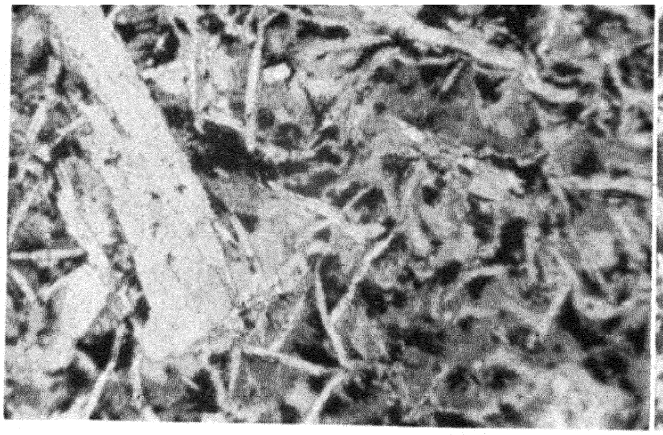


Figure 66. 47 ×. Thin section—plane light. Example of a trachyte from a collection of European rocks

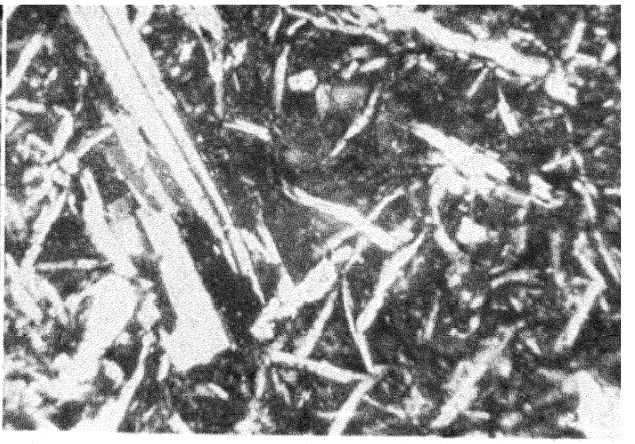


Figure 67. 47 ×. Thin section—polarized light. Same

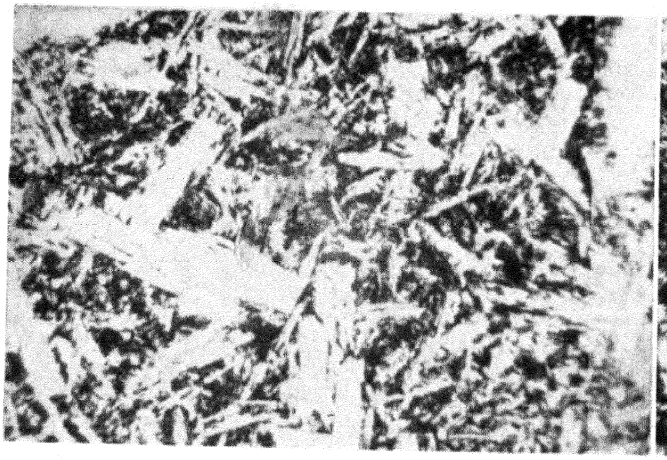


Figure 68. 47 ×. Thin section—plane light. Igneous rock, metamorphosed and altered, which resembles sedimentary R.A.T. in plane light. The similarity between the white laths and feldspars of the trachyte in Fig. 66 is striking

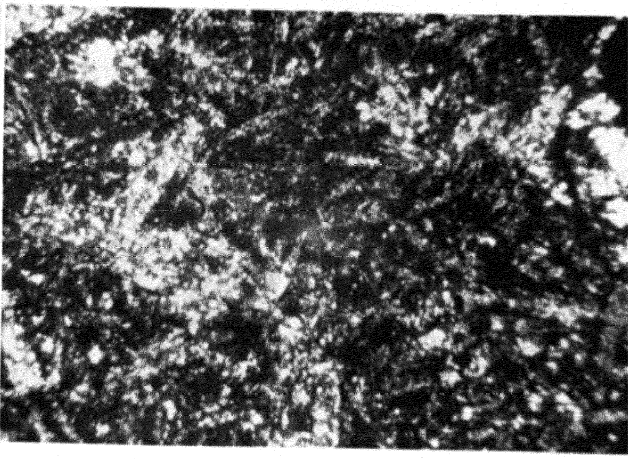
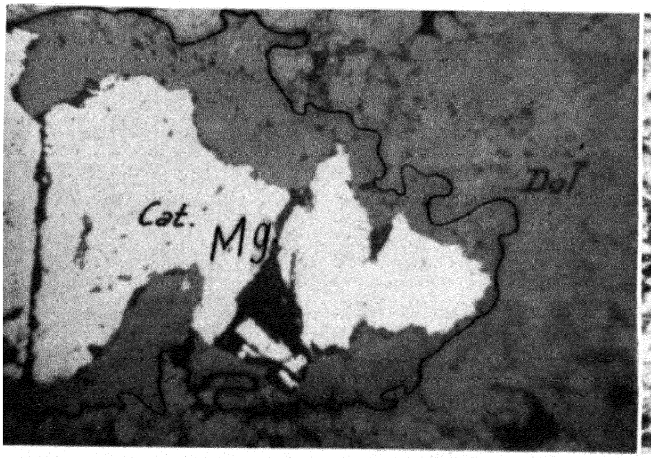


Figure 69. 47 ×. Thin section—polarized light. Same thin section and field as Fig. 68. It can now be seen that the feldspar laths are altered completely to chlorite. Despite intense chloritization, the rock should originally have been a trachyte



igure 70. 47 ×. Part of an acicular black crystal of magnesite in dolomite. The core of the crystal is replaced by cattierite

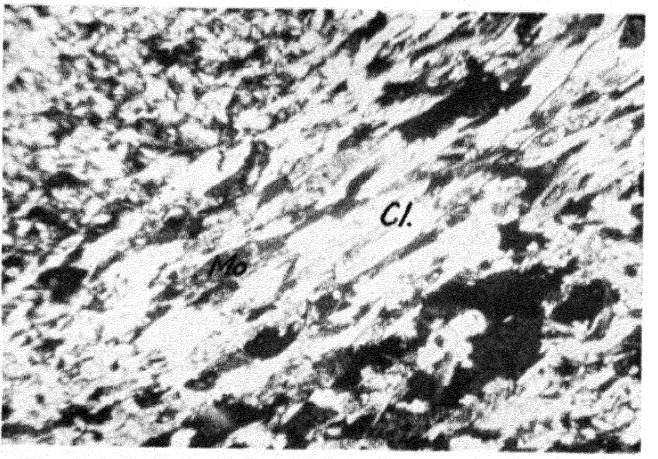
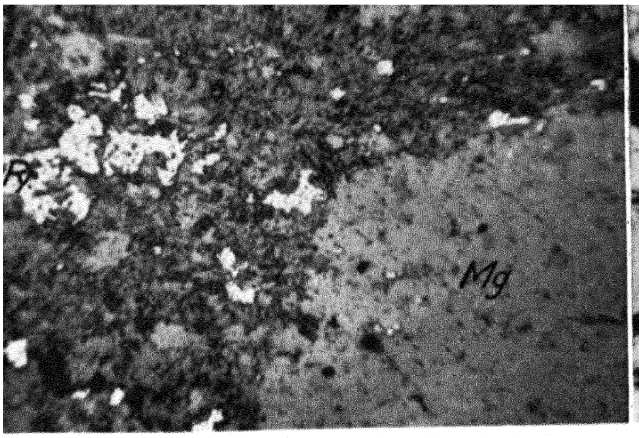


Figure 71. 47 ×. Thin section. Parallel growth of chlorite (cl) and elongated crystals of monazite (Mz). Note also the intimate association of the two minerals



igure 72. 47 ×. Acicular black crystal of magnesite in dolomite. The pyrite crystals (py) are found only in dolomite

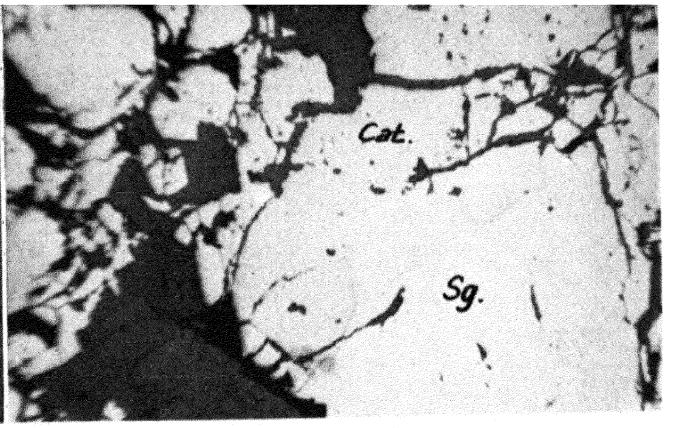
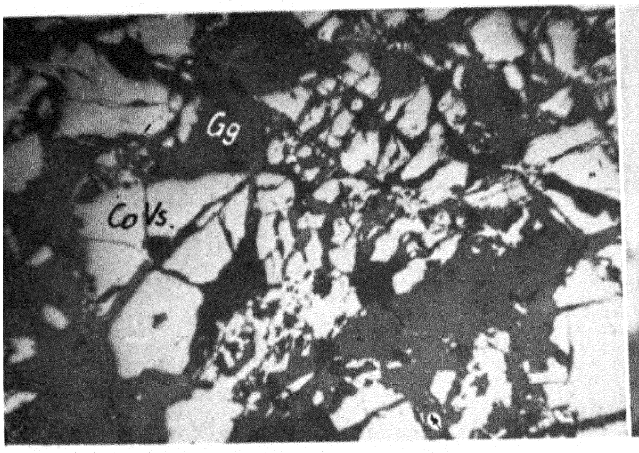


Figure 73. 47 ×. Fractured cattierite, partly replaced by siegenite



igure 74. 47 ×. Cobalt-vaesite, crushed. The dolomitic gangue fills the breaks

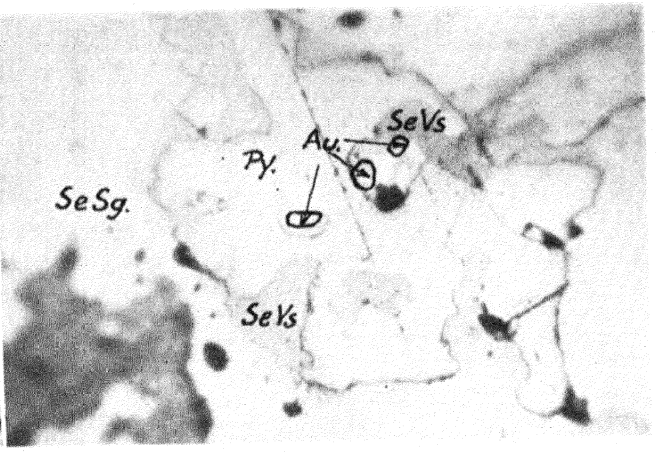


Figure 75. 290 ×. Strongly corroded pyrite crystal, lost in selenio siegenite. Selenio-vaesite is preserved in the hollow part of th crystal. Some native gold color occurs between vaesite and pyrite. I so far as they are nearly invisible, despite considerable enlargement we blacken them with India ink

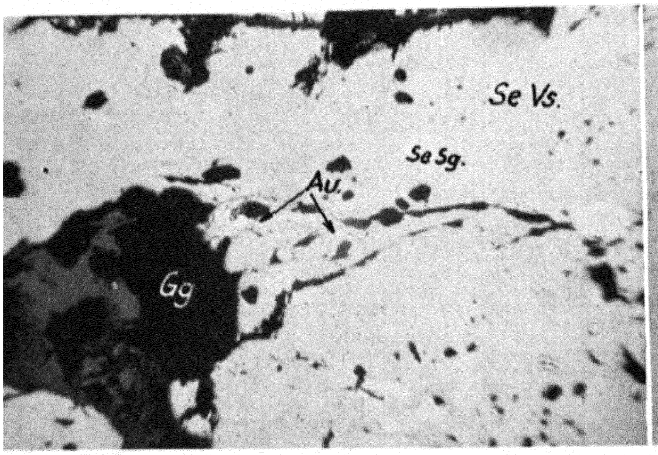


Figure 76. 170 ×. Two small masses of native gold deposited in a fracture which cuts the selenio-vaesite (Seva), some small patches of selenio-siegenite (seSg), and of an undetermined white selenide (sel.)

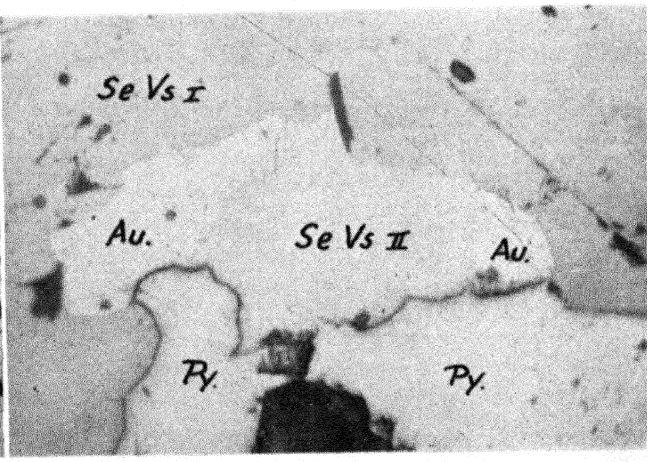
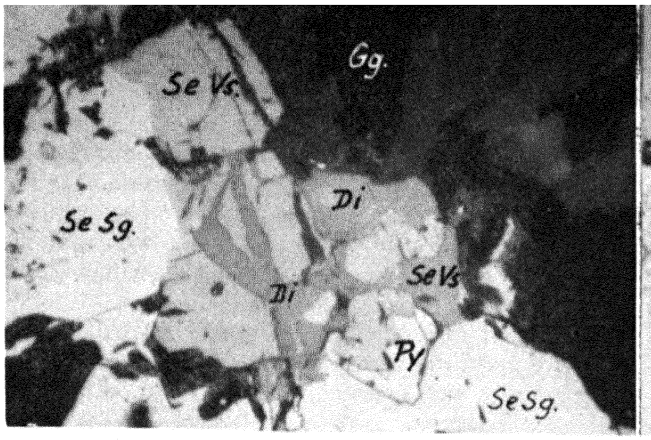


Figure 77. 290 ×. Detail of Fig. 41



igure 78. 170 ×. Small masses and veins of digenite in selenio-vaesite, near the dolomitic gangue

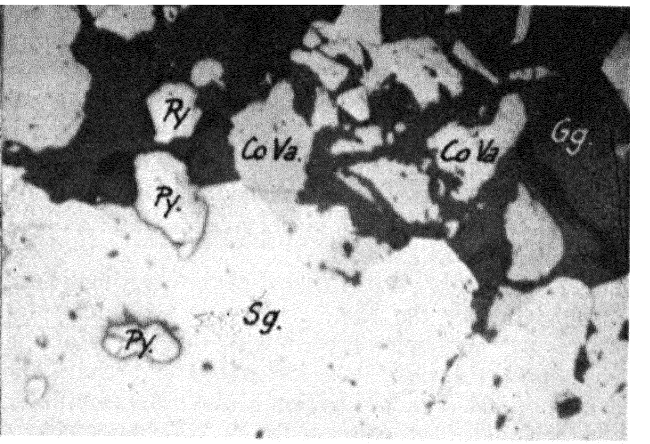


Figure 79. 47 ×. Cobalt-vaesite crystal, broken, the fragments of which are separated by penetration of the dolomitic gangue

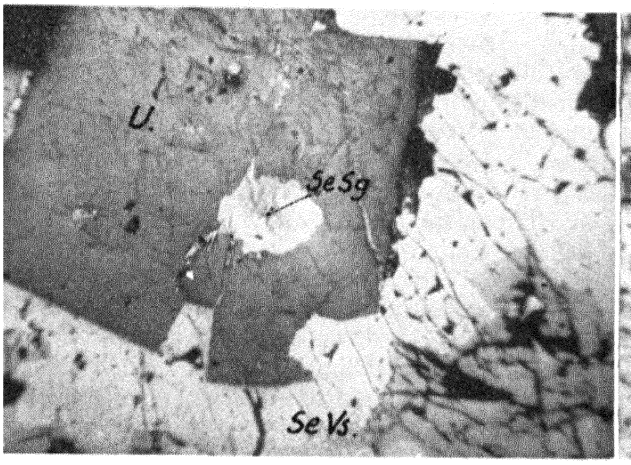


Figure 80. 47 ×. Uraninite crystal in selenio-vaesite

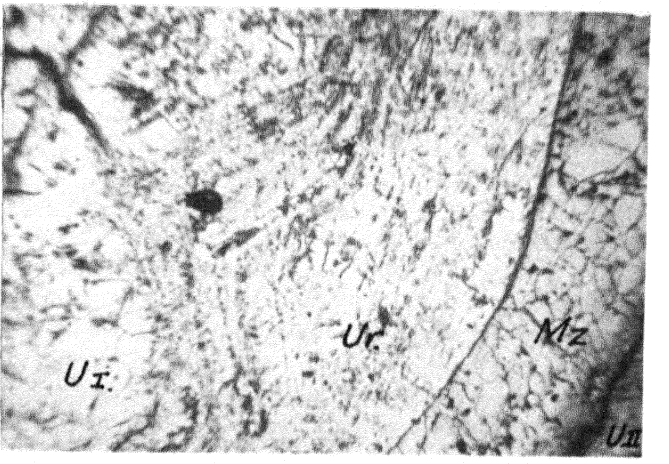


Figure 81. 47 ×. Uraninite crystal (U I) being alterated to secondary minerals of uranium (Ur). Filling up of the crystals of monazite (Mz) between the uraninite crystals (U I and U II)

CHAPTER VI. THE GENESIS FROM THE GEOLOGIC STANDPOINT

Consideration of the Occurrences

108. The Shinkolobwe deposit is located in a mass of the Mine Series in one of the faulted and more or less transported folds of the Katanga geosyncline.

The schisto-dolomitic base has been folded and overturned against a Kundelungu spur and considerably elongated in an east-west direction. Figure 82 is a schematic longitudinal cross section of the deposit.

The F–G and C_1–I faults are symmetrical, and the latter dip to the east, the former, to the west. Up to level 255, all mineralization is localized between these two faults. It disappears at depth in the central part, but traces occur along the F–G fault and in substantial amounts, on either side of the C_1–I fault.

It appears that there are two sages of mineralization, the latter being more important than the former. The migration of mineralization is believed to have occurred as follows:

109. Rising from point I at depth, the mineralization affected, as it went by, Spur IV to the east and the barriers C.M.N. and S.D. of the Massif Principal to the west. After reaching point C_1 it split and one part moved along the Kundelungu where deposits occur in Spurs I and II. The other part passed under the R.A.T. nappe where it deposited here and there in the lower beds of the Massif Principal. It accumulated under the dome of level 114 where it broke through the barrier and connected with Fault F–G to form the enrichment between levels 132 and 79, to complete the mineralization of the upper spurs which had been started by the third branch of the I–C_1 occurrence.

110. Between the Kundelungu and Mine Series, there is always a certain thickness of breccia which formed at the expense of the R.A.T. Mineralization reaches this breccia, but never crosses it, Although it seems to concentrate preferentially in the lower beds of the Mine Series, it is only because the frac-

tured layers against the Kundelungu spur are the nearest receptive area. When, due to faulting, the clay-talc barrier moves and even cuts the Mine Series as does the R.A.T. nappe, the mineralization follows the path imposed by the water impervious layer. It appears, therefore, that the mineralization which travelled along one of several main faults, more or less mineralized the wall rock, and became localized at the impervious rocks.

111. It seems evident that the cross cutting of the Mine Series by the R.A.T. nappe is a phenomenon which was contemporaneous with deposition of the series and, therefore, was integrated with the Kundelungu folds. The localization of the uranium mineralization under the dome of the R.A.T. nappe shows definitely that it occurred after the folds, and therefore, is younger than the Kundelungu formations.

Since it was established that the age of the uranium mineralization is on the order of 630 million years, it followed that the Kundelungu system had to be pre-Cambrian.†† This correlation with the geological time scale generally is not accepted,†† but the structural evidence at Shinkolobwe is mentioned for the first time in support of this determination.

Considerations on the Metallic Occurrences

112. In all the papers on metallic deposits of the upper Katanga, the authors assume that uranium and copper mineralization are directly related.

We note first that in all mineralized occurrences of the Mine Series, copper is very abundant, and that where cobalt is associated, it is present in a minimum ratio of six parts of copper to one of cobalt. It should be noted also that while copper is present almost everywhere in Shinkolobwe, it is there in such minute quantities that it cannot be spoken of as a copper-bearing deposit; cobalt, however, is abundant. This change in the ratios constitutes a startling anomaly in the Katanga deposits.

In addition, the latter deposits always are stratified, except the Kipushi which occurs in veins. Shinkolobwe also is a type of vein. To this extent, it also is abnormal.

Finally, nickel which is so abundant at Shinkolobwe and in any case closely related to uranium, is practically non-existent in the classic deposits of Upper Katanga.

113. These three considerations have lead us to a certain amount of scepticism as to the contemporaneous nature of the uranium and copper mineralization; at least as far as the deposits of the Mine Series are concerned.

114. Some attempt may be made at convincing us, by noting that the absence of copper from Shinkolobwe may be accidental but uranium occurs in small quantities in some of the classic deposits of the region. It seems to have been overlooked that uranium is not found in the copper-bearing ore bodies, but rather is stored in small isolated pockets at the impervious talc and clay formations which bear no genetic relation with the deposit proper. The conditions under which deposition took place are identical, everywhere, with those which were described in Paragraph 110.

115. The mineralization of the Shinkolobwe deposit is so different from that of our other deposits that we are led to ascribe to it a peculiar origin, in the same way that Kipushi always is dissociated from the mineralization proper of the Mine Series.

†† At least the lower and middle series which are folded.
‡‡ According to L. Cahen, Geology of the Belgian Congo, 1954, but contrary to the opinion of M. Robert, Geological Notice of the Geological Map of the Southern Katanga, 1949.

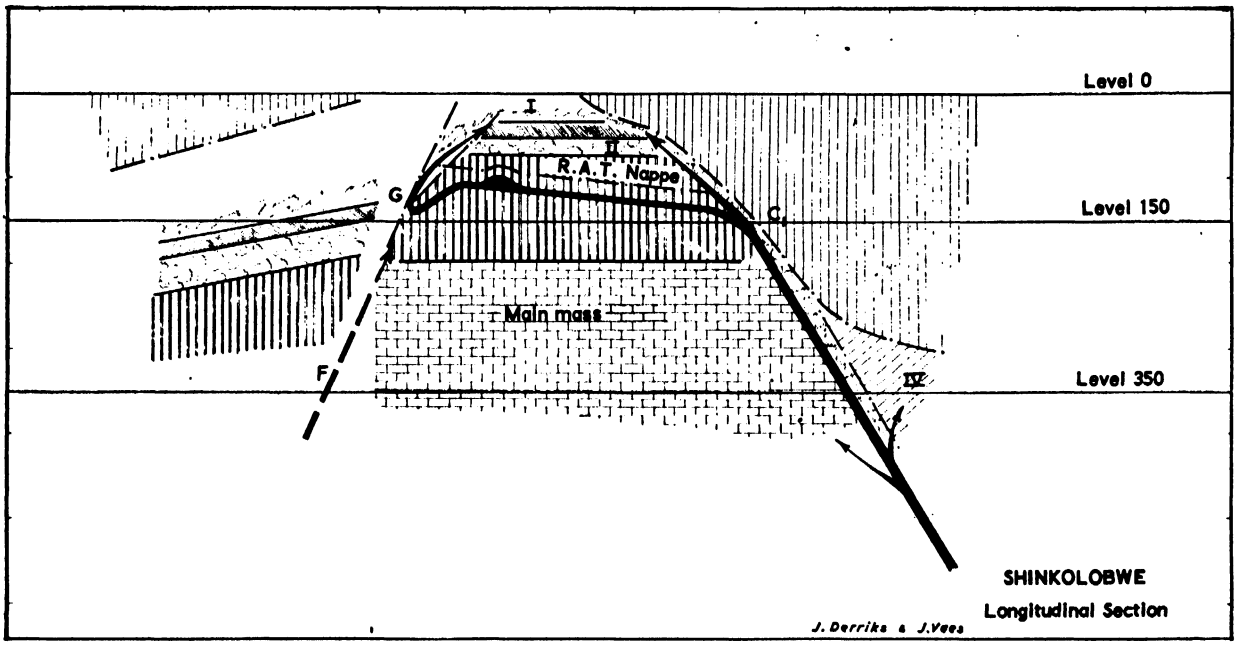


Figure 82. Shinkolobwe—Longitudinal section

CHAPTER VII. GENESIS OF THE DEPOSIT FROM THE MINERALOGICAL STANDPOINT

Magmatic Occurrences

116. "A magmatic origin cannot be questioned: there must be at depth an intrusive magma, whose mineralizing solutions from differentiation account for the uranium deposit." This idea, which is put forward in the study of Messrs. Thoreau and du Trieu was confirmed by the discovery, to the east of the mine, of several outcrops of igneous rock.

These outcrops have been found in shallow folds, and the specimens obviously are very altered. Under the microscope in plane light the rock appears to consist of small feldspar laths and has the appearance of a trachyte. In polarized light this pattern disappears completely, and the rock appears to be a mixture of nearly submicroscopic, colorless chlorite flakes (Figs. 66, 67, 68 and 69).

Microscopically, these rocks are identical with the pink R.A.T., but any detrital origin must be ruled out. This is a decomposition residue from an igneous rock, probably of the trachyte family.

Observations

Magnesite is Older than Cobalt and Nickel Sulphides

117. The large white magnesite vein is mostly free from any mineralization except for traces of pyrite. However, its north side along the C.M.N. contains cattierite as well as cobalt sulphide. The apophyses and large crystalline magnesite masses found in the C.M.N. fractures also contain cattierite. The magnesite in the latter occurrence often is lilac in color, due to the presence of cobalt. Magnesite also occurs as gangue with some of the cattierite veins.

118. The very important appearance of magnesite altered the dolomites of the Mine Series to highly magnesium rocks. It is introduced into the dolomite as acicular crystals which are black due to the presence of a fine pigment. Some crystals have been replaced by cattierite (Fig. 70).

The Principal Magnesite Occurrence is Older than that of the Monazite

119. The magnesite deposited on the edges of the dolomite blocks in the brecciated zone of level 114 often forms a border for monazite veins. The monazite crystals probably flowed into the open fractures, and more or less followed the zig-zag rhombohedral outlines of the magnesite (Fig. 64).

Uraninite is Earlier than Monazite

120. In monazite masses, isolated idiomorphic crystals of uraninite occur. When monazite contacts larger masses of uraninite, the phosphate penetrates the uranium oxide crystals, and this penetration takes on a fluid appearance (as in magnesite (Fig. 65)).

These fluid-like bands of small monazite crystals suggest that the phosphate was introduced in a saturated solution, and that the monazite began to crystallize as these solutions cooled in contact with the wall rocks which they traversed and which were at lower temperatures than the solutions.

Monazite is Older than Co and Ni Sulphides

121. When nickel and cobalt sulphides exist in a mass of monazite (which is unusual), they always are finely disseminated, as in the schists.

Molybdenite and Monazite

122. We have found the molybdenite-monazite association only in a few specimens from level 96, east of the F–G fault in the S.D. In thin section, a few small crystals of monazite with a molybdenite pigment are seen. The relation of the pigment and monazite makes it impossible to tell which of the minerals is older.

Molybdenite is Older than Chlorite

123. In a molybdenum-bearing breccia derived from the selenide zone of level 144, we have observed in thin section masses of molybdenite which are cemented by interlaced chlorite rosettes.

Chlorite is Contemporaneous with Monazite

124. In the same part of the deposit chloritic rock is cut by veinlets of monazite, the grains of which are oriented parallel with the margins of the veinlets. At a point where one of these veinlets thins, monazite is associated with similarly oriented chlorite which does not occur as rosettes (Fig. 71), as might be expected.

Molybdenite is Later than Uraninite but Earlier than the Cobalt and Nickel Sulphides

125. The molybdenite-uraninite and molybdenite-nickel sulphide associations are contemporaneous. In the case of uraninite crystals which are surrounded by sulphides, the molybdenite very often is found deposited on the uraninite, or concentrated nearby. At times, it corrodes the cubes of this uranium mineral (Figs. 53, 54 and 55).

Vaesite, siegenite as well as the gangue which accompanies these two sulphides, often contains fibrous balls and coatings of molybdenite (Figs. 46, 47 and 48). Vaesite does not corrode the molybdenite sulphide, and when siegenite appears to attack it from the center of the balls, it probably is nuclei of gangue being replaced by siegenite or an unknown mineral replaced by siegenite (Fig. 59).

In several specimens of selenio-vaesite, thin coats of molybdenite occur in a pattern which seems to indicate that molybdenite was deposited on the surface of unknown crystals which are replaced completely by the selenium-bearing siegenite (Figs. 50, 51 and 52).

Pyrite is Earlier than Molybdenite

126. Pyrite is found almost everywhere in the deposit, both in the mineralized layers and in the upper C.M.N. It occurs as thin disseminations or as fracture fillings; and is also an accessory with the cobalt and nickel sulphides. Its crystals nearly always are strongly corroded by the other sulphides (Figs. 26, 29, 34), even by molybdenite (Figs. 56 and 57). Therefore, its occurrence must precede the latter.

Pyrite is Later than the Main Magnesite Deposition

127. In a specimen from the C.M.N. which contains acicular black magnesite crystals, pyrite occurs particularly in the granular dolomite between the acicular crystals. It occurs here as isolated crystals, as small masses and as thin lenses in dolomite filled fissures which cut the associated rock.

In the magnesite crystals nearly submicroscopic specks of vaesite, chalcopyrite, bornite as well as pyrite crystals are noted. The pyrite crystals are much smaller than those observed in the dolomite which surrounds the black needles (Fig. 79).

In Paragraph 117 we described the replacement of magnesite crystals by cattierite. Here, again, extremely fine mineralization is the beginning of replacement, and it is believed that pyrite came after the magnesium enrichment of the rocks.

Pyrite is Younger than Uraninite

128. We have not found any pyrite in the uraninite. It is probable, therefore, that pyrite is younger. On the other hand, this iron sulphide as already stated, is corroded by molybdenite which is later than the pyrite.

Quartz is Younger than Magnesite

129. Smoky quartz crystals occur in open fissures, and have been deposited on magnesite, accompanied by crystals of Ni and Co sulphides.

Deductions

130. On the basis of the evidence, we can draw certain conclusions about the genesis of the deposit. We have seen that the succession is as follows:

1. Magnesite, then pyrite (Paragraph 127), then molybdenite (Paragraph 126).
2. Uraninite is earlier than pyrite (Paragraph 128).
3. Uraninite is earlier than molybdenite (Paragraph 125).

Uraninite and magnesite, since they precede the pyrite, offer two possibilities: (*a*) Magnesite was the first indication of mineralization, (*b*) Uraninite precedes magnesite.

If uraninite were deposited first, the magnesite which comes later, must have filled the space left by the first mineral.

Molybdenite, which came later, would have to disperse through the magnesium gangue, and, contrary to that which has been observed, it is not concentrated close to the uraninite.

On the other hand, uraninite frequently is deposited in open faults. Thus, if it came first, it could have been deposited in the large faults of the C.M.N. We note, on the contrary, that this fissure is filled by a vein of very pure magnesite, which contains no uraninite, not even along its walls.

131. Phase A. *We feel therefore that the formation of the magnesite vein and the magnesium enrichment of the rocks of the Mine Series is the first indication of mineralization.* But the lilac magnesite which contains cattierite, as well as the masses of cattierite accompanied by a magnesite, indicates that the history of the carbonate deposition is long. The magnesite vein must have formed in an open crack which probably enlarged as the carbonate was deposited. A replacement of the C.M.N. beds would never have resulted in as pure a magnesite.

132. Phase B. *The phase of major magnesite deposition was followed by uranium deposition.* The fact that open cracks filled by uraninite crystals, as well as the rectangular walls of several veins, seems to indicate that at least, some of these have formed in open fissures. The smaller masses, as well as the disseminated minerals in the rock, must have formed partly by the replacement of the host rocks.

133. Phase C. *Uraninite is followed by molybdenite and monazite* (Paragraphs 120, 125). The order in which molybdenite and monazite were deposited is uncertain. In the thin section which shows S.D. with molybdenite and chlorite, *the chlorite certainly is later than molybdenite* (Paragraph 123). In the metamorphic rocks which enclose monazite veinlets (Fig. 71), it would seem that, in order to account for the parallel arrangement of *monazite and chlorite,* we must assume a *nearly contemporaneous* origin for the two minerals. It would seem therefore that molybdenite is older than monazite, and that the chloritization of certain rocks took place at about the time the phosphates arrived.

The weak nickel-sulphide mineralization which is disseminated in the monazite indicates that it was in place before the sulphides appeared (Paragraph 121).

134. Phase D. *The monazite-chlorite phase is followed by a strong mineralization of cobalt and nickel sulphides which, in turn, is preceded by weak quartz mineralization* (Paragraphs 121, 129). It is significant that nickel which occurs as vaesite follows the same course as the uranium, but overlaps it. Vaesite is found (almost exclusively) in the lower beds of the Mine Series, whereas cobalt is deposited nearer to the wall in the dolomite of the C.M.N. Where the two mineralizations are in contact, one finds sulphides of intermediate composition between a cattierite and a vaesite; this indicates that nickel and cobalt are contemporaneous. The fact that they occur together in two distinct zones of the mine is due, in our opinion, to a phenomenon of differential migration.

It is particularly by replacement of the wall rock that the sulphides have taken their place (disseminated ore, and some non-uranium-bearing veins). On the other hand, the sulphide masses in the large uraninite veins must have filled spaces left open in the uranium advance.

135. Selenium and tellurium are explained in two ways: (1) they accompanied the nickel and cobalt sulphides, and followed the same path as the nickel; their mobility carried them up to the impervious R.A.T. barrier; (2) they are earlier than the seleniovaesite and formed unidentified minerals which are now completely absorbed by the nickel sulphide.

A relict outline of these primary minerals occurs as spear-shaped dendrites which are now underlain by a fine molybdenite coating (Figs. 50, 51 and 52).

These crusts are high in selenium, and are hard to distinguish from the usual molybdenite; thus, it is thought that selenium and molybdenum are from the same phase and that as a consequence: the selenium and tellurium preceded the cobalt and nickel sulphides.

136. Phase E. *After deposition the sulphides were subjected to certain pressures, perhaps to tectonic movements.* The sulphides of several veins are crushed, and the resultant cracks are filled with dolomite (Figs. 73 and 74).

137. Phase F. *It is probably at the end of this era that chalcopyrite was deposited.* One often notices small masses of chalcopyrite which lie between vaesite and the dolomitic gangue. It appears as if the copper sulphide were introduced along this contact. Chalcopyrite has entered the fractures in the vaesite, and replaced the earlier dolomite (Figs. 38 and 62).

With the coming of the chalcopyrite, we come to the end of the evidence of magmatic origin.

Hypogene Activity

138. Hypogene alteration began after the deposition of chalcopyrite. The most important phase is the formation of siegenite.

Figures 38 and 39 show that siegenite was deposited after the fracturing and filling by dolomite and chalcopyrite.

Siegenite is higher in nickel than cattierite, and richer in cobalt than vaesite. Thus, we can exclude a second stage of cobalt and nickel as cobalt would have had to enrich the vaesite, and nickel would have migrated toward the cattierite. Thus, these two metals would have acted this time in a manner quite contrary to that of the first occurrence. It is more logical to assume that cattierite and vaesite which are formed at high temperatures, are unstable and thus transform easily to form a stable compound at low temperature (siegenite). The instability of cattierite is evident in our stockpile where it decomposes and becomes covered with cobalt sulphate.

139. Among other hypogene effects, we must include the change from chalcopyrite to digenite and covellite, as well as the deposition of native gold, umangite, and a blue selenide.

140. We do not know in what form the gold was introduced. It must have been as a telluride or selenide in the zone below the dome of the R.A.T. nappe, as it is in these selenio-sulphides that small patches of gold are more frequently found (Figs. 75, 76 and 77). Often, this precious metal is found at the vaesite-siegenite contact, which may indicate that it was deposited after the formation of the mixed sulphide.

Melonite was deposited later than the gold, as shown on Fig. 23, as it replaces the gold.

141. Umangite is intimately associated with digenite, and must therefore have the same genesis (Fig. 42).

142. The blue selenide occurs in very small veinlets in the vaesite, and forms small masses where these veinlets are in contact with the siegenite (Figs. 44 and 45). It appears, therefore, to have formed later than the siegenite.

Supergene Activity

143. The fact that cattierite is abundant in the unaltered zone of the deposit, but has not been found in the altered zone, seems to indicate that part of the siegenite which occurs near the surface is supergene.

The alteration of uraninite and the sulphides has been described in a study by Messrs. Thoreau and du Trieu. Below level 57, this alteration becomes weaker as we go deeper into the deposit. However, new minerals have been discovered; and they have been described in various specialized publications. However, they are of no interest as far as the genesis of the deposit is concerned.

Conclusions

Before summarizing briefly, what has been learned from this account, we should like to indicate that our findings reflect only our current opinion, and that we do not consider them as final. Let us say that they are an expression of the stage reached by our studies.

(1) The formations of the Shinkolobwe deposit form a spur of the Mine Series, which is wedged into a fold-fault.

(2) A review of the local tectonics leads us to confirm the view that the Kundelungu System is pre-Cambrian.

(3) The principal metals in the order of importance are: uranium, cobalt and nickel.

(4) The deposit is the vein type and of magmatic origin.

(5) The association of copper and uranium is not obvious.

(6) Cobalt and nickel are intimately associated; nickel shows a special affinity for uranium.

(7) The magmatic metallogenic origin (pneumatolitic and hydrothermal) seems to be as follows:

1st phase: Formation of the magnesite vein and magnesium enrichment of the Mine Series dolomite.

2nd phase: Deposition of the uraninite.

3rd phase: Occurrence of selenium (in an unknown form), molybdenite, and monazite, and chloritization of certain rocks of the Mine Series.

4th phase: Deposition of the cobalt and nickel sulphides (vaesite, cattierite and varieties). Compression of the deposit and crushing of the sulphides; dolomite deposition.

5th phase: Copper deposition.

(8) Hypogene processes gave rise to siegenite (in part), digenite, covellite, umangite, an unidentified blue selenide, native gold, and melonite.

(9) Included with the supergene minerals are

siegenite (in part), all the uranium minerals other than uraninite, and quartz.

ACKNOWLEDGEMENTS

In conclusion, the authors wish to emphasize that this study is the result of work by a team of geologists who should have the credit of having gathered the data on which the present work is compiled. The authors have endeavored to be faithful interpreters of the inspiration and advice of their chief geologist, Mr. H. Schuiling, to whom they express their deep gratitude.

They wish to thank the Union Minière du Haut Katanga for having entrusted them with this project.

Areas Geologically Favorable to Occurrence of Thorium and Uranium in Brazil

By Djalma Guimarães,* Brazil

Considering the vastness of the Brazilian territory an attempt is made to single out, on the basis of actual geologic knowledge, the areas more likely to hold significant uranium and thorium deposits.

INTRODUCTION

A novel tectonic-physical interpretation of the western Mediterranean has been produced recently by Glangeaud. It is founded on structural and paleogeographic characteristics and is indeed worth attentive study by geologists aiming at the solution of Brazilian tectonic problems.

The present writer has laid down his interpretation about the geologic evolution of sialic Afro-Brazilian blocks that were to uplift the Brazilian shield. Final causes, however, were not studied; but drift of continents was nevertheless accepted as an ascertainable phenomenon. At any rate, there is no need to invalidate the cartesian philosophy, as Glangeaud did, to support the belief of causes really subsequent instead of primary, as has been thought hitherto. Glangeaud states that polar drift, or drift of axis of rotation of the earth, and lunisolar attraction incident practically on the whole globe, seem to constitute geonomic phenomena of major import. It appears incontrovertible that polar drift must be ascribed to some cosmic cause, probably of a level of primariness diverse from that of lunisolar attraction.†

As regards the writer's interpretation, expounded in Bulletin No. 88, DFPM, Rio de Janeiro, the following Glangeaud points, stated in his Introduction, are worth referring to:

1. Development of littoral zones distinguished by nearly permanent disequilibrium is function of variability of thermo-dynamic gradient along border of continents;

2. When crustal units stand apart, no important interaction occurs. Borders undergo monoliminar evolution, independent and peculiar to each unit.

3. Utterly diverse phenomena arise upon reproduction of relative horizontal distance amid continents, whereat increase of range of biliminar phenomena and tangential effects are conducive to overlapping of continental units.

These points fit perfectly into the interpretation given in Bulletin No. 88 concerning the development of the Proterozoic geosyncline that has taken place from Huronian orogenesis to final cratonization of Archeo-Algonkian formations lying between Serra do Espinhaço, (formerly a range), and Serra do Mar.

Caledonian cratonization of continental platform east of Serra do Espinhaço, that is, consolidation of Proterozoic sediments, must have brought paroxysmal tangential stress to a close. Then, as pointed out by Glangeaud, regional isostatic compensations rose in their stead. And this seems to be exactly the "nearly permanent disequilibrium" which subsisted right on through the Tertiary.

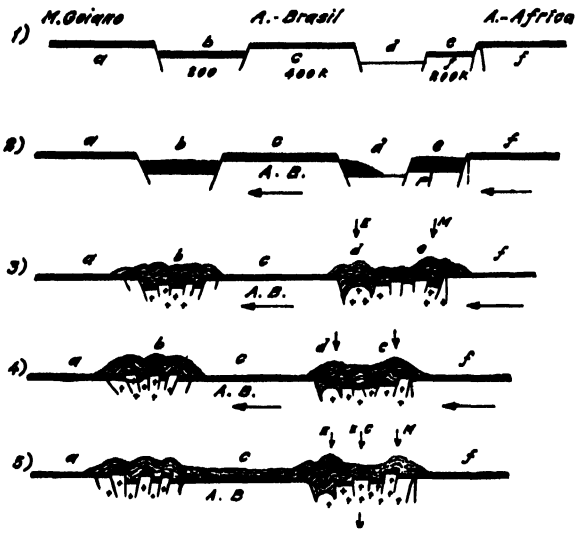
As regards the overlapping of a western continent (Archeo-Africa) on Archeo-Brazil (São Francisco basin and mid-North section of the country), the writer has described a permanent isostatic disequilibrium of Archeo-Brazil. The result would be spasmodic displacements ascertained to have occurred in the late Mesozoic in the area west of the São Francisco basin, and in the late Tertiary and Pleistocene at Serra do Espinhaço and eastern adjacent ground. Peneplanation of higher lands disturbed the equilibrium so much more too.

Field observation by de Morais corroborates the reality of a continental overlap. He has reported a geoclase along which Algonkian formations moved over the Ordovician-Silurian of the Bambuí Series, while the same evidence has been noted at the foot of Serra Mineira. The geologist W. Belezkij is to confirm in a forthcoming work the existence of a geoclase lying nearly NS along which masses drifted westward. And deep secondary folds, myllonization (ultramyllonites) and diaphtoretic phenomena along Serra do Espinhaço bear out such geotectonic feature.

Further evidence supports the writer's concept on the evolution of the Brazilian shield. Geotectonic surveys show that between the Goiaz massif and Archeo-Brazil no granitization of Proterozoic formations is to be found, except of Huronian diastrophic time; while the Caledonian would have witnessed epizonal metamorphism, as clearly indicated by the quartz veins of Serra dos Cristais and other places. It thus seems reasonable to believe in a

* Instituto de Tecnologia Industrial, Belo Horizonte, Minas Gerais, Brasil.

† The notion that the poles are drifting is incorrect. It is a matter of relative motion, whereby sialic shell drifts relatively to simatic shell and earth nucleus. Hence the apparent drift of poles with respect to continents.



a) ARCHEOZOIC MASSIVE OF GOIAS
b) MARINE SUBSIDENCE BASIN
c) ALGONKIAN GEOSYNCLINE
d) ARCHI-BRAZIL (S. FRANCISCO BASIN)
e) PLATFORM OF THE ARCHI-AFRICAN CONTINENT
f) ARCHI-AFRICA
M & E - AXES OF HURONIAN OROGENESIS;
E-PRE-ESPINHACO FOLDINGS;
M-PRE-SERRA DO MAR FOLDINGS
E. C. - AXES OF CALEDONIAN FOLDINGS
1) PRE-ALGONKIAN PHASE
2) PROTEROZOIC SEDIMENTATION
3) HURONION OROGENESIS WITH JOINING UP OF CONTINENTAL BLOCKS
4) PENOKEAN OROGENESIS, FINAL CRATONIZATION OF PROTEZOROIC SEDIMENTS
5) MARINE TRANSGRESSION IN ARCHI-BRAZIL DURING THE ORTOVINCIAN

Figure 1. Scheme of the geodynamic evolution of the Brazilian shield

rather deep Caledonian focus of granitization restricted to underlying Archean formations. This would mean that between the Goiaz massif and the S. Francisco basin there has been a deposition graben and not strictly a geosyncline. On the other hand, between Serra do Espinhaço and Serra do Mar, Caledonian granitization affected the Minas and Lavras Series reaching out through the Archeozoic substratum. This is supported by plenty of evidence, including the countless pegmatite veins yielding uranium-bearing minerals and monazite 370 to 400 million years old.

Constitution of Serra do Mar reveals tectonics of ancient orogenesis. Steady erosion and lasting tectonic activity would have raised the Huronian tectogene, an igneo-metamorphic nucleus with slightly granitized gabbroic and dioritic rocks as chief components. Works by Lamego, Guimarães and others, have ascertained the continuity of such formation from Rio de Janeiro to the State of Bahia. Prolonged tectonism that occurred in late epeirogenic stage indicates a liminar feature of Huronian-Penokean orogenesis, that is, the former existence of a continental border along the present Serra do Mar. The hypothesis has been supported by additional arguments in the aforesaid Bulletin No. 88; thus the Atlantic platform would be a remnant of ancient continent lying broken up along a Paleo-Mesozoic peneplane west of Serra do Mar. The likelihood of a marine trough adjacent to Archeo-Brazil on the eastern side has been studied in another paper; sedimentary facies of the Minas Series, particularly of the tectonic trough of mid Minas Gerais, seem to justify this belief.

Figure 1 represents relative positions of continental platforms at the outset of the Proterozoic, in accord with all geologic knowledge to date and the writer's personal observation. The approaching of continents released tectonic orogenic effects subsequent to the long-lived filling up of the geosyncline east of Archeo-Brazil and sedimentation at the western subsident basin, besides depression of the western border of Archeo-Africa, presently mid Rio Doce, Rio Jequitinhonha and State of Bahia's mid eastern area. Orogenic axes would have been along Serra do Espinhaço and Serra do Mar; cratonization of formations of the geosyncline displaced folding axes to opposite direction; the Caledonian would have led finally the chief folding axes half way up the Archean cupola formed by tangential thrust, and concomitant crushing of Proterozoic formations of Serra do Espinhaço, by the western edge of the Archeo-Africa against the Archeo-Brazil border.

Paroxysmal Caledonian stage would have released magmatic processes that produced extensive and intense granitization of Archeozoic nucleus and overlying Proterozoic formations. Steps of such geodynamic development are represented in Fig. 1, steps 1 to 5. Final agglutination of continent is shown in the ideal cross section, Fig. 2.

The Griggs hypothesis seems inadequate to account for the formation of a continent as large as that of South America. Geophysical evidence, besides the fact of the viscosity of sima beneath the sialic shell, allow certain skepticism about effects of convection flows in the crustal zones. However, if the Griggs hypothesis is ascribed an auxiliary function—in the Glangeaud manner—it becomes much more satisfactory and significant. Other primary causes would be responsible for the approach

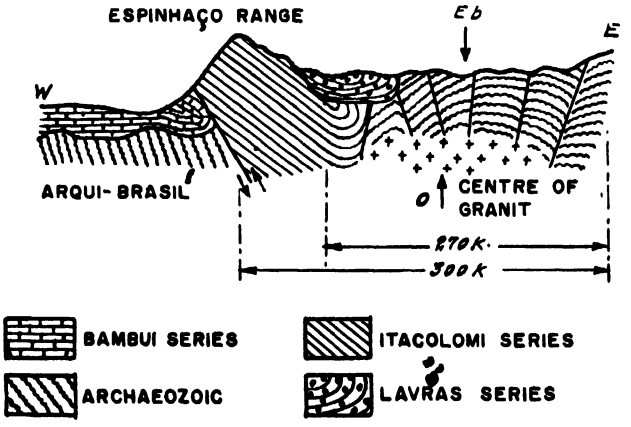


Figure 2. Cross section

of continents and break of thermodynamic equilibrium in the upper zones of sima would drive convection streams upward to sub-sialic zones, thereby adding to the continental thrust, and consequently modifying the direction of the drift and the style of tectonic deformity and displacement.

It is stimulating, however, to note that modern authors show a less hostile attitude towards the Wegener theory.

The mechanism of continental motion and the origin of driving forces are being extensively investigated.

The formation of the continent introduced an entirely different sequence of geologic phenomena. Cratonization went on throughout the Silurian and affected the ancient Proterozoic geosynclinal province. Granitization of Algonkian sediments and extreme metamorphism of Archean substratum consolidated at last the newly formed continent. Hydrographic basins began to form, one of them covering Archeo-Brazil, another surrounded by Serra do Espinhaço and Serra do Mar, still a third one developing in the Archeo-Africa shield. Chief water streams took the northern direction, while the African one extended the peneplanation commenced prior to Silurian times. Erosion lasted till the early Mesozoic in Archean ground subject to frequent epeirogenic displacements. Erosional cycle west of Serra do Mar did not affect the stability of the Archeo-Proterozoic massif, but introduced isostatic effects in the ancient Archeo-Brazil and Archeo-Africa borders.

In the Mesozoic the crust must have subsided along the African peneplan because of continental drifting forces applied in opposite directions. Mobility of Serra do Mar seems to have remained unchanged till the Pleistocene, but always of epeirogenic kind. Paleo-geographic development of the two other hydrographic systems was described in Bulletin No. 88, and need not be repeated here.

Purpose of the writer is to explain his general view on the geodynamic evolution of the massifs that composed the Brazilian shield.

Further study of details, however desirable, is quite hard to pursue. Most mid-Proterozoic formations have obviously been destroyed by glaciation at the end of that era and by the formation of the hydrographic basins described, till final peneplanation at the close of the Tertiary. A perfunctory glance at the geologic map of Brazil (by Oliveira and Leonardos, 1946) will explain the extensive and deep erosion that marked Serra do Mar and Serra do Espinhaço. The area encompassed by the two Serras would constitute the basin of a huge waterflow that discharged into the Paleo-Mesozoic sea located in the present States of Piauí and Maranhão and the northern section of the State of Goiaz.

During Ordovician and Silurian ages said Mediterranean sea extended southward, covering the mid-west of Minas Gerais, precisely where the Bambuí Series lies now. Proterozoic formations of the Rio Doce and mid Rio Jequitinhonha basins underwent

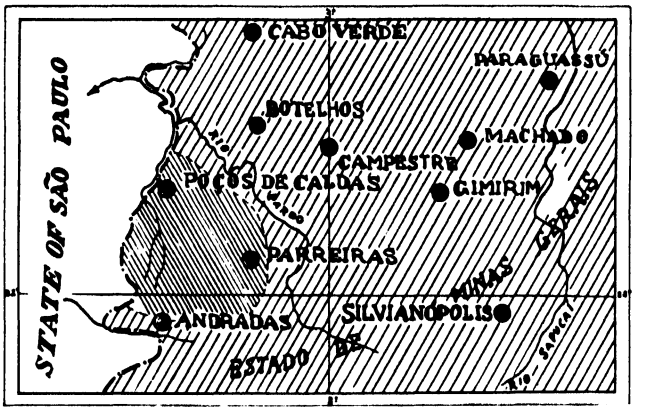


Figure 3. Poços de Caldas plateau

erosion to such an extent that today only remnants in the shape of islands of granitized rocks of the Minas Series are to be found.

METALLOGENETIC EPOCHS

Stratigraphic and tectonic evidence, together with petrographic research, produced chronogeological data that corroborates age determinations previously inferred for Proterozoic and Paleozoic diastrophisms, namely: (1) Huronian (orogenic); (2) Penokean (orogenic); (3) Cambrian (epeirogenic); and (4) Caledonian (orogenic).

These are the major upheavals of the crust; minor displacements may have occurred also in different places of Brazil. One of them is the epeirogenic diastrophism at the end of Archeozoic time and beginning of the Proterozoic, characterized by volcanic activity through most of the lower Algonkian.

Age ascribed to potassium-bearing pegmatites has likewise been checked to be correct. Their formation is related to the Caledonian orogenic phase. Therefore the difference between Proterozoic and Caledonian tectonic processes becomes quite obvious. Caledonian tectonics in Proterozoic areas east of, and along, Serra do Espinhaço, shows a more definite fractured character. This determined the prevalence of vertical displacements, which ultimately produced graben and horsts.

Results obtained employing geochemical criteria related to tectonic evidence are of great value. This method of geological investigation solved difficult problems of economic geology, especially in pre-Cambrian grounds. Recent data tends to establish the style of development of the Proterozoic geosyncline and the nature of the environment formerly prevailing in areas of sedimentation of iron- and manganese-bearing rocks. The reality of an Archean continent agreeing with most of the S. Francisco basin, whose marine platform reached the present right bank of Rio das Mortes, has been ascertained by geochemical procedure too.

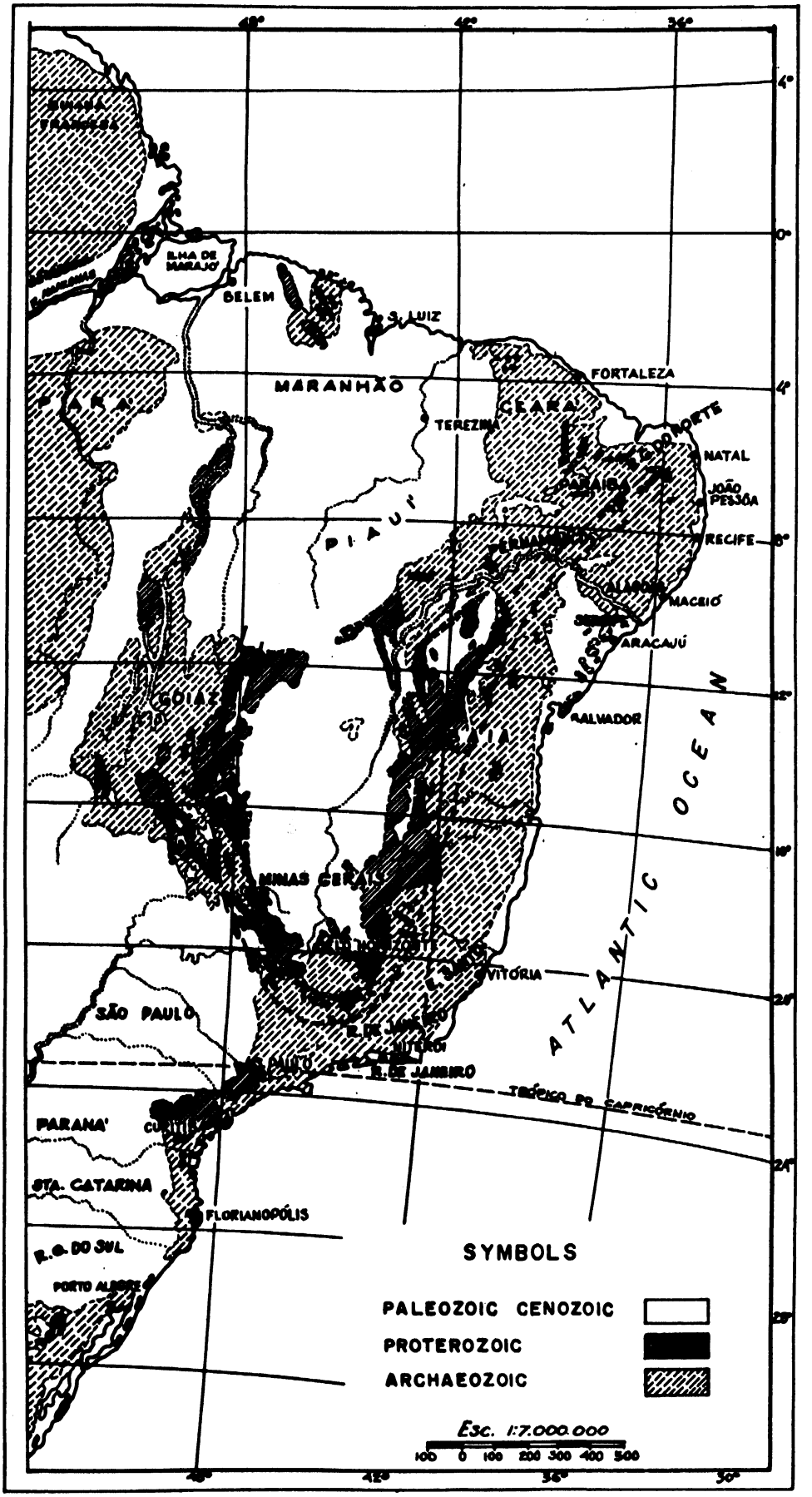

ILHA DE MARAJÓ
BELEM
S. LUIZ
MARANHÃO
FORTALEZA
CEARÁ
TERESINA
R. G. DO NORTE
NATAL
PARAÍBA
JOÃO PESSÔA
PIAUÍ
PERNAMBUCO
RECIFE
ALAGOAS
MACEIÓ
SERGIPE
ARACAJÚ
GOIAZ
BAHIA
SALVADOR
ATLANTIC OCEAN
MINAS GERAES
ESPIRITO SANTO
VITÓRIA
SÃO PAULO
RIO DE JANEIRO
NITERÓI
S. PAULO
R. DE JANEIRO
TRÓPICO DE CAPRICÓRNIO
PARANA'
CURITIBA
STA. CATARINA
FLORIANOPÓLIS
R. G. DO SUL
PORTO ALEGRE
SYMBOLS
PALEOZOIC CENOZOIC
PROTEROZOIC
ARCHAEOZOIC
Esc. 1:7.000.000
100 0 100 200 300 400 500
4°
0°
4°
8°
12°
16°
20°
24°
28°
48°
44°
40°
36°
32°

Figure 4

AREAS MOST LIKELY TO YIELD URANIUM AND THORIUM IN BRAZIL

The premise above tenders possible a choice of areas of greater possibility for prospecting for uranium and thorium.

If systematic prospecting for radioactive ore is to be as economical as possible, it must necessarily comply with requisites of geological order. In other words, it must conform with the latest geological knowledge about mineralization, which took place in several diastrophic stages of the Brazilian shield. Since loci of intense mineralization are closely related to major lines of fracture and to the geotectonic belt, it follows that these should accurately be investigated ahead of any other step.

Bulletin No. 88, DFPM, Rio de Janeiro, "Archeo-Brazil and its Geological Evolution", by the writer, expounds a thorough interpretation about the constitution of the Brazilian shield, achieved by agglutination of former Archeozoic continents. These components held, amid them, marine troughs gradually filled in the Proterozoic age. Such geosynclines became the focus of recurrent diastrophic phenomena, involving the geochemical upward migration of elements that were to form mineral deposits.

Ideal restoration of original, continent-forming remnants, and recognition of their shape, leads to knowledge on the geotectonics that went on till the Paleozoic age. After the Mesozoic, only epeirogenic processes seem to have occurred which, as far as the geochemistry related to formation of mineral deposits is concerned, were merely of restricted range.

Thus present knowledge on the dynamics of the Archean masses explains the choice of a belt most likely to yield uranium and thorium deposits. It begins in the northeastern pegmatite region which yields tantalite, beryl, amblygonite, spodumene, uraninite, etc. (see map). Extending southward, it crosses the State of Bahia through Paulo Afonso and Serra da Jacobina and Itambé area; as well as Minas Gerais as far as the Rio Doce basin. Turning westward, it reappears in the region of S. J. del Rey and reaches the Poços de Caldas plateau. Then it takes a northern direction, through Tapira, Araxá, Salitre, and extends toward Goiaz, in which State it is probably resumed in the contact of the Minas Series with Archean formations. All deposits known belong to said tectonic belt. To obviate loss of time and money it is most advisable to abide by the theoretical criterion described, unless new evidence shows the desirability to conform to a different directive.

As to the arguments above, the relative worth of known deposits could be discussed as follows:

(*a*) Northeastern Zone: uranium-bearing minerals have been found in the tantalite- and columbite-bearing pegmatites only. As to the two latter minerals, statistics show that 5000 to 7000 tons of ore are required to yield 1 (one) of tantalite. Current quotation of tantalum-ore justifies mining deposits as poor as that; but keeping in mind the price of uranium-ore, working these pegmatites out for recovering uranium-bearing species obviously cannot be regarded as economical at all.

(*b*) State of Bahia: the auriferous zone of the State of Bahia holds conglomerates and sulphides, gold-bearing and arseno-sulphide-bearing lodes. This is a promising area for uranium, particularly at Serra da Jacobina.

(*c*) State of Minas Gerais: the townships of Teofilo Otoni, Salinas, Ferros, Guanhães, Ubá, Pomba, Sabinópolis, hold uranium-yielding pegmatites containing polycrase, fergusonite, samarskite, etc., as well. As to these pegmatites and the possibilities they offer concerning uranium, their economy should be regarded similar to the northeastern ones. As to the quadrilateral located in the mid zone of the State, the diamond district at the northern zone, and Serra da Canastra at West, geology advises aero-scintillometric preliminary investigation. NW and W of Serra da Canastra, the Araxá deposit lately discovered marks a decidedly satisfactory occurrence. In the vicinity of Serra do Salitre interesting indications have also been found.

(*d*) The writer has already pointed out the convenience of an aero-scintillometric survey of volcanic centers of alkaline rocks at Poços de Caldas in Minas Gerais, and Ipanema, Juquiá, Jacupiranga and the basin of Rio Ribeira in the State of São Paulo, to define the areas of greater radiometric anomaly.

(*e*) Chances seem poorer south of the State of São Paulo. The Permo-Carboniferous glaciation which destroyed nearly all Proterozoic formations mineralized in the Huronian, Penokean and Caledonian stages of orogenic diastrophism does not favor at all the search for uranium-yielding minerals.

From a practical standpoint, evidence hitherto found can be regarded quite sufficient for exploitation, almost immediate, of the recognized deposits that are expecting methodical and thorough investigation. As regards the Araxá deposit, the Government of Minas Gerais, its owner, has already taken the necessary steps for proper exploitation. The occurrence has been checked to be the largest niobium deposit of the world. Uranium and thorium will be recovered as by-products.

The uranium-bearing caldasite deposit of Poços de Caldas in Minas Gerais has been recognized by de Morais merely by preliminary investigation. Whereas available alluvial and eluvial ore has been estimated with reasonable approximation, knowledge about proto-ore is restricted to its occurrence in veins and stockworks. The reserve itself is thus still unknown for lack of data, which of course prevents location of places to be worked economically.

Re-examination of the neighborhood of Serra do Salitre is desirable to find radioactive outcrops and to study its nature.

Known Occurrences of Uranium and Thorium in Brazil

By Luciano Jacques de Moraes,* Brazil

GEOLOGICAL DISTRIBUTION OF DEPOSITS

In connection with geological formations existing in Brazil, uranium and thorium occur as follows:

(*a*) In complexes of archaeozoic and proterozoic rocks formed of gneiss, granite schist, quartzite and other metamorphic rocks, with veins of quartz and pegmatite running through them, as found in various regions of the Country.

(*b*) In eruptive alkalic rocks from the upper Triassic Age, found on the Poços de Caldas Plateau between Minas Gerais and São Paulo, and consisting of foyaites tinguaites and other types of the same group; i.e., magma which also occurs in the Araxá region of Minas Gerais and other points in Brazil.

(*c*) In sedimentary phosphates associated with limestones of the Upper Cretaceous Period, found in Olinda, Pernambuco; and containing a small percentage of uranium, as is generally the case with similar ores in Northern Africa, Egypt, Palestine, and the United States of America.

(*d*) In reputedly pliocenic sediments containing monazite, which form the so-called "Barreiras" ("Barriers") along the coast of the States of Bahia, Espírito Santo, and Rio de Janeiro.

(*e*) In alluvium and residual deposits of recent formation. Within this group fall the monazite-bearing shore residual deposits in the foregoing States, the alluvium deposits of rivers presenting the same metal as widely found in the Hinterland of the Country, and alluvium deposits derived from the two first categories mentioned before.

Figure 1 points out where uranium and thorium ores chiefly occur.

Figure 2 details the area to the east of Minas Gerais and south of Bahia where these minerals are found. Mica-bearing pegmatites, semi-precious stones, and lithium, columbium and tantalum ores are also present here.

To category (*a*) above, belong the pegmatites with uranium found in Perús 28 (São Paulo); and with samarskite and monazite in Grama and Vargem Grande do Sul, (São Paulo); with samarskite and xenotime in Machado, Campestre, and around Poços de Caldas (Minas Gerais); with uraniferous ores of the samarskite, microlite and monazite groups in São João d'El Rei, in the (regions) of Tocantins de Ubá, Ubá and Miradouro, Antonio Dias, Nova Era, Santa Maria de Itabira, Ferros, Conceição do Mato Dentro, Sabinópolis and Itamarandiba (Minas Gerais), in the (regions) of Castelo and Afonso Claudio, (State of Espírito Santo), and of Itambé (Bahia); with thorite, in Massaranduba (Santa Catarina), discovered by H. Putzer. In the aqua marina and bismuth deposits of Brejaúba (Minas Gerais) uraninite has been found; this mineral has also been extracted in Ferros, and Piata (Bahia), and in the Seridó zone (Rio Grande do Norte).

In a recent work of prospection, the geologists Max White, Gene Tolbert, and Helem Bessa registered radioactivity in the gold zones of Jacobina (Bahia), an ancient proterozoic formation of the same type as the Witwatersrand "Reef" in the Transvaal, now an important source for uranium as a by-product from the gold exploited there.

Within category (*b*) above, come the uraniferous zirconium ores of Poços de Caldas, and the crumbling nephelinic rocks with high-grade contents of rare earths, found in Morro do Ferro; and the apatite and nephelinic syenites in the mountains of Araxá and Salitre, also with a high grade of thorium and rare earths, but so far revealing a low grade of uranium.

Prospection for uranium should be carried out intensively in areas of nephelinic rocks such as Lages and Anitápolis (Santa Catarina); Jacupiranga, Morro do Serrote, Cananéia, Juquiá, Ipanema and São Sebastião Island (São Paulo); in the massifs of Itatiaia and Tinguá, Cabo Frio Island, Alcântara, Sacramento, and Morro Grande de São João (State of Rio de Janeiro); the ranges of Marapicú, Mendanha and Gericinó, in the Federal District; the area between Araguáia and Goiás City; Pão de Açúcar (Mato Grosso); the neighbourhood of the River of Bruxas (Paraíba); in the islands of Trindade, Fernando de Noronha and the rocks of São Pedro and São Paulo.

Deposits of other categories are being studied, specially phosphates in Olinda; and monazitic sands along the coast of Espírito Santo. But the alluvial deposits of running water in the hinterland, where monazite has been registered, deserve careful investigation.

Petrified wood, lignites, and abundant oil shales have been left out in this study. Although used as raw material for uranium in other countries, testing with Geiger counters has revealed that in Brazil they have low radioactive contents.

* Departamento Nacional da Produção Mineral, Rio de Janeiro, D.F., Brasil.

Figure 1. Occurrences of uranium and thorium in Brazil

Only Triassic reptile fossils and coprolites both of permian and Triassic formation in Santa Catarina, Rio Grande do Sul, and Marahão have shown somewhat higher radioactivity.

In the search for uranium ores in Brazil, special consideration should be given to the rocks geologically similar to those where uranium is being exploited in the United States of America and other countries.

Thus, in the west of the State of Paraiba, the basin of the Rio do Peixe, of continental origin and the Mesozoic Age, has a certain likeness in rocks and fossils to the Upper Jurassic Morrison Formation of the Colorado Plateau, USA. The same applies to the sedimentary basin of Iguatú in Ceará; the Serra de Araripe, lying between Ceará and Piauí; the Jatobá series in Pernambuco; Alagôas, Sergipe and Bahia; and the Recôncavo series. All of them show the same characteristics and contain oil shales or fossil plants in the form of silicified and carbonized wood or lignites, the presence of which has been associated with the occurrence of uranium ores in Colorado, Utah, New Mexico, and Arizona. In the western regions of the United States other features, which we find in northeastern Brazil, have also led to the exploration of uranium ores for instance: light coloured or greyish sandstones of fluvial origin and arkosian nature, interstratified with shales and sandstone, often related to tectonic movements.

Although generally held to be Cretaceous, there is doubt as to the true age of the sedimentary basin of the Recôncavo, lying between the Tertiary and the crystalline shield. After studying the fauna yielded by drilling cores, Paleontologist Sohn related it to the Morrison formation (1946, Report of the National Petroleum Council of Brazil).

In some of their formations these Brazilian mesozoic basins, from the lithologic point of view, also

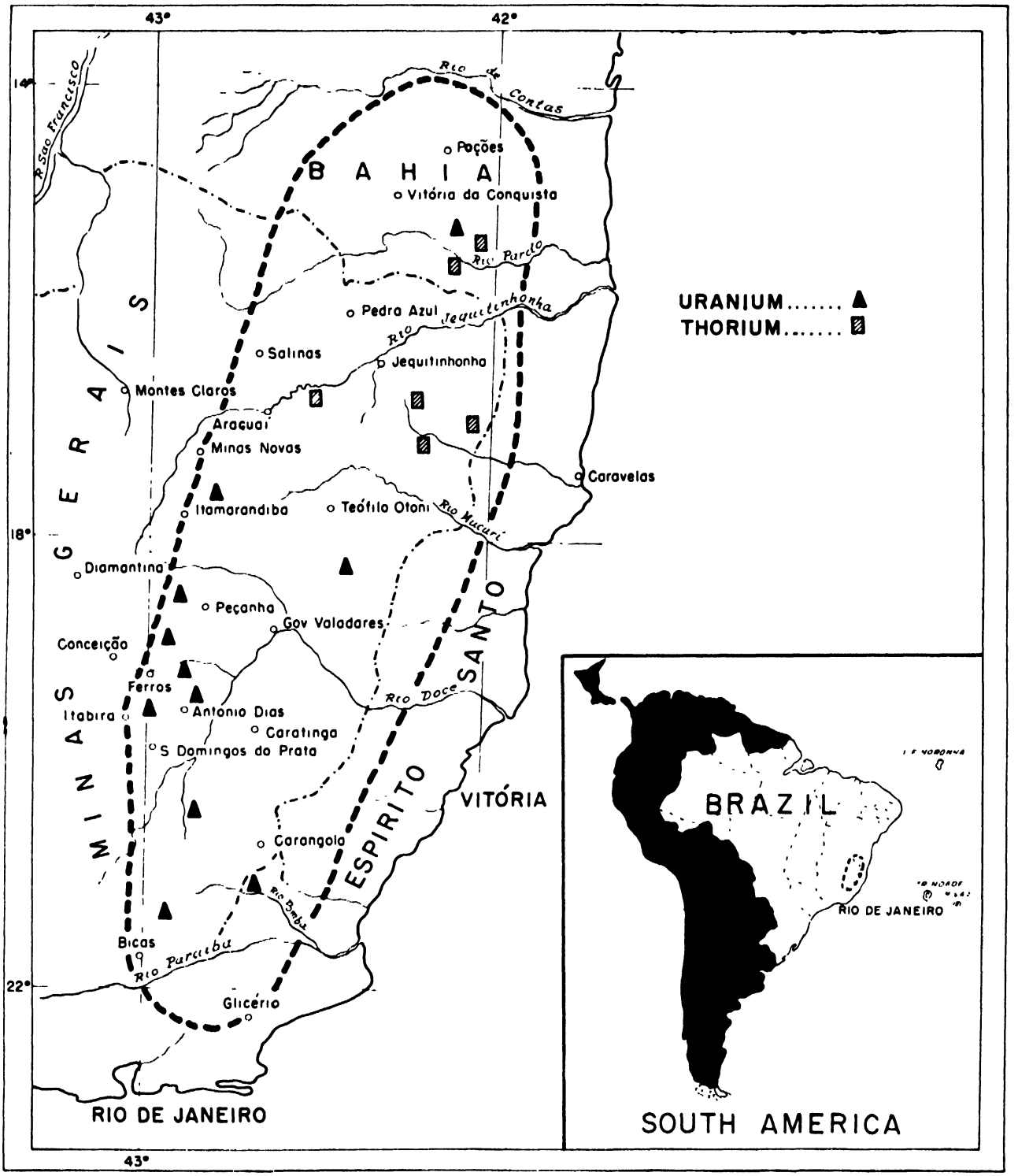


Figure 2. Principal region of occurrence of pegmatites with uranium and thorium minerals in Brazil

*

show likeness to the so-called "Shinarump Conglomerate" and to the Chinle Formation of the Colorado Plateau.

Most likely these Brazilian sedimentary formations hold uranium deposits for, not only do they lie upon granite-gneissic and schistose rocks, but also have been formed from the crumbling of the identical outcropping rocks cut by pegmatites which, in many other places, have proved to contain uranium and thorium. The same may be said in respect to the sandstone underlying the cretaceous limestone of the Chapada do Apodí, which stretches over Rio Grande do Norte and part of the Jaguaribe region, in Ceará. Moreover, our coal deposits should be prospected for uranium, in view of the fact that, in several places in the United States, coal layers have revealed uranium contents, even though of too low a grade to be considered as ores.

Since it has been proved that bituminous and anthracitic coals are not radioactive, and that uranium is only found in poor grade lignites and subbituminous coal there is here a new field of prospection in Brazil where the coal so far discovered has been of the semi-bituminous or subbituminous and semi-anthracitic types. These are known to occur in the Southern States, in the Piauí, Maranhão area, at Rio Fresco (Pará), Caçapava (São Paulo), Rezende (State of Rio de Janeiro), Gandarela and Fonseca (Minas Gerais), Itaparica (Bahia), Petrolândia (Pernambuco) and in the Amazon basin (lignites).

Our permian and mesozoic formation, of continental origin, should also be prospected for uranium, particularly the regions answering to the characteristics already specified, and those lying close to areas of granite-gneiss and crystalline schist intruded by granitic or alkalic magma.

Regions where copper is exploited also call for survey, for it must be remembered that uraniferous deposits at Great Bear Lake (Canada); in the Upper Katanga regions (Belgian Congo); and at Joachymov (Czechoslovakia); are found in association with copper, silver, lead, and zinc ores and in metamorphic rocks similar to our proterozoic formations in São Paulo, Minas Gerais, and elsewhere. Special mention must be made of the copper ores in Caraiba-Curuçá (Bahia); Viçosa and Aurora (Ceará); Pedra Branca, (between Paraiba and Rio Grande do Norte); Itapeva e Apiaí (São Paulo); Lavras, Encruzilhada (Rio Grande do Sul); and Pitanguí (Minas Gerais).

For the same reason we should also analyse the lead and zinc deposits often containing copper at Ribeira do Iguape, (São Paulo and Paraná) of the Ribeira series, both of proterozoic formation as well as the silurian deposits of the Bambui series in Minas Gerais in the regions of Januária-Itacarambí; Ribeirão do Chumbo; in Abaeté and in the Vazante Zone; in the northwestern parts of the States, covering also other layers or occurrences of minor importance.

After these general considerations have been taken into account, let us look closer into the two principal groups of radioactive minerals to which special attention has been given in Brazil, within recent years: minerals containing fossil elements, found in the northeast part of the country [category (*a*)]; and zirconium and uranium deposits in the Poços de Caldas Plateau [category (*b*)].

MINERALS CONTAINING FOSSIL ELEMENTS

These are extensively found, chiefly in Rio Grande do Norte and Paraiba (Fig. 3). They have been located in the ancient criptozoic rocks prevalent in these two States, along the boundary line between Paraiba and Ceará and in the central area of the latter State. Though their presence had been known before, it was the need for strategic material during World War II, that led to the discovery of new sources of radioactivity minerals in northeastern Brazil, nearly all of them in the Seridó basin.

In 1954, the writer had the opportunity of doing some prospection in the region. Many new sites of radioactive minerals were then located. After studying the material collected in the field, the radioactive minerals found in the northeast of Brazil were classified into three groups: (1) those containing uranium, such as uraninite, zircon, and niobo-tantalites—the latter group including betafite, samarskite, fergusonite, and euxenite—besides uraniferous tantalite, columbite, and tapiolite; (2) those presenting high-grade percentage of thorium, such as monazite, fluocerite, and thorianite; (3) the allanite group, containing cerium and other rare earth minerals and, occasionally, uranium.

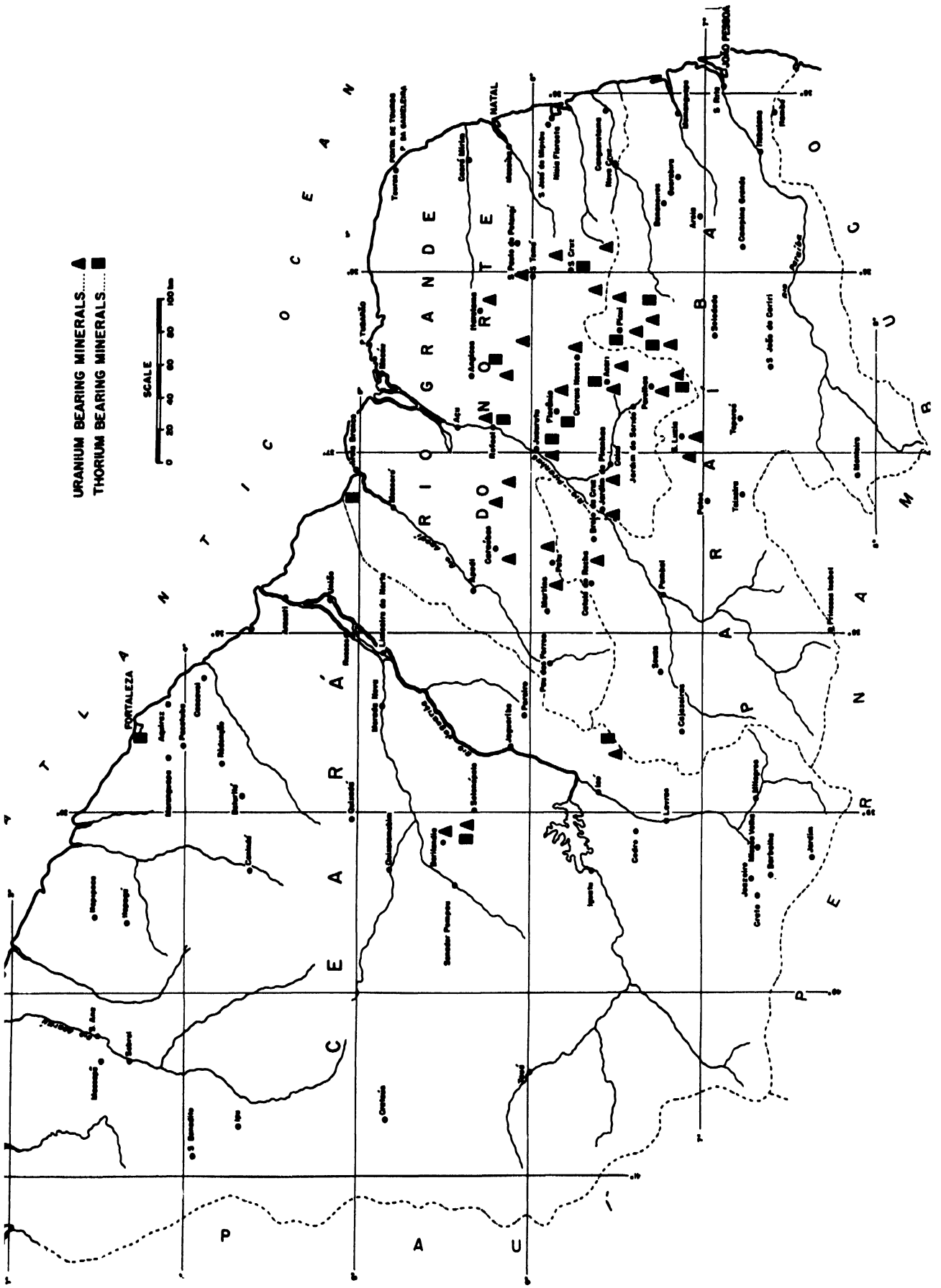
Uraninite and its alteration products such as gummite, torbernite, and autunite were only located at Seridó in the counties of Parelhas and Carnaúba dos Dantas, and generally found in the same pegmatite deposits where tantalite, columbite, and beryllium are exploited. The niobo-tantalites of the betafite-samarskite families are usually present in these pegmatite deposits.

Several years ago samarskite was discovered at Poço do Rancho, near Mata Grande (Alagôas); and in 1953, de La Rue and Dias registered the presence of gummite in Arcoverde (Pernambuco).

Monazite was recently found in the counties of S. Rafael and Florânia in alluvium deposits. It was also registered in the counties of Acarí, Carnaúba dos Dantas, Currais Novos, and other places in Seridó (Rio Grande do Norte); and in Piaui (Paraiba), here both in alluvium deposits and in pegmatites.

Allanites ores occur in the counties of Santa Cruz, Coronel Ezequiel, Angicos, and S. Rafael (Rio Grande do Norte).

Except in the case of the monazite found in alluvial deposits, in our opinion radioactive ores in the Northeast of Brazil can only be economically exploited as by-products, wherever tantalite, columbite, beryllium, and lithium are mined.


URANIUM BEARING MINERALS
THORIUM BEARING MINERALS
SCALE
0 20 40 60 80 100 km
O C E A N O A T L Â N T I C O
RIO GRANDE DO NORTE
PARAÍBA
PERNAMBUCO
CEARÁ
PIAUÍ
MARANHÃO
PARÁ
FORTALEZA
NATAL
JOÃO PESSOA

In the samarskite betafite group, the uraniferous deposits of highest concentration seemed to be in the counties of Acarí, Carnaúbas, Almino Afonso and Patu (Rio Grande do Norte), Catolé da Rocha, and Picui (Paraiba).

At Icozinho (Ceará), fluocerite and thorianite were discovered in Brazil for the first time.

The results of this survey lead to the conclusion that the time is not far, when Brazil will hold an important place as a supplier of material for nuclear fission.

THE URANIFEROUS ZIRCON ORES OF POÇOS DE CALDAS

Though autoradiographic experiments carried on some time ago by Resk Frahya had registered the presence of radioactive elements in the zirconium deposits at Poços de Caldas, the matter only acquired real interest after the high grade of uranium contained in them had been tested in samples sent to the US Geologic Service.

Under the auspices of the National Research Council of Brazil, geologists White and Tolbert, experts in radiometric survey, undertook the prospection of the region.

Their work revealed these zirconium ores to have radioactivity, in some cases the high grade of the uranium reaching up to 1% and, in rare instances, topping 2%. It has also been proved that not only the low-grade zirconium ores but also their residues and country rocks are radioactive, their uranium contents being some times higher than those of high grade zirconium ores.

The Poços de Caldas zirconium deposits stretch over 460 square kilometers i.e., approximately over half the area of alkalic rocks in the Plateau. They are located in a rectangle, the longer sides of which run 37 kilometers in an east west direction, from Cascata to Pocinnhos do Rio Verde on one side, and south of the zirconium deposits of Chapada, Lagoa Dourada, Campos do Aterrado and Potreiro Árvore Grande, on the other. The smaller sides measure 16 kilometers.

Zirconium ores are more concentrated along the diagonal line of the rectangle, running for about 30 kilometers between Cascata and Potreiro Árvore Grande.

Radioactivity, as registered by Geiger counters, is more intense in the iron ores at Morro Ferro and in the crumbling alkalic rocks found on the slopes of the same mountain where it reaches its maximum.

Analyses of the clay resulting from the crumbling of the alkalic rocks of Morro Ferro revealed it to hold 14.344% of rare earths, 2.330% of thorium oxide and only a negligible percentage of uranium.

Next in the scale of radioactive contents come the vein zirconium ores grouped at Taquari, Dona-Irene, Itororó-Três Barras, Serrote-Quirinos-Brígida-Gigante, Campo do Villela-Mourões, Lagoa Dourada-Aterrado-João Diogo, Cascalho Branco, and Serra Grande, areas.

Copious material gathered at these sites was carefully studied by Djalma Guimarães at the Belo Horizonte Institute of Industrial Technology.

It presented sufficient data for an estimate on the importance of the large reserves of uraniferous zirconium ores found in the Poços de Caldas Plateau.

From the point of view of their occurrence, these ores may be grouped as follows: (*a*) vein deposits where the ore is caldasite, occurring in veins and lenses in the alkalic rocks; (*b*) eluvial deposits, consisting of fragments of veins and lenses, which occur on the mountain slopes mixed with detritic material resulting from the breaking up and crumbling of conterminous rocks; (*c*) alluvial deposits chiefly formed by rolling delleyite, commonly called "fava" or "favão", and found on the beds formed by running water, in the present or in the past.

It may be added here, that aeroscintillometric and aeromagnometric surveys covering this same area have confirmed the results of the field-work spoken of.

The National Department of Mineral Production, of Brazil, is proceeding with the exploration of the uraniferous zirconium ores in Poços de Caldas, by means of drilling and underground work supervised by Resk Frahya.

Uranium in the Serra de Jacobina, State of Bahia, Brazil

By Max G. White,* Brazil

The discovery or uranium in the Serra de Jacobina was made in late 1953. The identification of uraninite was made in the Laboratories of the Departamento Nacional da Produção Mineral in Rio de Janeiro and of the United States Geological Survey in Washington. The field investigation of this occurrence are still in the preliminary stages and no evaluation can as yet be made of the magnitude of its worth as a reserve of uranium. Although the gold-bearing reefs have been examined at various localities, they have been studied in greatest detail at the Canavieiras Mine near the town of Jacobina and, for convenience, it is the general description of the occurrence at this mining property that is presented here.

The Canavieiras gold mine is 6 kilometers (by a narrow dirt road) south of the town of Jacobina in the north central part of the State of Bahia, northeast Brazil. Jacobina is accessible from Salvador, the capital city of the State of Bahia, on the coast by a dirt road; the road distance is about 360 kilometers. Although the town is not a scheduled stop of any commercial airline, it has an airstrip which may be used by small planes. The Estrada de Ferro Leste Brasileiro (Brazilian Eastern Railroad) connects the region with the seaport of Salvador.

The Serra de Jacobina, in which the Canavieiras mine is located, is a narrow prominent range that stands out in sharp relief over the adjacent plains and has altitudes of 600 to 800 meters with peaks up to approximately 1100 meters. The adjacent plains have an elevation of about 450 meters. The mine itself has an elevation of approximately 520 meters.

The gold ores in this region have been known and mined since the latter part of the 17th century. Most of the mining has been on a small scale, both of the ores and of the placer gold from the streams that drain off the serra. A few attempts have been made to establish large scale mining operations but these have failed for various reasons not always related to the tenor of the gold ore.

GEOLOGY

Little is known of the details of the geology of the Serra de Jacobina. General geological reconnaissance reports have been published by Branner[1], Williams[2] and Mello.[3] Capper Alves de Souza[4] published a detailed description of many of the gold mines and prospects in the serra.

Branner[1] described the rocks of the Serra de Jacobin and gave them the name Jacobina Series. The section includes mostly quartzites with some slates and schists, and conglomerate beds at the base, in the quartzite. Oliveira and Leonardos[5] state that the series commonly contains massive hematite interbedded in the quartzite. The hematite is of the "itabirito" type of iron ore found in the State of Minas Gerais. Oliveira and Leonardos consider the Jacobina series to be of Lower Algonkian age, corresponding for the most part to the Minas Series which contains the extensive iron ores in the State of Minas Gerais but partly also to the Itacolomí Series, also of the State of Minas Gerais. The conglomerates are basal and are restricted largely to the western flanks of the serra. So far the conglomerates are reported to have been found only in the southern portion of the serra, that is, from a few kilometers north of Jacobina south to the end of the range, a distance of about 25 kilometers air-line.

The conglomerates are the chief gold-bearing rocks of the region. Their similarity to the gold-bearing conglomerates of the Witwatersrand System of South Africa has been pointed out.[5]

The Canavieiras mine is near the base of the east wall of the canyon-like valley cut by Canavieiras Creek, a northward flowing stream. Bedrock in the stream bed on the mine property is a highly disintegrated, dark dike with strike nearly parallel to the enclosing sedimentary rocks. The geologic section at the property consists of an underlying white quartzite containing countless beds of hard silicified conglomerate beds, overlain by a white, barren, massive, hard quartzite that contains no conglomerate. The conglomerate beds range in thickness from a string of pebbles 2 or 3 centimeters wide to beds up to two meters thick. Most of the conglomerate beds are made up of gray to white quartz pebbles with diameter up to three inches, set in a white fine-grained matrix. This type of conglomerate is called locally "chabú". A small amount of gold is reported to have been produced from some of the thicker of these conglomerate beds. There are two very hard, gray, light

* Consultant, Conselho Nacional de Pesquisas, Rio de Janeiro, Brazil.

† The term "reef" is used locally, as in South Africa, for the gold-bearing conglomerates. For convenience, "reef" is adopted here.

to dark green, and chocolate brown conglomerate beds on the property containing zones of heavy sulphide mineralization—mainly pyrite. One, the Liberino reef,† has been opened in a small amount of development work by the mine operators; the other, the Piritoso reef, constitutes the main gold-bearing pyritic ore body of the Canavieiras mine. These are known locally as the "piritoso" type of conglomerate bed. The thicknesses of the quartzite-conglomerate formation have not been measured. A magnitude of thickness is obtained from the difference in elevation of the mine, stated as 520 meters, and that of the highest peak in the vicinity of the Canavieiras mine, said to be about 1100 meters, and reported to be of quartzite. The formations strike essentially north-south and dip 45 to 65 degrees to the east.

STRUCTURE

The Canavieiras mine is located on the east valley wall of Canavieiras Creek. The strike of the sedimentary formations, including the gold-bearing conglomerates, at the mine is about north-south. The dip of the rocks ranges from 45 to 65 degrees to the east. The gold-bearing reefs are exposed for a distance of no more than about 600 meters on strike on the mine property. They are cut off to the north by a nearly vertical fault. On the south they are covered by a heavy mantle of soil and, inasmuch as none of the reefs are exposed to the south of this mantle, they are either off by faulting or they pinch out.

The thickness and shape of many of the conglomerate beds are quite variable. They may thicken or thin out to a line of pebbles, and sometimes appear to be lens-shaped. Because of the close proximity of the beds, the variable thickness, and the pinching out of many of them, it is frequently difficult to trace a given bed along its strike length. gold-bearing reefs at the mine, have an average The Piritoso and Liberino reefs, the two pyritic gold-bearing reefs at the mine, have an average thickness of about 60 centimeters. They thin out to the north.

The outcrop thickness of the Piritoso reef where it is being mined is about one and one-half meters. This thickness is more or less maintained down dip all the way to the cutting face of the mine. The dip of the reef at the outcrop is 45 degrees to the east. At the 30 meter level and the 55 meter level the reef is cut by reverse faults, with displacements in each case of no more than two meters. Between the surface and the first fault, the dip of the reef decreases to about 40 degrees; between the first and second faults, the dip decreases to about 35 degrees, and at the mine face the dip is about 30 degrees.

RADIOACTIVITY INVESTIGATIONS

Standard Geiger-Mueller and scintillometer equipment was used in the field studies. Detailed examination was made of four of the gold-bearing reefs on the Canavieiras property. These reefs are called, stratigraphically from top to bottom, Maneiro, Hollandez, Liberino and Piritoso. The first two are white, coarser, "chabú" type of conglomerate that is gold-bearing but otherwise not well mineralized. The latter two are "piritoso" of green to chocolate brown pyritic reefs that are the principal gold-bearing rocks, not only at the Canavieiras mine but in all of the conglomerate formation of the Serra de Jacobina. The principal workings of the mine are in the Piritoso reef.

All four of the above mentioned reefs were sampled at intervals of about ten meters on the outcrop. These samples were tested for radioactivity and uranium content in the laboratory. The results listed below show the uranium content in terms of equivalent uranium (e.U.)‡ but chemical analysis for uranium of a selected number of the samples shows the radioactivity to be due entirely to uranium series and, since the results of chemical determinations are essentially the same as the equivalent uranium results obtained from radioactivity determinations—thus indicating the uranium to be present in equilibrium amounts with its daughter products—the e.U. values given may be considered as equivalent to uranium values.

	Outcrop length sampled (meters)	*Average per cent equivalent uranium in samples taken*
Maneiro Reef	300	Less than 0.001
Hollandez Reef	420	Less than 0.001
Liberino Reef	375	0.001
Piritoso Reef	350	0.006

From the above listed e.U. values it is apparent that the average radioactivity of the reefs at the outcrop is quite low. The values given for the Maneiro and Hollandez reefs closely approximate the magnitude of radioactivity highs in those reefs. The equivalent uranium values in the Liberino reef range from nil to 0.006 per cent, and the values for the Piritoso reef range from nil to 0.024 per cent. Therefore, except for occasional highs, radioactivity traverses along the outcrops of the reefs do not present very impressive results, and it is only when the reefs are penetrated to some depth that apparently significant radioactivity is found.

There are no accessible mine workings in either the Maneiro or the Hollandez reefs and consequently nothing is known of the radioactivity of these reefs at depth. Present indications are, however, that they will not contain appreciable amounts of uranium inasmuch as they do not carry significant sulphide ore bodies.

The Liberino reef, which carries an appreciable amount of mineralization, has been opened to a depth of about 20 meters in a pyrite ore body. The sampling in this development indicates the presence of 0.005 per cent equivalent uranium.

‡ Equivalent uranium (e.U.) A measure of the radioactivity of a rock or mineral sample, derived by comparing the radioactivity of a given sample to that of a sample with known uranium content that has the same geometry and grain size.

The Piritoso reef has been opened for a distance of 115 meters along strike and to a depth of over 80 meters, following the closely-spaced position of pyrite-gold ore bodies in the reef. The mine workings were sampled at intervals of 5 to 10 meters along the dip of the reef. This sampling shows the presence of an overall average of 0.01 per cent e.U. The uranium content of the samples ranges from nil to 0.2 per cent e.U.

The most radioactive samples are of fresh, unweathered, hard, closed, silicified conglomerate carrying large amounts of pyrite. The least radioactive are those samples that are in advanced stages of decomposition or that are subject to weathering. Thus the least radioactive samples collected were those from the outcrop of the reefs and the samples collected from the two fault zones in the mine where the rock is in advanced stages of decomposition. The uranium is closely associated with the gold-pyrite mineralization and the higher the grade in pyrite in an ore body, the higher the uranium content. Medium to low grade pyrite-gold ores show corresponding uranium values. Recent tests on the pyrite-gold ore being produced at the mine from the Piritoso reef shows that there is approximately 0.03 per cent uranium present in the run-of-the-mine ore. The final reject tailings from the mill processing contain 0.015 per cent uranium.

MINERALOGY OF THE GOLD ORES

Uraninite is the source of the uranium in the pyritic gold-bearing reefs. The chocolate-brown colored portions of the reef at outcrop are due to the limonite resulting from the decomposition of pyrite. The green color which is characteristic of the ore bodies is due to chromium, possibly to the presence of a chrome mica. Whereas no chromium minerals were found in concentrates of the conglomerates, the heavy mineral concentrates in Canavieiras Creek contains 35 per cent chromite, thus indicating a source for chromium in the rocks nearby.

Some visible free gold is present in the pyritic reefs but the principal occurrence is in rather intimate association with pyrite. The uraninite is closely associated with the gold-pyrite ore. Low, medium, and high grade gold ore have corresponding values of uranium. Fragments of uraninite have been found intergrown with crystals of pyrite.

Significant uranium values are found only in fresh, unaltered and unsheared pyrite-bearing ore. Heavy mineral studies of the weathered surface or outcrop samples and those from the decomposed rock of the fault zones—all of the samples containing less than 0.002 per cent e.U.—carry very little fresh pyrite. About 35 per cent of the heavy mineral fraction can be removed with a hand magnet and the bulk of the remainder of the concentrate is limonite and decomposed pyrite. Fresh unaltered samples of the ore which contain relatively high amounts of uranium contain relatively little limonite and much fresh pyrite. The heavy mineral concentrate of one fresh sample containing 0.2 per cent e.U. contains only about 5 per cent of material that may be removed with a hand magnet, very little limonite, some altered pyrite and about 50 per cent fresh pyrite.

In view of the uraninite-pyrite-gold association in the ore bodies, it is assumed that uraninite at one time was present in the weathered or altered zones of the ore bodies because these zones contain commercial grade gold ore. It is apparent that the chemical processes that are attendant to the oxidation of pyrite and the formation of limonite have removed the bulk of the uranium from the weathered zones in the conglomerates. On the other hand, the sampling to date has shown no evidence of there being any zones in which uranium is present in less than equilibrium amounts with its daughter products, as might be expected in an oxidizing sulphide environment. No secondary uranium minerals have been found as yet. Further studies will be needed to determine the reasons for the absence of uranium in the weathered outcrop as opposed to its presence in the fresh pyrite ore bodies at depth. It is obvious that this question is of importance inasmuch as it has a direct bearing on the method of prospecting for uranium in other pyritic conglomerate zones throughout the Serra de Jacobina.

CONCLUSIONS

The investigation of the uranium-bearing gold ores of the Serra de Jacobina is only in its initial stages and this paper is intended as a report on the preliminary work that has been done in the region since its discovery in late 1953. Whatever the importance of these deposits as a source of uranium, it is already clear that the uranium can only be produced as a by-product of a large scale gold-mining industry.

REFERENCES

1. Branner, J. C., *Geology and Topography of the Serra de Jacobina*: Amer. Jour. Sci. vol. 30, p. 385-392 (1910).
2. Williams, H., *Estudos Geológicos na Chapada Diamantina*: Serviço de Geologia e Mineralogia do Brasil, Bull. 44 (1930).
3. Mello, Jr., J. L., *Gelogia e Hidrografia do Noroeste da Bahia*: Serviço de Geologia e Mineralogia, Bull. 38 (1938).
4. Capper Alves de Souza, H., *Ouro na Serra de Jacobina*: Div. de Fomento da Produção Mineral, Bull. 51 (1942).
5. Oliveira, I. O. and Leonardos, O. H., *Geologia do Brasil*: Magnetite and Biotite

The Stano-Tantalo-Uraniferous Deposits and Occurrences in the Region of São João del Rei, Minas Gerais, Brazil

By D. Guimarães* and W. Belezkij,* Brazil

Tectonic-stratigraphic observations as well as petrographic investigations led the authors to chronogeological conclusions which confirm determinations previously arrived at by us on the age of Proterozoic and Paleozoic diastrophism, or in other words: (1) Huronian (orogenic); (2) Penokean (orogenic); (3) Cambrian (epiorogenic); (4) Caledonian (orogenic).

These are the major revolutions of the crust but dislocations of lesser importance, or those limited to certain regions, may have occurred in different parts of the country. An example is the epiorogenic diastrophism occurring at the end of the Archean and at the beginning of the Proterozoic one, as proved by volcanic activity which extended towards a large part of the lower Algonkian.

There was also confirmed the age of potassic pegmatites, the genesis of which is connected with the Caledonian orogenic phase. The difference between the tectonic Proterozoic processes and the Caledonian process became evident; the fractures of the latter slope towards a different direction.

The Caledonian tectonic, in the Proterozoic areas of the Serra de Espinhaço along this formation is of a strongly marked fractured nature, therefore indicating predominance of vertical faults from which grabens and horsts originate.

The conclusions arrived at regarding the use of geochemical criteria, which are subject to the aspect of the tectonic evolution of the area under study, are very interesting. This method of geological investigation has aided the solution of difficult problems of economic geology, especially in pre-Cambrian areas.

On the other hand, new data were obtained for the purpose of establishing the style of geologic evolution of the Proterozoic geosynclinal and the conditions of past surroundings in the sedimentation areas of non-manganese and manganese-bearing rocks.

There is also confirmed the existence of a corresponding Archean continent; now mostly in the basin of São Francisco River; the marine shelf of which reached the present bank of Rio das Mortes.

Finally, the geologic and structural map prepared for the above region gives sufficient explanation for well-directed prospecting operations in order to find other pegmatites containing uraniferous minerals, besides those which are already being explored.

A glance at the regional geology served as a basis for the establishment of a more interesting area from the point of view of the occurrence of uranium minerals.

A study of the eluvial deposits of cassiterite in the areas around Penedo, Santa Rita and the alluvial areas of the Rio Santo Antonio indicated a frequent occurrence of monazite and djalmaite in the panning concentrates. This fact revealed the possibility of finding new deposits of this uraniferous mineral. The results obtained from this study were given in a separate report signed by D. Guimarães.

The geologic and structural study undertaken by Wladimir Belezkij was limited to an area to the south and north of the Rio das Mortes which corresponds to the district of Nazareno. Scientific and practical conclusions have been reached through facts resulting from observation and petrographic studies, since they offer safer guides for prospecting other pegmatite dikes located on a belt parallel to that of Volta Grande, the possibilities of which as uraniferous-bearing minerals are still unknown.

Moreover, by the physical and chemical characteristics shown in the tectonic analysis and regional geochemistry, the location of dikes bearing those minerals can be foreseen not only in the area under study but in neighboring areas which have not yet been studied.

The sampling of outcrops for chemical analysis has now been completed; and the amount of analytical work was considerably large due to the known extensive amount of Volta Grande pegmatites which are being mined for cassiterite.

In this connection it must be remembered that D. Guimarães had already called attention to the considerable volume of pegmatitic rock, bearing spodumene, cassiterite, tantalite and djalmaite, found in Volta Grande and Germinal.

The exploraiton of deposits is limited to the parts indicated on the map covering Germinal and Volta Grande. The result was 10,000,000 tons, of which 5,000,000 tons were characterized by systematic samplings, not only from those obtained in the surface but also through drilling. In this way it was found out that, in certain pegmatite blocks

* Instituto de Tecnologia Industrial Belo Horizonte, Minas Gerais, Brazil.

(No. II) the composition of ore does not change at a depth of 100 meters.

Data covering djalmaite, tantalite, cassiterite, and spodumene reserves show that a deposit can be economically exploited for utilization of the four minerals, without considering the possibility of a market for feldspar and quartz, separated by flotation. It is anticipated that the total djalmaite reserve is about 2500 tons, in the prospected area.

In a previous report, mention was made of the extensive area of the mineral belt, that is: the continuance for several kilometers, of a system of pegmatite dikes, already marked on the general and detailed map. The prospected area corresponds to less than ¼ of the total area of the dikes; so that the anticipated geologic reserve must exceed 40,000,000 tons of ore (pegmatitic mass). These figures correspond to about 10,000 tons of djalmaite and 1,550,000 tons of spodumene.

The uranium content of djalmaite varies from 1% to 2% and the lithium content of spodumene from 5.5 to 6.0% of Li_2O. These last figures for mineral reserves are due to extrapolation, based on geologic data.

It is known that the market for feldspar has improved considerably in the country; and spodumene will also be placed in some of the glass-manufacturing centers.

In case of the total utilization of useful minerals, a part of the spodumene could be released for consumption in the country, in view of its high production which exceeds the initial needs of the Atomic Center, to whom the lithium-bearing concentrates will be destined.

It was possible to establish a tentative plan for processing pegmatite rocks by means of preliminary tests for treatment carried out by D. Guimarães. This has already been mentioned separately in other notes.

STANO-TANTALO-URANIFEROUS DEPOSITS IN THE MUNICIPALITY OF SÃO JOÃO DEL REI

In this preliminary note only a faint idea is given of the data and information gathered to date. Detailed work was carried out on the structural geology of the area to the east of São João del Rei and south of the Rio das Mortes as well as of a belt on the right bank of the same river in order to find out the manner in which tin and uranium pegmatites occur.

The first pegmatite to be prospected is that of Volta Grande at the Rede Mineira da Viação Railway, crossing the Rio das Mortes in a northeastern direction. About 4 kilometers to the east of the Volta Grande dike there is another line of fault in pegmatite dikes extending 10 kilometers to the northeast. Ten kilometers further to the east of the Volta Grande dike there is a third line of fault in dikes, approximately 10 kilometers in length, of which 3500 meters are potentially uraniferous. Further to the east of the latter line, there is another extensive dike on which there is no information yet.

At this time prospecting is restricted to the Volta Grande dike, although the other pegmatite dikes already exploited for cassiterite, reveal the existence of djalmaite.

The structural map of the region shows all the known dikes which are being mined for cassiterite by a French company over a 1000 meter area on a kaolinized surface.

The Conselho Nacional de Pesquisas prospected the same dike to the northeast over a 2800 meter area. The thickness of the dike is above 50 meters in the outcrops adjoining the Rio das Mortes. Its thickness is maintained between 20 and 30 meters to the northeast and crops out in high localities (900 meters) or 60 to 80 meters above the river level (815 meters).

The portion of the Volta Grande dike to the south of the Rio das Mortes has a known area above 2000 meters but it is a fault area and its sections are displaced.

Experience obtained through exploitation and treatment for the extraction of cassiterite, has shown contents varying from 0.1 to 0.4%. The concentrates obtained contain: cassiterite, 55%; tantalite, 25%; and djalmaite, 20%.

The analysis of fresh pegmatite gave the following results:

	Per cent
SiO_2	74.22
Al_2O_3	17.87
Fe_2O_3	0.44
FeO	0.14
MnO	0.96
CaO	0.30
Na_2O	2.27
K_2O	1.30
Li_2O	1.67
H_2O	1.10
Total	100.27

The lithium content corresponds to approximately 25% spodumene, but there are concentration areas with about 30% spodumene.

In the area, to the north of the Rio das Mortes, pegmatite is richer in djalmaite; therefore concentrates obtained may contain 30 to 40% djalmaite. The rock contains 0.4 to 0.5% heavy minerals (tantalite, cassiterite and djalmaite), but this content is higher in the stockwork.

The approximate composition of pegmatite, in the areas mentioned is:

	Per cent
Feldspar (quartz and mica)	74.6
Spodumene	22.0
Cassiterite, tantalite and djalmaite	0.4
Total	100.0

Estimated reserves of pegmatite rock, above sea-level, amount to about 20,000,000 tons. The above mentioned reserves are almost double in the 3800 meter area already explored. There are still 2000 meters to be explored.

A djalmaite occurrence is reported in the other pegmatite dikes, running parallel to that of Volta Grande, but it has not yet been studied.

It is planned to carry out geophysical prospecting operations by means of scintillometers, over a 1000 km² area where there are occurrences of pegmatite, containing cassiterite, tantalite and djalmaite.†

They only use cassiterite, the concentrates of which are exported to England. This concentrate contains from 15 to 17% tantalite and djalmaite. Mining by scrapers is being undertaken in kaolinized pegmatite. This partially kaolinized pegmatite, contains about 1.30% of lithium. A small part of the lithium belongs to lepidolite the content of which increases in the southern part of the dike.

GEOCHEMICAL STUDIES‡

Initially, we will mention the facts which have occurred and which are necessary in order to arrive at geochemical conclusions:

(1) As has been stated many times by D. Guimarães, djalmaite appears as a secondary mineral formed by tantalite. In other words, two elements enter into the composition of djalmaite: niobium-tantalum which is derived from the alteration of primary tantalite, remnants of which can still be found in the pegmatite; and uranium which is brought up from depth, the source of which is not yet known.

(2) There have been found inclusions of muscovite in djalmaite as well as inclusions of djalmaite in muscovite.

(3) Areas were found in which lepidolite is abundant.

(4) Areas of unmined pegmatite were found next to mined pegmatite areas.

(5) Two generations of cassiterite were found: one containing large, well-formed crystals; the other, euhedral medium-sized crystals.

(6) At times the presence of magnetite mixture is seen, at other times magnetite is absent. As rare minerals we have tourmaline, colorless garnet, bityite and zircon.

(7) In some parts spodumene predominates; in others, lepidolite. The latter, according to studies made by D. Guimarães, is a secondary mineral formed by the alteration of spodumene.

(8) Tectonic dislocations took place prior to the mineralization.

We find two phenomena connected with several mineralization and tectonic processes: (1) Previous to the formation of djalmaite, tectonic processes may be observed and its effects verified but after the deposition of this mineral, there is no possibility of observing other tectonics. (2) In the earlier mineralization, we can reestablish vertical geochemical zonings, which are now disturbed by dislocations.

Thus, recrystallization and alteration of uranium mineralization took place in several stages and, therefore, showed different results. That is why the same uranium emanations filtering along the same channels, through the earlier tantalite zones or through the earlier zones not containing tantalite, have placed uranium on a new geochemical level, that is, of djalmaite, or else they become lost. To study these processes, it is necessary to list them on a chart and as much as possible recover them in time. Table I below, shows the location of the minerals in the original dike, according to their energy characteristics:

Table I

Muscovite	2.8	450°
Tantalite	3.5	480°
Spodumene	4.0	550°
Magnetite Biotite	—	600°

As a general rule, all minerals in the pegmatite occur together, so zoning is revealed only where one or more characteristic minerals predominate.

As is known, based on microscopic studies, that the Caledonian granitization was the last one, consequently, it took place after the faulting of the same phase. However, as was said before, faults and, further the oldest ones divided the body of the original dike into separate blocks dislocating some more than others, both in a vertical and horizontal direction (the latter being very rare). Due to this fact, the geochemical zones which differ from the Caledonian orogeny reached different zones of the original dike.

It is not possible to foresee all the combinations of variable conditions so it is assumed in the chart that in each block formed there is a disturbed part corresponding to a geochemical zone of the original dike or to only one zone.

Since solutions which crossed dislocated blocks represented different energy levels, alteration which represents various stages of equilibrium appears.

From the table shown in the general geochemical chart, it may be seen that it was possible for djalmaite at its energy level in the Caledonian Age to be formed only in areas where tantalite was stable.

In addition, djalmaite must have formed in larger quantities where the earlier tantalite zone approached djalmaite's geochemical zone. In this case, tantalite was easily changed to djalmaite. In cases where the location of the tantalite zone was much lower than the zone in which djalmaite is formed, tantalite became more stable thus offering less possibilities for replacement.

On this basis, it may be concluded that locally it is possible to note an increase in tantalite although the depths of djalmaite have not increased or even suffered a reduction. In cases in which djalmaite is formed, these two minerals are found together and it is estimated that the percentage of djalmaite is in

† The "Companhia de Estanho São João del Rei" is mining the part of pegmatite located on the left bank of the Rio das Mortes, at the rate of 400 to 500 cubic meters per day.

‡ By W. Belezkij.

proportion with the percentage of tantalite. The results obtained by chemical studies clearly show the proportional rate between tantalite and djalmaite.

It was not possible for the upper blocks of the old original dike which are separated from the rest by tantalite concentration to form djalmaite, because of the absence of tantalite which precipitates uranium.

On the other hand, the formation of microlite also through tantalite and even microlite without uranium, shows that, in this case, the solutions did not contain uranium.

In the same geochemical chart, it can be seen that the hematite zone is lower than the djalmaite zone and that the lepidolite zone is lower still. It can also been seen that the great abundance of lepidolite is an indication of the non-existence of djalmaite. The highest limit of djalmaite is apparently indicated by the appearance of tourmaline and higher still by microlite. The djalmaite zone is almost the same as the zone of the second generation in which muscovite is formed. This means that muscovite of the second generation indicates the concentration zone of djalmaite. On the contrary, findings of vast masses of old muscovite (curved and folded) indicates the non-existence of djalmaite.

From a practical viewpoint, all of the above may be summarized as follows:

1. Rich zones of old muscovite, curved and folded, are unfavorable to djalmaite. Presence of djalmaite at a depth is not promising in these zones.
2. If in the upper horizons a certain quantity of djalmaite is found, and at a certain depth tantalite begins to appear, there is no great hope of an increase of djalmaite.
3. The richest spodumene zones are the poorest in djalmaite. In this case, the quantity of djalmaite may only increase in higher horizons.
4. Frequency or large quantities of lepidolite is not a favorable indication of the existence of djalmaite.
5. In zones where tourmaline appears, there is a possibility that djalmaite may be found at a depth.
6. Fresh non-tectonic muscovite of a newer generation is a favorable indication of an increase of djalmaite at a depth.
7. Sometimes small quantities of lepidolite and the non-existence of tantalite may indicate larger concentrations of djalmaite.

Taking into consideration local conditions, attention is called to the following:

1. In the mining areas of Fazenda de Coqueiros, higher geochemical horizons of the Caledonian age outcrop. These horizons reach the old tantalite zone. The absence of uranium in microlite and the presence of tantalite indicate the total non-existence of uranium in the solutions filtering into the old pegmatite of this locality.
2. In the area called "Fundão" where pegmatite outcrops, the secondary muscovite predominates. This is an indication of its non-existence.
3. In the hills to the southeast of the cheese plant, almost pure lepidolite concentrations outcrop, that is to say: they are deeper zones than the djalmaite zones. In this region passing from the red-colored zone to the more extensive area, it is necessary to search for the highest possible zones with possibly higher concentrations of djalmaite. It is quite possible that this place corresponds to the spot where Hole No. 8 is planned.
4. The region in which Well No. 207 is located (prospected by the Company) is the place where a higher percentage of uranium is to be found than in any other known place (5.4 g of U_3O_8 per ton). In this place the tantalite content is also higher. As another characteristic of this place, the non-existence of magnetite was also noted. This apparently is a most favorable condition for finding djalmaite and may continue along a certain depth.
5. In some parts of Germinal where spodumene is abundant, djalmaite may not exist. In this area, it is necessary to choose the zones located on the lowest geological levels or in highest topographic places. With this in mind, prospecting operations in places marked by stakes I.T.I. 5, I.T.I. 9, should be carried out more fully.

Exploration of Monazite and Associated Minerals in the Province of Taiwan, China

By J. T. Shen,* China

During World War II, Chinese geologists discovered some uranium minerals in the eastern part of Kwangsi province and identified them to be phosphuranylite, gummite and crystalline uraninite. In the same district, monazite, thorite and zircon were also found in stream sands. At that time only academic interest had been aroused. Samples of these minerals were sent to the wartime capital, Chungking, for exhibition. No detailed exploration was made.

After the war, the exploration of uranium and thorium minerals was planned by the Chinese Government. An investigation was made in 1946 in the northwestern region of Kwangsi province and southwestern region of Hunan province. Monazite was found in Kianghwa of Hunan and in Chungshan, Fuchuan and Kungchen of Kwangsi, principally associated with cassiterite, magnetite and ilmenite as placer deposits. Euxenite, samarskite, gummite and betafite are the uranium-bearing minerals found at Haicheng, Liaoning province. Monazite sands also occur in considerable amounts along the coast of Liaoning and Shantung provinces and on the stream sands of Heilungkiang province. Sinkiang and Suiyuan provinces are also the promising regions for exploring uranium. Unfortunately, due to the insurrection of Chinese Communists on the Mainland, the exploration of uranium and thorium minerals in the aforementioned districts was completely interrupted. The work of geological survey was then confined to the province of Taiwan and some off-shore islands of Fukien province.

In 1952, Mr. P. F. Chen, a geologist, found some black heavy sands containing magnetite, zircon and monazite on the coast of Quemoy, an off-shore island of Fukien province. This gives geological evidence regarding the origin of monazite in Taiwan which is only about 100 miles off the Fukien coast.

In Taiwan, monazite was first discovered in 1930 at Hualien district by a survey group searching for gold placers. After 1935, monazite and zircon sands were found on various localities in western Taiwan. Since them, it has been generally known that monazite-bearing sands occur in nearly all stream beds and along the beaches on this island. An amount of about 200 tons of zircon sand was produced and shipped to Japan between 1943 and 1945 for industrial use. Little work was done by Japanese on monazite exploration.

Upon the restoration of Taiwan to China, attention was paid by several government organizations to the resources of monazite and its associated minerals. It was finally decided by the Ministry of Economic Affairs in the spring of 1951 to establish a special organization for the systematic survey of monazite placers in Taiwan.

PROSPECTING WORK

The Taiwan Monazite Prospecting Bureau was established by the Ministry of Economic Affairs in June 1951. The bureau was charged with the task of (1) exploring monazite and its associated minerals and estimating their reserves; (2) determining the quality of monazite and its associated minerals; and (3) making recommendations on the advisability of mining operations. It was scheduled to complete the work in a period of one year.

Dr. K. T. Li, a physicist, was appointed the director of the bureau. Geologists, mining engineers, chemists and other technical personnel were temporarily drafted from other government organizations, such as Taiwan Geological Survey, Gold and Copper Mining Bureau, etc. The field work started in August, 1951, and was completed within 115 working days.

Three sets of 4" Empire Drills capable of drilling 50 feet below the surface were used. The spacing of drillings was made according to the area, richness and accessibility of the placers, being generally 100 meters apart. More drillings were made in the placers of northwestern Taiwan where accessibility is better. On the off-shore sand bars, tidal fluctuations made the survey work difficult to carry out, especially during the autumn season. Iron pipes (6" × 2') were generally used for sampling the sand in order to cope with the local condition and to save time and labor.

In total, 334 holes were drilled at different localities covering the placer area of about 1600 hectares.

TOPOGRAPHY AND GEOLOGY OF TAIWAN

The Central Range of Taiwan, which trends in a NNE direction, divides the whole island longitud-

* Director, Union Industrial Research Institute, Ministry of Economic Affairs, Taiwan, China.

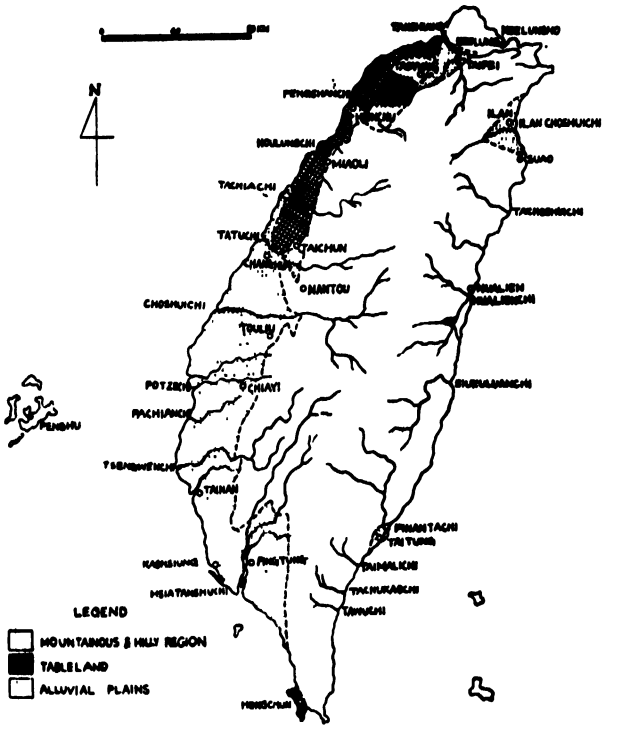


Figure 1. Map of Taiwan

inally into two unequal parts: a steep slope on the east and a relatively slow and gentle slope on the west (see map).

The coastal profile along the northern coast of Taiwan is rather steep. The shore zone is very narrow and is covered with sand or gravel varying with localities.

On the northwestern coast the shore zone is broader and more gentle than that on the northern coast. Its width ranges from several scores of meters up to about three hundred meters. The coast is fringed discontinuously with coral reefs. The shore is covered mainly with medium to fine sand. Sand dunes usually stretch along near the coast.

In southwestern Taiwan, the wide alluvial coastal plain slopes very gently toward the sea. This extensive coastal flat is drained by several streams running westward from the hilly areas. Tidal marsh, which is composed of mud and silt, extends several kilometers outward from the shore at low tide. Several off-shore bars have been developed along the southwestern coast. They are arranged in rows roughly parallel to the coast and are usually several kilometers away from the shore.

The alluvium, consisting of both fluviatile and littoral deposits of recent age, is widely distributed on the western coastal region of Taiwan. Its constituents are principally rock debris and their alteration products, derived from the eastern slopes which are mainly composed of Neogene sedimentary formations in the hilly regions and of Paleogene slate in the mountainous regions. The Neogene formations generally consist of sandstones and shales. The Paleogene slate contains black slate and quartzose sandstone with a few shale interbeds. In addition, lava-flows are scattered in northwestern Taiwan, intercalated among these Tertiary formations.

Sand is generally the most dominant sediment on the beaches along the northwestern coast and the southwestern off-shore bars as well as in the streams on the southwestern coastal plain.

ORIGIN OF MONAZITE

The monazite-bearing sands are generally found along the present beaches, stream beds and off-shore bars in western Taiwan. The associated minerals of monazite in the heavy sand are chiefly zircon, ilmenite and magnetite. Other minerals such as basaltic hornblende, epidote, garnet, hypersthene, staurolite, tourmaline, rutile, etc. are also present in small amounts.

The geological occurrences of monazite are usually found in granites, gneisses and pegmatites, but these acidic igneous rocks are very rare in western Taiwan. The source of monazite placers is therefore not quite clear. However, it is generally thought that the main source of most monazite placers in western Taiwan has been derived principally from the Tertiary sedimentaries which received their original sediments from monazite-bearing igneous rocks on the oldlands. The natural disintegration of the rocks liberated this mineral as well as other heavy minerals contained therein. They are then carried by running water to join the sands and gravels along streams or marine beaches, so that small amounts of monazite in association with other heavy minerals are sporadically distributed in most of western Taiwan. After repeated sorting by the action of running water, wave, tide, or wind, the monazite and its associated heavy minerals are separated from lighter minerals and concentrated at some favorable localities, forming beach and stream placers.

GEOGRAPHICAL DISTRIBUTION OF MONAZITE

The heavy sand deposits in Taiwan may be grouped into three main types as follows: (1) beach and dune deposits along the coast, (2) beach deposits found on the barriers off the southwestern coast, and (3) fluvial deposits.

The geographical distribution of monazite placers on the island can be divided into five regions: (1) northern Taiwan, (2) northwestern Taiwan, (3) central western Taiwan, (4) southwestern Taiwan, and (5) eastern Taiwan.

Northern Taiwan

This region includes all the main drainage area of Taipei and the northern coast. The crescent beach along the northern extremity is very narrow. The black sands are accumulated mainly on the beach along the high tide line. The thickness varies from several centimeters to about 40 centimeters. The black sands contain about 18% of ilmenite and 56% of magnetite which are derived chiefly from the andesites of the Tatun Volcano group. Only traces

of monazite have been found in these sands. Occurrences of monazite are also rarely found in the stream sand along the streams flowing through the district of Taipei, although the first discovery of zircon and monazite placers on the island was made in the fluviatile sediments in the Keelungho.

Northwestern Taiwan

This region covers three districts: Taoyuan, Hsinchu and Miaoli. Along the northwestern coast, the heavy sands are scattered largely in thin layers on the beach and dunes, and are richly accumulated near the high tide line. In Taoyuan district, the deposit was found to be particularly abundant in heavy minerals, of which the average percentage in beach sand is about 4.5% and the average depth is 1.2 meters. In some enriched parts, the amount of heavy minerals may reach as high as 40% of the beach sand. Heavy sands are also found in the sediments of nearly all the streams in the Taoyuan district. The placers have been concentrated mostly in the lower courses and the mouths of the streams. The average composition of heavy minerals is about 8% of zircon, 3.4% of monazite, 22% of ilmenite and 47% of magnetite.

Central Western Taiwan

This region covers the districts of Taichung and a part of Miaoli and Yunlin. The stream channels of this region are covered with coarse pebbles or boulders instead of fine materials. It is difficult to carry out prospecting work due to the scarcity of sand.

Southwestern Taiwan

The coastal plain in southwestern Taiwan is drained mainly by four principal streams from north to south; namely Pekang-chi, Potzechi, Pachiang-chi and Tsengwen-chi. They all run westward from the eastern highland carrying with them detritus of rock disintegration from the hilly regions. The heavy sands are generally distributed in layers on the superficial part of stream bars. They are particularly developed several kilometers upward from the mouths of the streams. The placers are usually shifted from place to place along the course by variation in the volume of flow in the streams. The average content of heavy minerals in the stream sand is low, generally below 2%. The heavy minerals contain about 5% of monazite, 10.8% of zircon, 39% of ilmenite and 6.6% of magnetite.

There are eight off-shore sand bars, stretching from Yunlin to Tainan district and about two to eight kilometers apart from the southwestern coast. These off-shore bars commonly form elongated ridges. They are mostly one or two hundred meters wide and their length in total is about 30 kilometers. Important heavy sand placers were found by the Prospecting Bureau on the off-shore bars. High grade concentrates of black sand are distributed along the high tide line on the seaward side of the bars. The black sand contains enriched interlayers of heavy minerals up to 30% near the surface, but diminishing downwards to about 1% at a depth of about one meter. The heavy sands contain an average 5% of monazite, 14.7% of zircon, 19% of ilmenite, and 9.6% of magnetite.

Eastern Taiwan

Both zircon and monazite have been found in the fluviatile sand at the north of Hualien and along the coast east of the Coastal Range. No prospecting work has been done in eastern Taiwan because it is poor in accessibility and is not justified in economic value.

PHYSICAL PROPERTIES OF HEAVY MINERALS

Density

The bulk density of the heavy sands is closely related to the mineral content. On the northern extremity, the bulk density of the black sands containing high percentage of magnetite is about 2.8 kg/liter, being the highest density among all other heavy sands on this island. As the magnetite sand decreases in amount southward, the bulk density of heavy sands elsewhere generally ranges between 2.4 to 2.6 kg/liter.

Size

The grain size of the heavy minerals found in western Taiwan are rarely over 0.5 mm or smaller than 0.05 mm in diameter. Most of the grains are between 0.08 and 0.25 mm in diameter and correspond to grades of fine sand and very fine sand according to Wentworth's scale. The grains may be in perfect crystal forms, in angular fragments, or in well-rounded shapes.

Color

Along the north and northwest coast, the heavy sands always exhibit a black or dark gray color due to the presence of considerable amounts of magnetite. On the southwestern coast and along the streams, the heavy sands are commonly gray or purplish gray and usually display glaring colors under sunlight since zircon is the main constituent in the sands.

MAGNETIC SEPARATION OF HEAVY SANDS

Samples of crude sand taken from holes of different localities were washed on the wilfley table for gravity separation in order to obtain the heavy sand. Heavy sands having specific gravity over 3.0 were retained on the table known as table concentrate and table middling. After drying in an oven, the heavy sands are separated into magnetite, ilmenite, monazite and zircon in magnetic separators based on their difference in magnetic attractability which is shown below, taking pure iron as a standard index:

Mineral	*Magnetic attractability*
Iron	100.00
Magnetite	40.18
Ilmenite	24.70
Monazite	2.00
Zircon	1.10

The electric current used for the production of magnetic field in a magnetic separator increases as the magnetic attractability of the minerals decreases. For instance, to separate ilmenite from monazite and zircon, requires 50,000 to 60,000 ampere turns while 100,000 ampere turns are needed to separate monazite from zircon. After every separation, the minerals were examined under microscope to determine their purity. The process was repeated, if necessary, until the minerals had reached the required concentration.

The average percentages of monazite, zircon, ilmenite and magnetite are listed in the following table:

Region	*Monazite*	*Zircon*	*Ilmenite*	*Magnetite*
Northern extremity	trace	trace	18	56
Northwestern coast	3.4	8	22	47
Off-shore bars	5.1	14.7	19	9.6
Streams on the southwestern plain	5.1	10.8	39	6.6

CHEMICAL ANALYSIS OF HEAVY MINERALS

Chemical analysis of different minerals obtained from the magnetic separation of heavy sands was made by the following laboratories: the Chemical Department of National Taiwan University, the Ordnance Research Institute, the Provincial Industrial Experimentation Laboratory, and the Sinchu Research Institute of Chinese Petroleum Corporation (now reorganized into Union Industrial Research Institute).

For comparison of the analytic data, samples of monazite separated from the heavy sand of off-shore bars were sent to the Associated Metals and Minerals Corporation in the United States for analysis. The results of analysis in different laboratories all agreed fairly well.

Composition of Monazite from Off-Shore Bars

Composition	*Analyzed by Sinchu Research Institute* %	*Analyzed by Associated Metals and Minerals Corporation* %
Total rare-earth oxides (including ThO_2)	63.26	64.00
ThO_2	5.66	5.69
CeO_2	—	26.40
P_2O_5	27.95	—
ZrO_2	2.95	—
TiO_2	0.15	—
SiO_2	1.33	—

A more complete analysis of monazite sample from the stream bed of Keelungho was made, giving the following:

Composition	*Per cent*
ThO_2	6.79
UO_2	0.05
CeO_2	29.06
La_2O_3 etc.	27.36
Y_2O_3	2.95
Fe_2O_3	1.39
Al_2O_3	0.33
TiO_2	0.55
ZrO_2	trace
CaO	2.48
MnO	0.01
PbO	0.06
SiO_2	1.52
P_2O_5	27.82

The thorium content as ThO_2 in monazite samples from various localities varies from 4.21 to 6.79%, averaging about 5%.

Representative analytical data of zircon, ilmenite and magnetite are shown in the following table:

Composition	*Zircon*	*Ilmenite*	*Magnetite*	*Remarks*
$ZrO_2 \cdot HfO_2$	65.45%	5.63	0.25	$\frac{HfO_2}{ZrO_2} = 0.016$
TiO_2	0.52	26.54	6.01	
Fe_2O_3	1.43	52.70	72.69	
ThO_2	2.15	—	0.11	
Al_2O_3	0.33	1.40	3.94	
Cr_2O_3	—	0.21	0.01	
V_2O_3	—	—	0.37	
CaO	0.02	2.33	2.35	
MgO	1.09	—	2.35	
SiO_2	28.99	4.79	8.24	
MnO_2	—	—	0.20	
UO_2	trace	—	—	

ESTIMATION OF RESERVES

From the records and data of exploration, the total reserves of heavy sand in western Taiwan are estimated to be 200,055 metric tons. The average content of heavy sand in the crude sand is 2.7%. This figure represents only the reserve of accessible and workable placers having economic value. The reserves of heavy minerals in different regions are tabulated (in metric tons) in the table below:

Region	*Heavy sand*	*Magnetite*	*Ilmenite*	*Zircon*	*Monazite*
Northern extremity	21,650	12,200	3962	—	—
Northwestern coast	18,922	9030	4280	1540	637
Off-shore bars	135,533	13,086	26,919	19,914	6925
Streams on the southwestern plain	23,950	1589	9405	2583	1229
Total	200,055	35,905	44,566	24,037	8791

It may be concluded that the total reserves of crude sand in western Taiwan are about 7,500,000 metric tons, from which 200,000 tons of heavy sand can be obtained. On the average, the heavy sand contains 4.4% of monazite, 12% of zircon, 22.3% of ilmenite and 17.9% of magnetite.

REFERENCES

1. Li, K. T., *A Report on Monazite Prospecting in Taiwan* (in Chinese), Ministry of Economic Affairs, Taiwan, China (1952).

2. Chen, P. Y., *Heavy Mineral Deposits of Western Taiwan* (in Chinese), Bulletin of the Geological Survey of Taiwan, No. 4 (1953).
3. Ho, C. S., *Mineral Resources of Taiwan,* Ministry of Economic Affairs, Taiwan, China (1953).
4. Chen, P. F., *The Mineral Resources of China* (in Chinese), Chinese Cultural Publishing Committee, Taiwan, China (1954).
5. Tann, C. F., *Monazite, Hidden Treasure of Taiwan,* Industry of Free China, Vol. II, No. I, 1-4 (1954).

The Uranium Deposits of France and French Overseas Territories

By Marcel Roubault,* France

HISTORY

The existence of uranium-bearing minerals in France has been known for a long time. Thus, in 1800, barely a few years after the discovery of the element by Klaproth, De Champeaux found at St.-Symphorien de Marmagne, near Autun, the mineral now universally known as autunite.

This memorable discovery was followed by that of several other phosphate deposits in the French Massif Central: first, autunite at Chessy (Rhône, Beudant, 1832) at Bourg-Lastic (Puy-de-Dôme, Gonnard, 1891), in the vicinity of Limoges (Chanteloube, Chabanne), etc., followed by the discovery of chalcolite in essentially the same localities, as well as in the region of Entraygues (Aveyron, Boisse, 1952), etc. In general, it would not seem that these findings had more than a purely mineralogical interest.

The discovery of radium by Pierre and Marie Curie in 1898 gave new impetus to the quest for uranium-bearing minerals, since these were natural sources of the newly found element, and much activity was begun in France along those lines — at least for a few years. A certain number of mining works go back to that time: the exploration of Marlot at St-Symphorien de Marmagne (Saône et Loire), the locality of the first autunite (1903 to 1910) discovery, those of LaSalle at the locality known as "le Crot Blanc" near Grury (Saône et Loire) from 1930 to 1932, the work of Thave and Demarty at Lachaux and St. Rémy sur Durolle (Puy-de-Dôme) from 1925 to 1927. At the same time some rather important studies were being made on the Island of Madagascar.

However, none of these investigations showed a truly workable deposit and French activity in the search for uranium stopped almost entirely. On the eve of the Second World War, only Madagascar was delivering each year a small and irregular amount of niobo-tantalite. This was derived by the leaching of eluvial pegmatitic material. However, these investigations enabled France to prepare a "mineralogical file," the value of which was suddenly apparent with the creation within the Commissariat à l'Energie Atomique, of a Bureau of Research and Mining.†

On the basis of this already known data, prospecting started again in March, 1946. In addition to the conventional type of exploration, the use of Geiger counters and the creation of specially equipped parties were added immediately.

In 1946 and 1947, the old indications were confirmed and new ones were observed. However, they still remained of mere mineralogical interest. From 1948 on, prospecting was systematically developed. Chronologically, the principal discoveries were as follows:

In November, 1948, the La Crouzille deposit (Haute Vienne), the first massive pitchblende deposit known in the French territory, a strike which was followed, among others, by that of numerous uranium-bearing formations in the Limousin.

In July 1950, pitchblende (also massive), at Bauzot, near Issy l'Evêque (Saône et Loire), which led to the discovery of fluorite and disseminated pitchblende at depth.

In 1951, the first known traces of mineralization in the region of the Bois Noirs (12 km ESE of Lachaux, Puy-de-Dôme) followed, at the beginning of 1954, by the finding of a particularly rich vein deposit.

In 1951 and again in 1952, the first indications at Vendée in an area where it was unknown previously and where two mines now are ready for operation (La Chapelle Largeau and L'Ecarpière).

In 1953, in cooperation with the Geological Department of Madagascar, deposits of urano-thorianite in pyroxenite, in the southern part of the island, W-NW of Fort Dauphin.

At the same time, there are other teams which have completed their work or are still investigating regions where no actual projects had been started, but where indications and even formations which may later be worked, already have been noted (Vosges, Allier, Beaujolais, Creuse, etc.). Finally, outside of France and aside from Madagascar, prospecting is going on in North Africa, in French Equatorial Africa, and in the Sahara.

THE URANIUM DEPOSITS OF FRANCE

At present, almost all of the indications or places showing uranium mineralization are in the hercynian territory, namely the Massif Central, Massif of Britanny and the Vosges. The only localities which are an exception, although the rule remains nearly absolute, are at the border of the Vanoise and various

Original language: French.

* President of the Mining Committee of the C.E.A.

† Director: J. Mabile; Chief of Research Department: A. Lenoble; Chief of Mineralogical Department: J. Chervet.

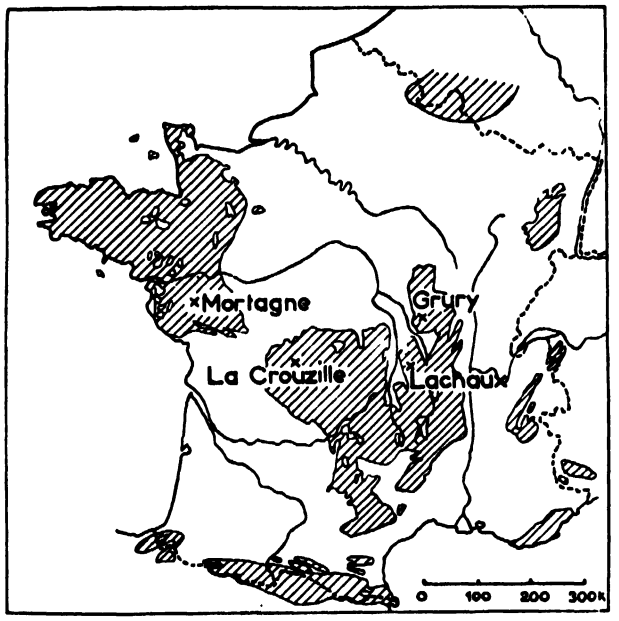


Figure 1. The four principal uraniferous centers of France. Hachures show the Hercynian zones

traces in the Pyrénées; for the moment these are no more than mineralogical indications.

Aside from the uranium-bearing carbonaceous schists of the Schaentzel, which are near St-Hippolyte in the Vosges, and the indications, now no longer being investigated, of the coal seams of Ronchamp (Haute-Saône), all the known formations are the "hydrothermal" vein type. The pitchblende is localized in acid crystalline formations or in the secondary mineralization directly derived from above (quartz veins, parsonsite and other oxidized minerals, deposits of various forms of autunite and chalcolite).

The deposit will be described by region in their chronological order: Autunois and Morvan, Auvergne, Limousin and Vendée.

Autunois and Morvan

Geologic Location

The uranium-bearing mineralization of the Morvan and Autunois are nearly all localized in the granite Massif known as the Luzy batholith; this batholith consists essentially of *granite porphyry* with large orthoclase crystals which vary from light gray to pink. They are coarse grained and contain a small amount of mica. In addition, it is cut by *veins* of a variety of rocks which may be acid (microgranite), or more alkaline (lamprophyre).

General Distribution of the Mineralization

On the surface of the Luzy batholith and at the southern end of the granitic zone of Château Chinon, we now know of more than 40 uranium-bearing locations. Most, merely reflect the presence of supergene minerals, essentially autunite and chalcolite: in fact, this was true of the St-Symphorien de Marmagne deposit which is not being worked, but retains historical interest. It may lead sometime to deeper formations of practical value. The centers where the presence of pitchblende was shown, all on the western margin of the batholith, may be grouped in three sets of fractures which are from south to north: (*a*) the set of Grury Sud—La Faye, Les Vernays, les Gaulins, les Brosses deposits; (b) the set of Issy l'Evêque—Bauzot and Le Batou deposits; and (*c*) Luzy set—Oudots deposit.

Essentially, there are two deposits of special significance which form the mining centers of the region: La Faye and Bauzot.‡ The La Faye deposit, located approximately 1500 m to the south of the village of Grury, has been the object of extensive mining from 1947 to 1951. Several hundreds of meters of galleries were dug at two levels (—15 and —30), and exploration was started at greater depth (—80); this work then was held up for a year and a half, but started again in 1953 on a larger scale, particularly at the —80 level.

The host rock is the usual porphyritic granite of the batholith. It is intensely altered for a thickness of several tens of meters; this granite is cut locally by aplite and lamprophyre veins (kersantite), the latter being more important in the NE-SW direction.

The mineralized formations consist of: (*a*) siliceous veins which trend N 10° W; the most important is the La Faye vein; (*b*) veins or veinlets of pitchblende in particular the Hélène vein which is parallel to the main eastern vein, and the vein called the Atelier du Fond which is parallel to the principal western vein. A mass of material which is rich in pitchblende is located at level —15 in the latter vein and this should be correlated.

The La Faye vein is large and consists of cryptocrystalline silica which is greyish or reddish and associated with fluorite. It has a variable thickness (0.50 to 1 m), dips to the east (40 to 75°), and is locally and irregularly mineralized with uranium. Mineralization is complex in the upper parts of the vein where it is nearly all secondary (chalcolite, autunite, kasolite); in the deeper parts, on the other hand, it is silicious with disseminated and sooty pitchblende, pyrite and, at times, sulfides of the BGPC group.

The Les Vernays vein, located 600 m to the east of La Faye, and discovered in 1948, is a fluorite silica vein. The Les Gaulins and Les Brosses formations, close to each other and approximately 7 km to the south of Grury, are correlated with the same system.

The Bauzot deposit, which is the center of mining activity in the Grury area, is approximately 2 km to the SE of Issy l'Evêque. The first indication, discovered in January 1950, was exceptional and not very representative of the deposit. Here, there is a very beautiful fluorite massive pitchblende lens

‡ Leading Eng. C.E.A.: M. Beulaygues (Mine), H. Carrat (Geology).

with a width which locally exceeds 20 cm. The minerals are accompanied by gummite, uranotile, autunite and limonite.

In addition to this lens—which had a favourable effect on the development of the workings—the structure of the Bauzot deposit has the following appearance: from the surface level 100, the structure is a simple, single vein, namely the La Borne Pilot vein, which has a general SE-NW trend and dip of 80° SW. Beyond the 100 level, the structure is more complex. In addition to the La Borne Pilot vein, there is the parallel Alphonse vein. Another complex which is similar to the other veins in reverse, is called the Combes-La Verchère vein. The primary rock is a beautiful porphyritic granite with magnificent orthoclase crystals which are several centimeters in length.

From the mineralogical standpoint, the principal characteristic of the La Borne Pilot vein is the presence of fluorite which at times is very abundant. It contains finely disseminated pitchblende and is associated with quartz. The ore is of low content (1% or less).

Diagramatically, from the granite layer, the following succession is seen: a thin strip of colorless quartz, a mixture of fluorite and pitchblende which is often ribboned with dark purple fluorite, often the antozonite type, abundant red "rusty" quartz, small amounts of dolomite and abundant calcite.

Auvergne

The uranium-bearing district of the Auvergne, generally known as the Lachaux district,§ occurs in the Forez and Madeleine mountains between the Allier and Loire valleys and at a distance of approximately 20 km to the SE of Vichy. This region, essentially granitic, is characterized by a fairly complex set of faults which are closely related to the mineralization. It is bounded on the west by the large fault which separates the Forez from the Limagne Tertiary plain.

The deposits are arranged in two groups which are separated by a barren zone: the Lachaux proper, which was known previous to working, and the Black Woods to the SE, which is a recent (1951) discovery. These represent two different types of deposit: the Lachaux essentially is characterized by parsonite; and the Bois Noirs, by pitchblende (the veins of Bigay and Gourniaud located at Lachaux are the second type).

Parsonite Deposits at Lachaux

From the mineralogical point of view this is an exceptional locality and the uraniferous mineralization of this region is the most important of its type in the world. Parsonite, a double hydrated phosphate of lead and uranium, is a fairly common oxidized mineral usually found in very small amounts. However, at Lachaux it is present in sufficient quantities as to be a true ore, capable of supplying a concentration plant for many years.

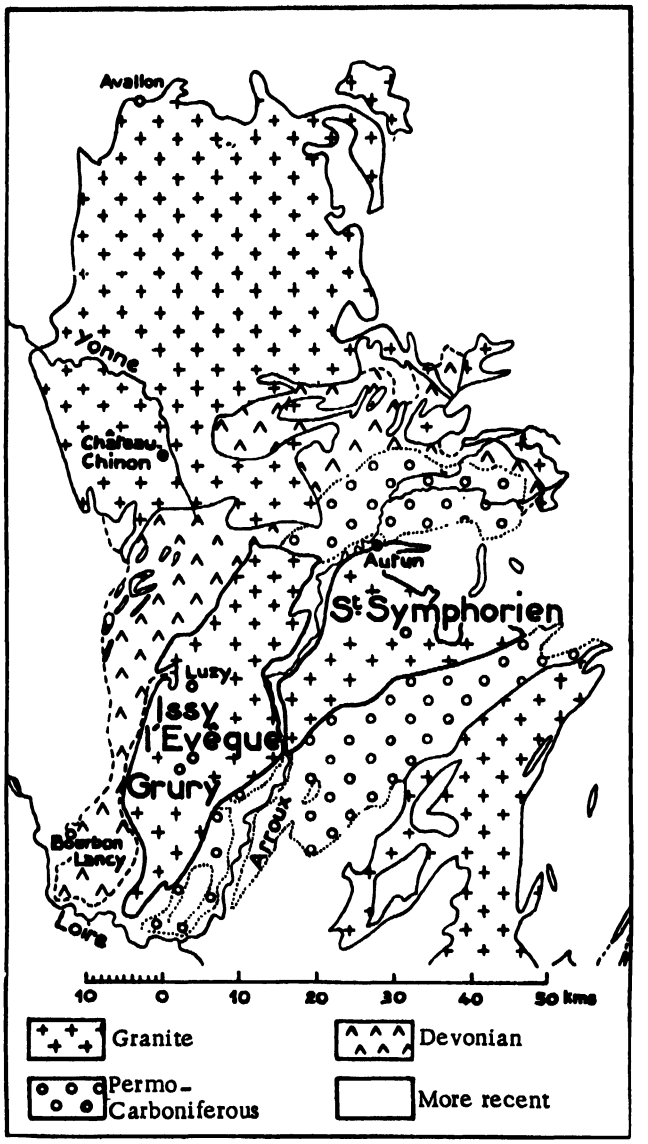


Figure 2. Geologic map of the Autunois and Morvan

The parsonsite zone is similar to a quadrilateral which in general is defined by structural limits and is occupied by a granite with two intensely altered micas, chlorite, hematite, and a number of argillaceous channels. The granite is cut by lamprophyre (diorite). In addition, and this is important, it is crossed by numerous smoky quartz and opal veins.

The principal known deposits are: Reliez, l'Etang de Reliez, Bancherelle and Gagnol. The largest, Etang de Reliez, is given as an example. Essentially, it consists of an important quartz and opal vein which contains parsonsite and galena as a fine dissemination which, at times, is not visible to the naked eye. Microscopically, the parsonsite fills the breccia diaclases which consists of smoky quartz and various other forms of barren silica, with a resinous opal cement. The vein has been explored by extensive mining down the —120 level and by drilling, to the —140 level. It is wide, usually over one meter.

§ Leading Eng. C.E.A.: X. Des Ligneris (Mine), A. Poughon (Geology).

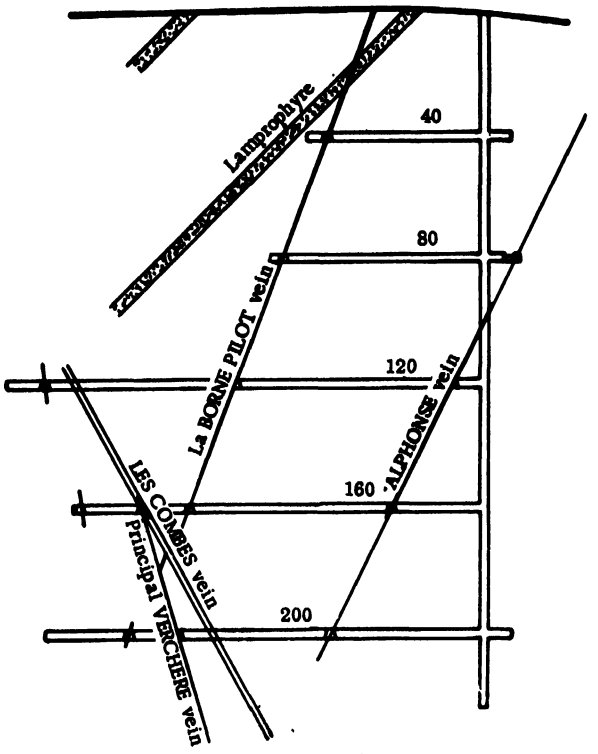


Figure 3. Morvan—Cross section of the Bauzot deposit

In detail, the structure of the deposit is complicated by the presence of fractures at right angles to the direction of mineralization. There are actual faults filled with clay, and shears, which cause intense brecciation.

From the practical standpoint, these deposits are of limited importance. However, local enrichment of the uranium is observed near the lamprophyre veins; but in general, at the Etang de Reliez and other neighboring deposits, the average mineral content remains very low (1 to 2% to a few 1/10,000). Drilling shows a very sharp depletion which increases at a fairly high rate with the depth. Operation, which also is difficult because of the structural complexity of the deposits, is almost stopped; nevertheless, it supplied an appreciable uranium tonnage at a time when the recent important deposits were unknown.

Pitchblend Deposits of the Bois Noirs

The mineralized zone of the Bois Noirs is located on the eastern edge of a granite massif which is limited to the west and east by two large faults, the more important second one is known as the Forez fault. Several deposits or occurrences of mineralization are recognized (Le Fratay, St. Priest, Viaduc des Peux, La Gadaillère, Limouzat); all of which are related to fractures which have a general NW-SE trend, and in general are parallel with the Forez fault.

The Limouzat Deposit

This, the most important deposit is given as an example. This deposit which has been explored by drilling to a depth of 200 m already, is cross-cut by large workings and appears to consist essentially of a breccia lens which is bounded by two faults. It is approximately 150 m long, and an exceptional width which may reach 25 m at the center. The breccia consists of silicified microgranite which is considerably crushed at the top. Pitchblende, as disseminated spherulites or in bands, occurs in the "rusty" silica cement. The supergene minerals are relatively abundant, particularly near the surface (chalcolite, autunite, various phosphates). A peculiarity of the deposit is the abundance of the mauve uranium hydrate which is similar to the Katanga ianthinite. In addition, various sulfides occur (galena pyrite, marcasite). The average uranium content of the Limouzat breccia is high, and much higher than the low grade deposits at Lachaux. This deposit may be considered as being important.

Limousin

The uranium-bearing mineralization of Limousin occurs in the granitic and granulite Massif of Ambazac. This outcrops largely to the north of Limoges, and to the southeast of the principal fault known as the Argentat crushed zone. It is coarse, a grained granite, which is rich in scattered pegmatitic masses (pegmatites of Chabannes). It is cut by a system of variable lamprophyre veins which generally trend NNE-SSW, and dip 55 to 75° WNW.

These uranium deposits¶ form two groups: A southern or *La Crouzille* group, from the name of the first workable deposit discovered which is located close to Ambazac and 20–25 km to the north of Limoges; and a northern group, or *Bessines* group. This system is related to a considerable mineralization, the only points shown on the map are the centers which are now being worked. The localization of the uranium-bearing deposits seems to be related to the lamprophyres, particularly for the southern group, in which they are widely represented. Here, the uranium-bearing masses or veins appear to fill faults which generally are oriented perpendicular to the lamprophyre veins.

The principal known deposits recognized are: (*a*) in the southern group: La Crouzille, Les Sagnes, Fanay, les Tenelles, Augères, Fraisse-Jalinour, La Borderie, Ritord, Margnac I, II and III; (*b*) in the northern group: Brugeaud, Champ Malauzat, Villard, Varnac.

The deposits of the southern group are related unquestionably to lamprophe veins with the exception of the Margnac area. To the north, on the other hand, the uranium-mesocratic-rock relation has not been observed yet.

Massive Pitchblende and Mesocratic Rock

Example: Henriette Shaft at La Crouzille.

This pitchblende deposit, the first discovered in France, lies at the intersection of three microsyenite or micromonzonite (locally called "minette") veins. They are oriented NE-SW and dip approximately 70° NW. There is a series of fractures which are perpendicular to these veins.

¶ Leading Eng. C.E.A.: R. Avril (Mine), A. Sercia (Geology).

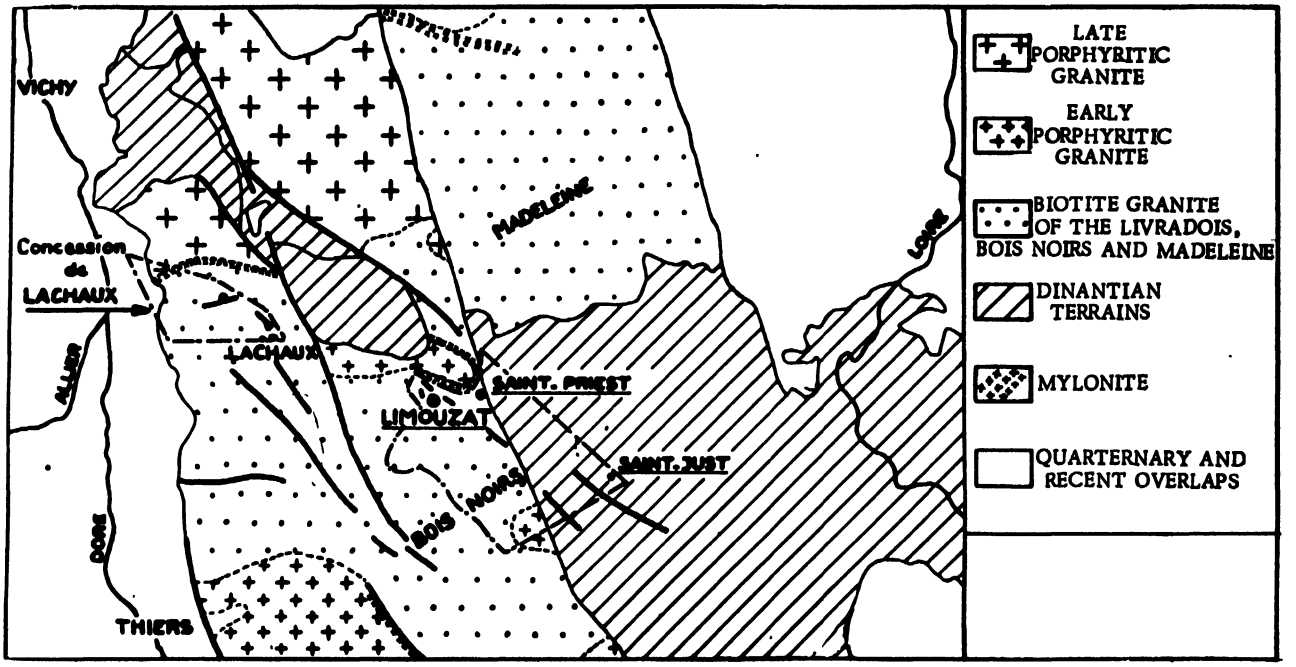


Figure 4. Auvergne—Geologic map of the Lachaux region

The structure of the deposit itself is very simple and aside from the "Cantiant Column", which has been explored only in its upper parts, it appears to be a true "knife edge" which dips nearly vertically into the granite and is strictly localized in the roof and wall of one of the minette veins. Horizontally, it extends for a distance of 10 to 15 m; its thickness is variable, although in general it is several centimeters.

Mineralization consists of massive pitcblende, which is intimately associated with later pyrite and marcasite; locally there are traces of sphalerite, galena and bismuthinite. An exceptional fact is that the supergene alteration is weak and the pitchblende is relatively fresh at the surface. At the highest levels it appeared unaltered and practically free from orange-yellow secondary products and fortunately of the chalcolite-autunite phosphate types. Near the principal mineralization, the La Sapinière fault contains low grade mineralization in carbonate gangue.

The Les Sagnes deposit, approximately 2 km to the NE of the previously mentioned one, is similar although its structure is somewhat more complex; the relationship between uranium mineralization and lamprophyre veins also is distinct.

Massive Pitchblende Deposit Unassociated with Mesocratic Rock

Example: Le Brugeaud.

This deposit, located close to Bessines approximately 20 km to the north of that above, is related to a series of fractures or crushed zones which have a general NW-SE trend and a dip SW. At present it is explored to the —30 and —65 levels. Mineralization consists of pitchblende with pyrite, marcasite, galena, and chalcopyrite above a thin strip of quartz. Occasionally, there is calcite which fills later fractures and locally affect the veins.

Near the surface we find the usual supergene mineralization of orange and yellow gummite and phosphates of the autunite group which are accompanied by limonite. Finally, one often notes "black oxides" (a super-oxidized form of pitchblende) the original of which is poorly defined.

Irregular Pitchblende Deposits and Supergene Products

Example: Margnac.

These deposits are very different from those mentioned previously and are recognized at the surface by zones of gummite and autunite. The latter may be disseminated abundantly in the granite areas at the surface. Locally, these form true ores which can be worked in open pits. At depths and in general the deposits of the Margnac region are related to discontinuous mineralization of fractures.

At Margnac II, for instance, there is a system of essentially parallel faults which form an important structural mass. The mineralization is localized in rich irregular lenses which are separated by poorer mineralization. The pitchblende, which impregnates the crushed and altered granite is associated with a small amount of pyrite and marcasite which tends to be associated with biotite masses in the host rock. There also is a small amount of galena as well as hematized calcite, which often is an abundant gangue.

The uranium-bearing mineralization of the Vendée is closely related to the granite massif of Mortagne.** On the southern side, this massif is in metamorphic contact with the brioverian and crystalline schists under which it appears to plunge. On the northern

** Leading Eng.: J. Sornein (Mine), H. Sanselme (Geology).

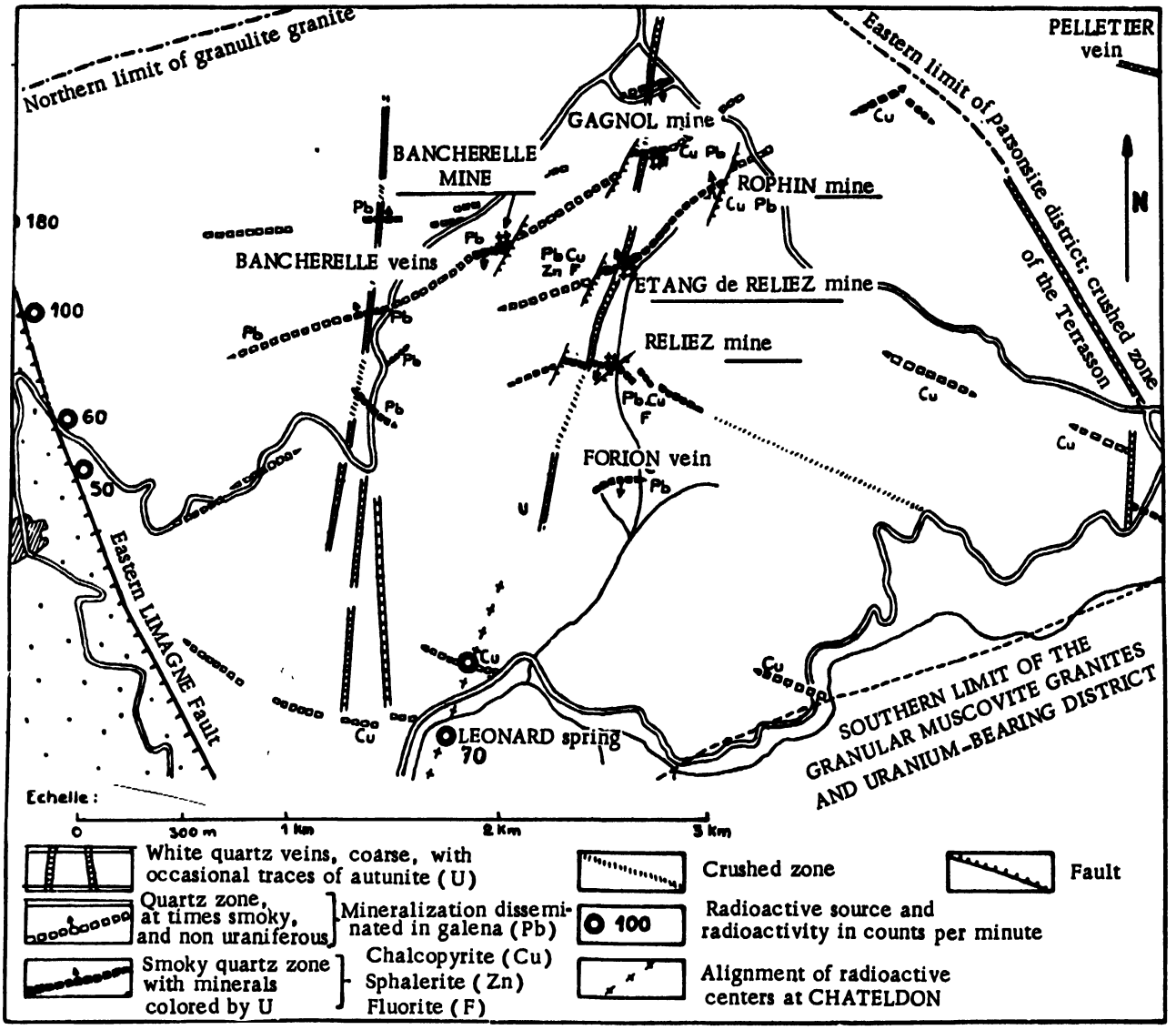


Figure 5. Auvergne—Structural map of the parsonsite zone (Lachaux is on the eastern edge of the map)

flank it is still in contact with the brioverian and crystalline schists, along a fault.

The mineralized locations are grouped essentially in four regions: (1) *Clisson* (L'Écarpière), mineralization in granite, along the brioverian contact. (2) *La Chapelle Largeau,* similar, mineralization located a few hundred meters from the granite, diorite contact. (3) *Mortagne,* mineralization in the granite proper. (4) *Les Herbiers,* mineralization exception for France as it is localized in micaschist and gneiss, although they are not more than a few to a few hundreds of meters from the contact.

Clisson Group

The four localities known at present are localized on the southern rim of the La Moine River. Essentially, they are aligned E-W, and their extreme points are separated by approximately 4 km. The principal one is the deposit of the Écarpière, which currently is being prepared for operation (a depth of about 140 m, and approximately 900 m of galleries have been made to the various levels); this deposit will serve as an example.

It consists of seven mineralized fractures which are oriented WNW-ESE. Of these the Rousseau and Sénécal veins are the most important. These almost vertical fractures are cut to the east by an EW fault, which is also vertical.

The mineralized zones were explored by approximately 40 drill holes. The maximum depth of mineralization to date is approximately 200 m. In plan, the length so far explored is about 600 m. The host rock is a very red granite with porphyryoblasts of strongly twinned orthoclase.

Metallogenically, the veins are fairly consistent in appearance: they vary in thickness from a few decimeters to one or two meters, have a characteristic ribbon structure, and characteristics similar to those of the Bauzot deposit in Saône et Loire. It contains black antozonite fluorite and chalcedony (no quartz) which are impregnated with pitchblende, either as

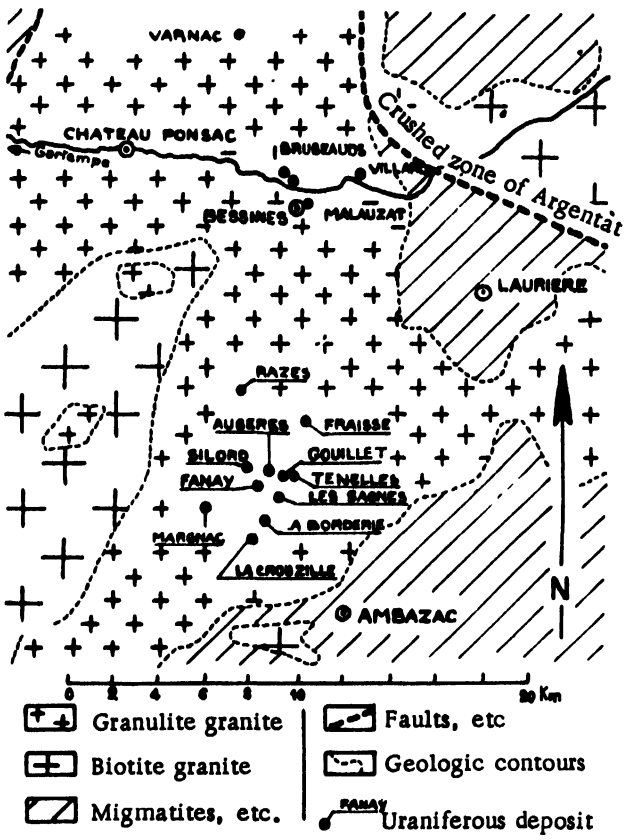


Figure 6. Map of the Limousin uraniferous region

fine nodules (approximately 0.02 mm diameter), or as veinlets which have a thickness of 0.1 mm to 1 mm.

The pitchblende is localized fairly consistently at the border of the fluorite and quartz zones. In addition, pyrite is a frequent even constant associate and is more abundant as the proportion of pitchblende increases. As at Bauzot, this is generally a low grade deposit. The average ore has a uranium content of 0.5 to 2%; the tonnage is sizeable.

Group of La Chapelle Largeau

The explored mineralized localities (there are about ten) are distributed in three parallel rows which trend NNW-SSE; the principal one is that of Belair.

The Belair deposit is a rather complex structure: there is a large fault oriented E-W, which is related to an important crushed and laminated zone which is about thirty meters thick and known as the Calvaire fault ("shear zone"). In addition, there is a set of parallel fractures which generally are oriented N-S.

This area is silicified by a considerable amount of resinous and barren opal. Later, a siliceous gray mineralization of pitchblende and pyrite associated with traces of galena and covellite was deposited. The pitchblende occurs as spherulites which have diameters of 1/50 to 1/100 mm and are disseminated in the silica. The pitchblende also occurs in veinlets with a thickness of about 3 or 4 mm and located at or near the boundary of the grey silica. The lateral extension of the deposit is known to be

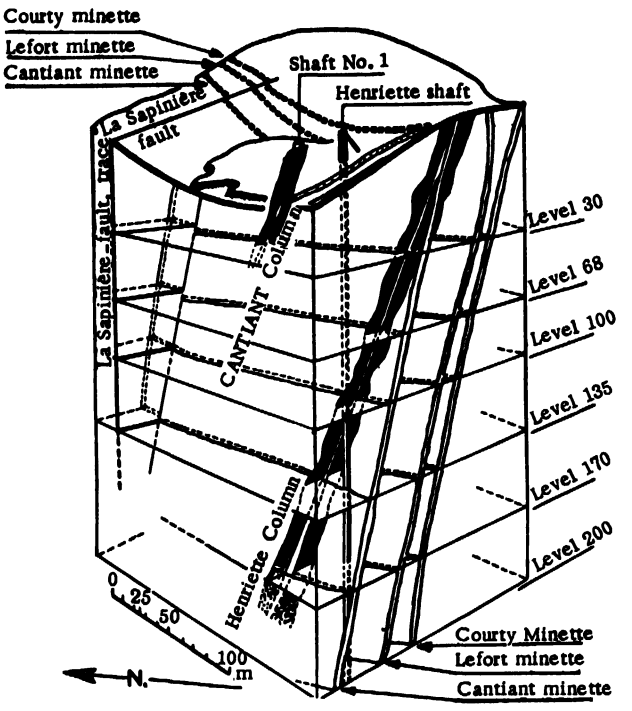


Figure 7. Limousin—Block diagram of the Henriette well

approximately 200 m. Several mining levels have been outlined. Drilling has indicated the presence of the mineralization to beyond a depth of 100 m. Over 1500 m of galleries already have been dug.

Group of Mortagne

The mineralization of the Mortagne group is known only by surface workings and drilling. These occurrences are aligned NW-SE and are probably intermediate between the deposits of Clisson and La Chapelle Largeau. The mineralization contains red silica, grey silica, and fluorite.

Group of Les Herbiers

The Les Herbiers group was first recognized in the Vendée mineralization. It is characterized by a very regular E-W alignment of about ten occurrences.

All these occurrences lie in a band of micaschist which extends south of the Mortagne granite massif, which is present north of the schist and brioverian quartzite boundary. This micaschist zone is characterized by a series of E-W fractures which are interrupted by N-S faults. The only deposit in which deep workings have been started is that of Edrillère which is being explored to a depth of —40 m. This appears to be an E-W fault, which dips 70° S and is filled with silicified clay. It is somewhat similar to the La Chapelle Largeau deposit.

Other Mineralized Regions in France

Aside from the regions already described in which uranium occurs in crystallines, and which are the only ones that have been worked to date, there are many other similar occurrences. However, at present these are only indicators: the principal ones occur in the following areas:

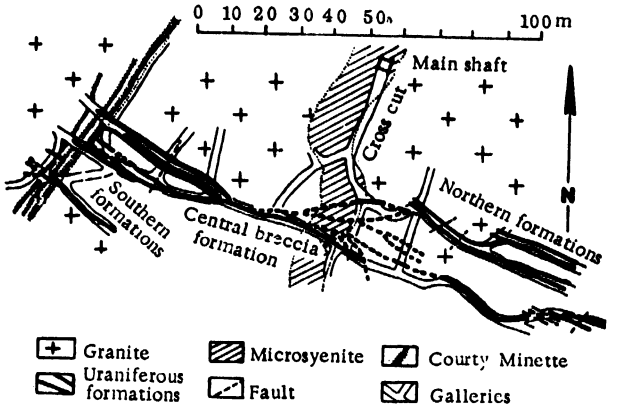


Figure 8. Limousin—Geologic map of the Les Sagnes deposits (level—40)

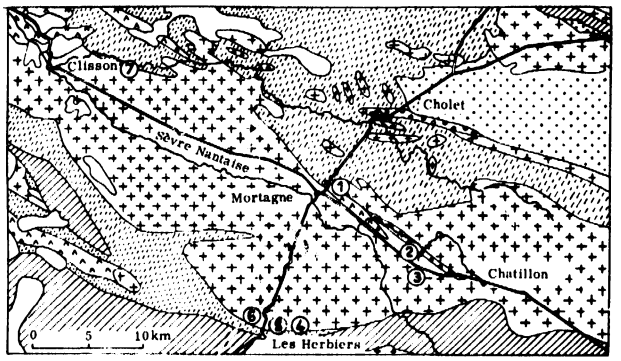


Figure 9. Map of the uranium-bearing region of the Vendée. Deposits: 1. Le Poitou; 2. La Chapelle Largeau; 3. La Commanderie; 4. L'Edrillère; 5. La Goriandière; 6. La Tudière; 7. L'Ecarpière

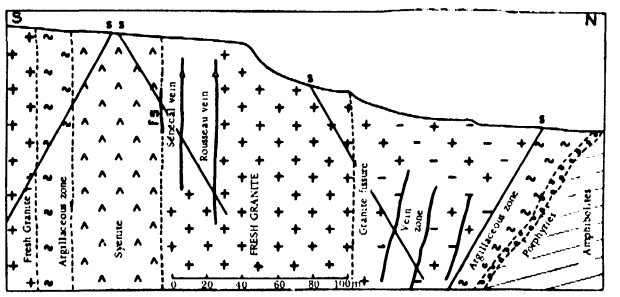


Figure 10. Vendée—Geologic cross section of the Escarpière deposit. S—drill holes

Creuse

Occurrences which appear to be similar to those at Limousin, particularly in the region of Boussac where pitchblende is associated with sulphides.

Beaujolais (South of Morvan)

Essentially, secondary mineralization with indications of pitchblende, and mineralogical associations which are similar to those of Lachaux-les Bois Noirs.

Vosges

Kruth (Valley of the Thur) occurrence of pitchblende, fluorite, Pb, Zn, Cu sulfides, and traces of Co and Ni, is somewhat similar to that at Wittichen (Black Forest).

South of the Massif Central

Deposits of smoky quartz and supergene minerals (chalcolite-autunite) which occur at many places

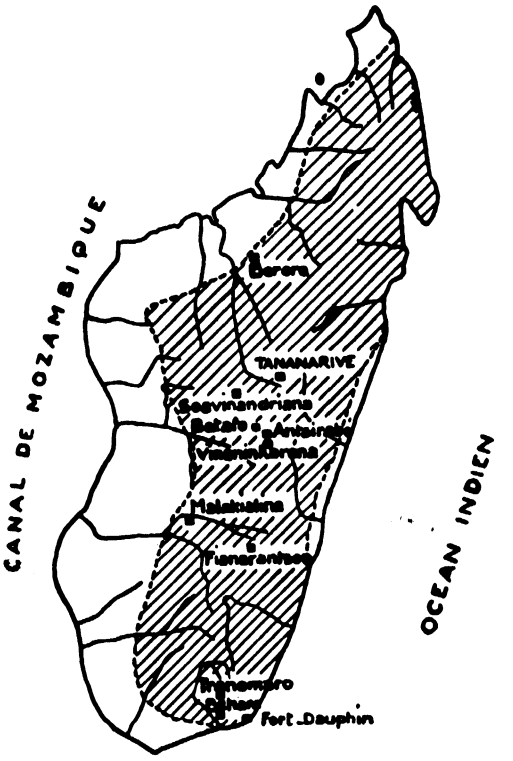


Figure 11. Map of Madagascar: hachures show the crystalline base of the Island

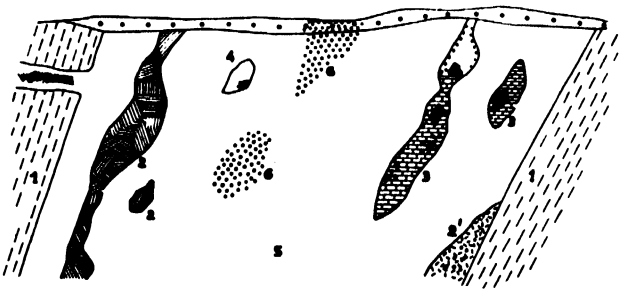


Figure 12. Schematic cross section of a pyroxenite formation (from H. Hésairie and G. Noizet): 1. Crystalline schists; 2. Phlogopite; 2'. Phlogopitic; 3. Lenses containing calcite, wernerite and uranothorianite; 4. Anorthite; 5. Pyroxenite; 6. Uranothorianite and "clouds"

in Aveyron and Lozère. Traces of pitchblende also have been recognized in the Lozère and Gard (Lead mine of the Orb).

Finally, a very different type of deposit is recognized in the Schaentzel (Haut Rhin). It consists of carbonaceous Westphalian schists and is related to the small basin of St. Hippolyte which formerly was worked for coal. These schists have a fair uranium content, although the form has not been identified mineralogically. It represents an important tonnage of metal.

MADAGASCAR

The presence of uranium-bearing mineralization in Madagascar has been known for a long time; however, only recently (1953) deposits in the south of the island which could lead to a production of truly industrial character have been recognized. This

Figure 13. Auvergne—Black Woods Area. Limouzat Mine. Level—40. Close-up: the drift cuts for several meters into the mineralized breccia which contains pitchblende and quartz

mineralization is varied and is of three separate types: lacustrine sedimentary, pegmatite, and uranothorianite in pyroxenite.

Lacustrine Sedimentary Deposits

These deposits, located near and to the south of Antsirabe at Vinaninkarena, have been known from the beginning of this century. They are related to an important quaternary lacustrine sedimentation which overlies the crystalline basement and in which certain argillaceous-sandy beds are locally impregnated with uranocircite (barium-autunite) in finely disseminated crystals. Several attempts at operation, before the C.E.A. and by the C.E.A. itself (after prospecting and careful investigation) have been made, but for the present they are abandoned (due to low content and working and concentration difficulties).

Pegmatite Deposits

Mineralized Madagascar pegmatites have been known for a long time and, in 1922, they were studied in detail by Lacroix, who described their uranium-bearing niobotantalates. At the same time Mlle. Brière discovered a sample of uraninite at Malakialina. From 1947 to 1950, prospecting and actual mining (the latter carried out even at depth when this appeared favorable) were conducted in the central part of the island which is particularly rich in pegmatites. However, this did not lead to any appreciable production and has been stopped.

Deposits of Urano-Thorianite in Pyroxenite

These deposits are the only ones which appear to be of current interest. Petrographically they are very different from the others, particularly the lacustrine deposits. Their recent discovery by the joint local Geological Department†† and the C.E.A., is the result of prospecting which began on the island since 1946 and is in progress.

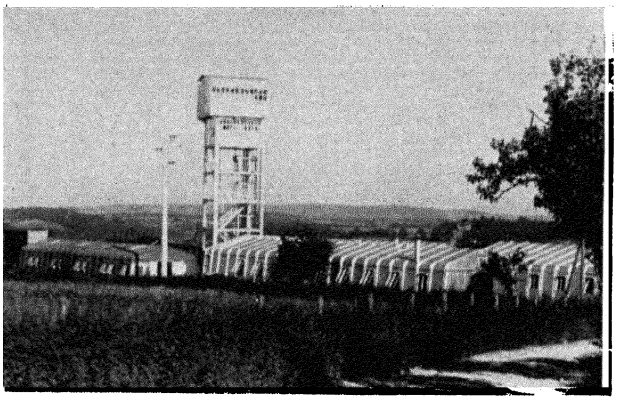


Figure 14. Autunois and Morvan—Grury Division—Bauzot Mine

Urano-thorianite is closely associated with masses or lenses of pyroxenite which contain diopside and are interstratified in pre-Cambrian crystalline schists from which they are inseparable. The length of the lenses varies but may reach several hundreds of meters. The mineral occurs in much the same way that the phlogopite mica does. This mica is worked in the same region and is associated in the same rocks.

The uranium-bearing rocks are localized in a large band in the form of an arc which is approximately 150 km long. It trends substantially S-N and is 30 to 40 km wide in the central part. This arc begins near the side west of Fort Dauphin and expands to the north in the basin of the Mandraré River. It is separated from the eastern side by an important granite massif.

From the practical standpoint one can distinguish between the *deposits already* in place, in which the urano-thorianite is associated either with vein masses of phlogopite or with "pegmatitic" masses of calcite, phlogopite, and anorthite—or else in "clouds" disseminated in the pyroxenite—and the *secondary deposits* which are alluvial or eluvial and are derived from an earlier deposition.

Prospecting and particularly mining research for the estimation of tonnages are in progress. However, as yet there is no accurate evaluation of the reserves, although it appears that this may be an important uranium and thorium district.‡‡

CONCLUSION

After less than ten years of prospecting and mining exploration, France now operates several important uranium deposits. In addition, many occurrences suggest that there are other workable deposits in the country. This is the result of continuous and methodical effort, during which insofar as possible nothing was left to chance. It is an example of what

†† Chief of Department: H. Besairie, Mineralogist: J. Behier.

‡‡ Head of Mission C.E.A.: P. Therene, Leading Engineers: A. Gangloff, Y. Puybaraud.

can be accomplished with a team of men who cooperate closely on a task which serves the national interest.

Geologically, these results show the existence in the French Hercynian massifs, of uraniferous mineralization which occurs in the areas *which have been known for a longer time* between the Erzgebirge and Portugal. Thus, on the basis of mineralogy and environment, the "French uranium region" unquestionably is similar to that of the "Portuguese uranium region."

Overseas, Madagascar is, at present, the only productive territory. Other than its lacustrine minerals, which are interesting from the standpoint of origin but difficult to work, the pegmatites show, as elsewhere, very mediocre reserves of uranium; on the other hand the Pyroxenites of the South show the presence of unusual and interesting deposits.

Uranium and Thorium Occurrence in Greece

By The Atomic Energy Commission of Greece

The geological structure of Greece is such that the occurrence of uranium and thorium minerals is not to be excluded. In fact there are in the country many granitic rocks and other acid eruptive rocks with pegmatite veins. There are also formations of bituminous limestones and clays, in which, as is known, increased concentrations of uranium occur.

Up to this time no systematic search for radioactive minerals has been carried out in Greece. Recently, however, there have been indications of the presence of uranium minerals in the West Thracian mountain chain of Rhodopi, as well as in the Pelagonian mass of Macedonia.

The newly created Atomic Energy Commission of Greece will start in the immediate future, with the help of trained geologists, a thorough investigation for the localization of radioactive minerals in the country's most suitable areas.

Natural Occurrences of Uranium and Thorium in India

By D. N. Wadia,* India

RESOURCES IN URANIUM

Occurrences of uranium and thorium have been known in India for many years: pitchblende was found in 1901 in basic segregations in a mica-pegmatite in the Gaya district of Bihar, in nodules weighing up to 36 lb. The deposit, however, pinched out after yielding about 6 cwt. Similar smaller occurrences have since been observed in Ajmer and Nellore.

Uranium in India is principally a product of igneous and metamorphic rocks, its genesis being due to epithermal, mesothermal or hydrothermal agencies, in granitic magmas, or to epigenetic action in large shear or thrust-zones. No uranium ores associated with sedimentary rocks have so far been known but the possibility of the great pre-Cambrian formations, Cuddappah and Vindhyan, originating from the denudation of the Archaean rocks, the source of all heavy metal deposits of India, enclosing some uraniferous sedimentary strata of sandstones and shales cannot be excluded. The uranium ores of India belong to three categories:

1. Low grade ores disseminated in Archaean and metamorphic rocks: (i) along the Singhbhum thrust-fault zone, 65 miles long (the Bihar Copper Belt), associated with soda granite intrusions in apatite-magnetite rocks, chlorite schists, quartzites, etc.; paragenetic minerals are copper, molybdenum, pyrite and apatite; and (ii) as segregations and disseminations in granitic gneiss forming an irregular belt in the Aravalli series in Rajputana.

2. Ores in pegmatites: pitchblende, and complex niobates, tantalates and titanates of uranium.

3. Deposits of monazite in beach sands on the east and west coasts of India in a series of local concentrations in favourable situations.

Uranium mineralization in the deposits of category (1) above is associated with sulphidic copper and with oxidized iron rather than with gold, lead, zinc or vanadium. The mineralization appears to have occurred in two different periods—at the time of formation of the Dharwar System of rocks (Archaean) in Bihar and Rajputana and subsequently in the Eparchaean orogenic epoch which gave rise to large shear and thrust-planes, accompanied by igneous intrusions. In the Singhbhum field uranium occurs as disseminations in metamorphosed primordial sediments, phyllites, schists, quartzitic rocks, etc., closely associated with intrusions of acid granite, epidiorite and soda granite. Thirty-four prospects, along the course of the 65 miles long thrust zone, revealed by geological survey and isorad mapping, are being tested by diamond drilling. The uranium content in deposits of this category varies from 0.03 to 0.1%. While a few stringers of ore of higher concentration up to 2 to 3% U_3O_8 are dispersed at random through the country rocks cut by the core drills, radioactive logging of the majority of the boreholes discloses a general absence of veins or lodes in the Singhbhum field. In this area exploratory drilling up to 500 feet has revealed a large tonnage of low grade ore yielding from ½ lb. to 1½ lb. U per ton of rock. The ore mineral present in this type is probably a primary uranium compound, capable of simple chemical leaching by carbonate methods. Mining, milling and processing do not present any special difficulty and the cost of extraction and treatment has been worked out at a figure comparable with that of the other uranium-producing countries. The geological environment and structure control are somewhat more favourable in the uranium belt lately discovered in the tightly folded zone of the Aravalli range in northern Rajputana. Here uranium occurs in epigenetic association with copper ores in Archaean phyllites as well as in the primary state in coarse-grained granites and schists of later age. Ground and aerial surveys have indicated a number of locations of high radioactivity in the Aravallis, where detailed prospecting has disclosed uranium-bearing rocks within the 0.04 to 0.46% range. Three promising areas have been marked out for depth testing by diamond drilling. The ore here is a titanate suggesting affinities to brannerite or davidite.

Workable uranium occurs in copper mine tailings in the Bihar Copper Belt, but the extensive dumps of gold mines of Mysore carry values too low for remunerative working. Ancient slag heaps of copper, lead and zinc are likewise too low in U-content. The phosphatic nodules in Cretaceous Trichinopoly rocks carry up to 0.01% U_3O_8. So far no uranium is detected in asphaltic residues of oil-wells, or in coal or lignite-ashes in appreciable amounts.

The complex uranium minerals occurring in pegmatites (category 2) are of many varieties, few of which are of commercial value. The most important are samarskite, fergusonite, annerodite, betafite (?),

* Geological Adviser, Department of Atomic Energy, Bombay.

davidite, uraninite, pitchblende, and their secondary alteration products, uraniferous allanite, triplite, cheralite and monazite. The U_3O_8 content varies from 10 to 39% (in the case of pitchblende up to 80%) but the quantities available are small and their occurrence, as is the case with pegmatitic segregations, is highly erratic and elusive. Pegmatites are most numerous and wide-spread in the mica belts of Koderma, Nellore and in the Aravalli region where granite has intruded Archaean schists. No core drilling or extensive trenching is done in the prospecting of this type of deposits.

The Monazite Deposits of Travancore and Madras Coasts (Category 3)

The voluminous monazite sand accumulations of these areas constitute an easily accessible source of uranium, the exploitation of which will liberate large volumes of thorium and rare-earth compound. Average monazite yields from 0.2 to 0.46% U_3O_8 and from 5 to 11% ThO_2. The exact constitution of the monazite molecule, however, is not yet known with certainty; it is a matter of doubt whether the thorium and uranium are held in combination with phosphatic or silicic acid or whether they occur as uncombined oxides. There are varieties of monazite much higher in both thorium and uranium values, e.g., the newly discovered variant (?) of monazite, the rare *cheralite*, which carries 4 to 6% U_3O_8, besides 19 to 33% ThO_2. An estimate of uranium available from the major monazite deposits located in the Travancore-Cochin sector of the Malabar coast is of the order of several thousand tons. Detailed prospecting and quantitative estimation of monazite in the ilmenite sands of the Madras-Andhra coast, some of which are comparable in size and richness with the concentrations mapped on the west coast, is in progress. Several new deposits of heavy mineral sands on the east coast, carrying relatively much higher content of monazite than on the west coast, have been mapped in 1954 by a field party of the Department of Atomic Energy investigating the Andhra beaches.

RESOURCES IN THORIUM

Thorium was discovered in the monazite sand of Travancore in 1909, and since that date it has supported an export trade varying from a few hundred tons to 5200 tons per annum up to World War II, after which its export was banned for strategic reasons.

Pegmatite Occurrences

Thorite and thorianite have been observed in minute amounts in some rare pegmatites, unlike Ceylon, where the mineral thorianite (ThO_2–70%) was for several years worked commercially. The chief source of the fission metal thorium is monazite, the monoclinic phosphate of some 14 rare earths and metals of the cerium group, in which thorium occurs (8 to 10.5%) as a constant ingredient. The original home of monazite is in the biotite and hornblende-schists and gneisses and pegmatites in the Western Ghats and in similar rocks in Bihar, Rajputana and Mysore.

Beach Sands

Today the main commercial source of monazite is the beach sands and dunes of the Malabar and Coromandel coasts, stretching in intermittent patches from Cape Comorin, through Travancore-Cochin and Malabar up to the Gujarat coast on the west, and through Madras and Andhra up to Orissa on the east. The monazite has accumulated through ages by the concentrating action of sea waves along with ilmenite, rutile and zircon. Up to the present, a detailed quantitative survey of monazite reserves occurring on the Travancore-Cochin littoral has been nearly completed; it gives a tonnage of a little over a million tons for this sector of the west coast. A series of fresh occurrences of ilmenite sand in hitherto unknown parts of this coast, containing a variable percentage of this mineral, has been brought to light within the last three years at Ratnagiri, Marmagoa and along the Gujarat coast as far north as the Narmada estuary near Broach. To this are to be added the new occurrences being surveyed on the opposite east coast as mentioned above. These coastal sands and dunes thus constitute a thorium asset of world importance.

Estimated Reserves of Thorium

There has been no detailed survey in the past of the total monazite reserves on an all-India basis. Previous estimates have ranged widely from 2 million to 5 million tons of monazite in the Travancore-Cochin sector alone; but these were little better than guesses. The Indian Atomic Energy Commission in 1953 commenced a systematic survey and mapping of the monazite resources lying on the Peninsular sea-board. This survey will be a comprehensive one and will take some years to compute the total reserves of monazite along with those of ilmenite, rutile and zircon. The percentage of monazite in the black heavy mineral sands and dunes, intermittently lining the two coasts, varies a great deal from site to site, but an average of 2% monazite in the raw ilmenite sand would be a fair approximation. Fresh discoveries of monazite are extending the area of these sand spreads and, according to present knowledge, there are 12 major concentrations occupying patches from a few acres to a few hundred acres in extent. From data so far available, a provisional estimate of 2 million tons of monazite, carrying between 150,000 tons to 180,000 tons of ThO_2, may be accepted as a rather conservative figure. The field parties engaged in systematic prospecting and mapping of the individual deposits along the west and east coasts of the Peninsula are evaluating the monazite content by radio-assay and micro-counts from systematically collected samples, with occasional checking of the same by chemical analysis. This survey, when complete, will furnish reliable and authoritative statistics of the reserves of this highly potential fission metal.

The new mineral cheralite (composition ThO_2–31.4%, U_3O_8–4.48%, P_2O_5–24.55% and SiO_2–3.12%), and probably some other unnamed variants

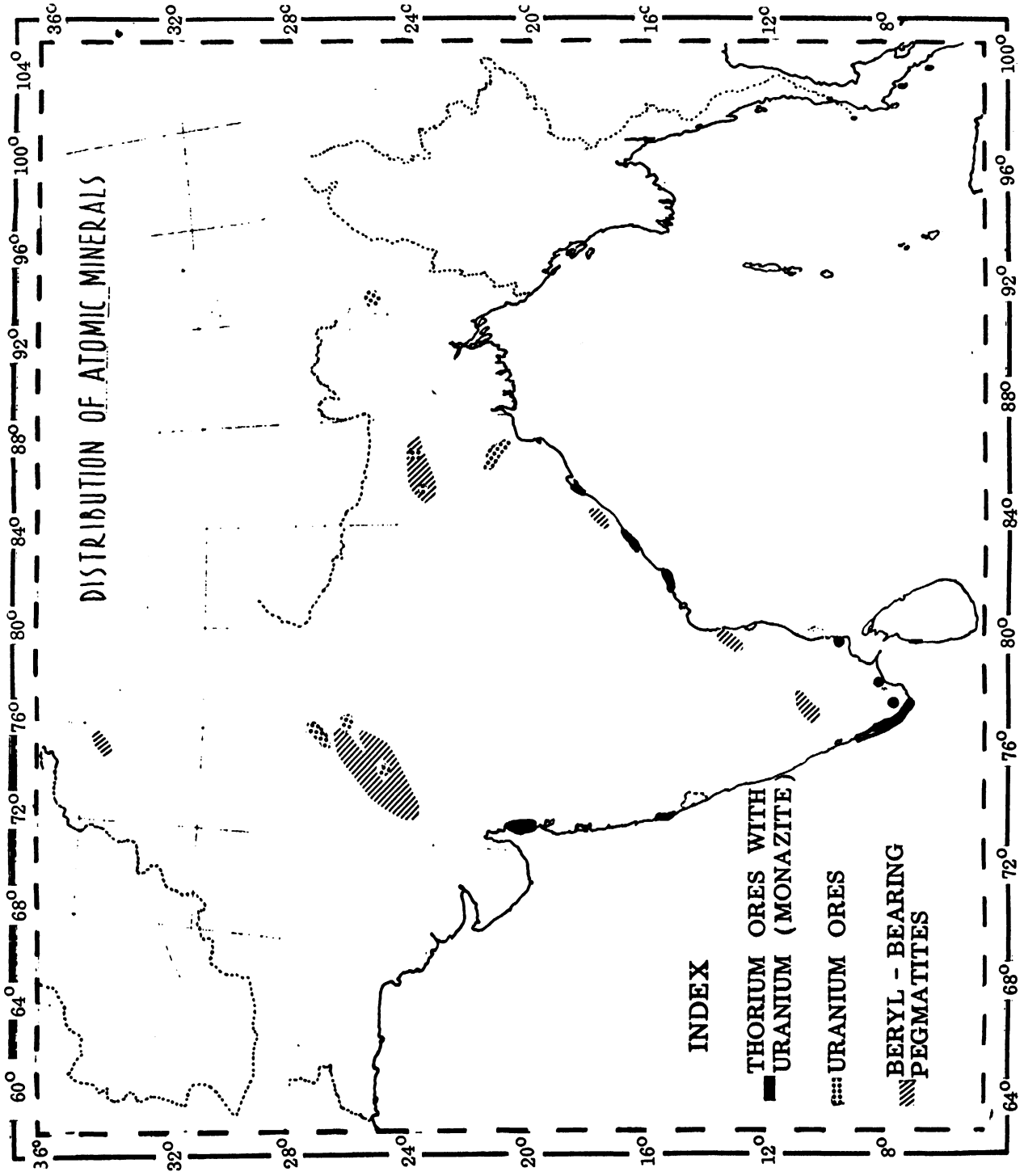


Figure 1. Distribution of atomic minerals

of monazite with thorium content as high as 19 to 33%, found in recent years in small quantities in their rock-matrices, though not likely to swell this figure materially, will form valuable local sources of supply for industrial purposes.

The intensely radioactive product *meso-thorium*, the natural disintegration product of thorium, is extractable from monazite.

FUTURE PROSPECT

The vast extent of country covered under ancient rock formations, both in the Deccan Peninsular shield and the extra-Peninsular region of the north, particularly the Himalayan terrain, yet remains to be examined for its uranium potential as well as for resources in ancillary atomic minerals. The million square mile Archaean and pre-Cambrian rock expanse, with its cover of basic lava flows in the northwest (many of which are known to have measurable content of uranium $\approx 10^{-6}$ gm per gm of rock), is covered only in comparatively insignificant proportions by systematic geological prospecting and survey. The Rare Minerals Survey Division of the Indian Atomic Energy Commission started work in 1949 by sending out small parties of geologists for preliminary reconnaissance of selected areas with the aid of Geiger counters, to be followed by more detailed prospecting and mapping of favourable ground. The thousands of mica pits and open-cast excavations of the ground offered good starting points in Bihar and Rajputana provinces for their work. But the extent of area covered by such operations, with a total force of 52 geologists and 30 physicists, yet remains small. So far the Himalayan region has hardly been touched by these surveys. The Himalayas are regarded as generally barren in sizable mineral or metal veins or lodes. Its very recent orogeny and the observed poverty of this region of middle and late Tertiary uplift in metallogenic provinces has influenced this attitude amongst Indian geologists. But large areas of the inner Himalayas are yet geological *terra incognita* and need to be investigated by aerial geophysical surveys, especially in the central and axial parts of the Range which are marked by a series of granitic and gneissic intrusions of immense sizes.

A planned programme of investigating these areas in the next two years is being formulated. The present strength of the geological and physical personnel engaged in the Raw Materials Division is being gradually increased.

A few trial flights with a helicopter fitted with scintillator have pointed out belts of radioactivity in the Aravalli mountains 100 miles southwest of Delhi. A small fleet of jeeps carrying radiation detecting devices is being put on the road for traverses over the country in extension of the ground covered by the field geological parties.

Airborne scintillometer reconnaissance as part of the routine geological survey is under organization. This is certain to extend the sphere of operations of the ground parties and reveal new areas of uranium mineralization in unsurveyed territories. It is also likely to throw light on the uraniferous rocks of the interior and marginal tracts of the Peninsula, which must be the carriers and ultimate sources of the large accumulation of coastal rare mineral (titanium, thorium, zircon and uranium) sands.

It would be hazardous to predict any large accessions of uranium and thorium from these hitherto unknown regions; at the same time the prospect of discovering many commercially workable uranium deposits in new fields cannot be ruled out. In the following list the more probable rock formations are indicated as well worth detailed exploration for workable uranium sources. Many of these are known to have radioactivity of varying intensity and need systematic aerial and ground investigations: (1) Archaean and Eparchaean granites of Rajputana, Madhya Pradesh, Nilgiri, Chhota Nagpur and Madras—Segregation pockets and fracture planes; (2) the Central gneiss zone of the Great Himalayan range; (3) the Khondalite series of Orissa and Madras—measurable uranium content has been observed in these; (4) the chromite-bearing gabbro sills and dykes of Dras, Kashmir; (5) the basic and ultrabasic intrusions in the inner Himalayas of Garhwal and Kumaon; (6) the black slates of the Cuddappah System; (7) the bituminous shales and dark sandstones in the Vindhyan System; (8) the radioactive constituents of the Sausar and Sakoli series of Madhya Pradesh; (9) the magnetiferrous sandstones of the Siwalik series of the Punjab foothills; (10) the Cretaceous phosphatic deposits of Trichinopoly; (11) tailings and old workings of the gold mines of Hyderabad and Wynad; (12) the more radioactive flows of the Deccan Trap and its acid and basic differentiations; and (13) some Tertiary lignites of Assam, Arcot and Bikaner.

Estimate of Total Amount of Uranium and Thorium Available in India

Uranium	*Thorium*
1. 6000 to 7000 tons from monazite sands; no mining required.	1. 150,000 to 180,000 tons from monazite sand easily and economically extractable. No mining needed. Simple electromagnetic refining to 99% purity from the larger deposits.
2. 3000 to 4000 tons from Singhbhum field; economically extractable.	2. A smaller tonnage from less concentrated deposits scattered in beach and dune sands and on the beds of lagoons and stream courses.
3. A minimum of 3000 tons from the Aravalli fields, Khetri, Dariba, Khandela, etc. In early stage.	
4. A much larger tonnage from 2 and 3 but at less economic rates.	

Present State of Uranium Surveys in Italy

By Felice Ippolito,* Italy

ABSTRACT

The knowledge of geochemical phenomena affecting the distribution of various elements in the different lithologic units of the earth's crust, and of the geological strata which gives the essential data on industrially available mineral deposits, now suggests the possibility of finding in a given region deposits of a certain mineral or groups of minerals. In the territory of Italy geological knowledge is such as to confine, at least in a preliminary way, uranium research to well defined areas, eliminating from preliminary investigation various regions of the Peninsula from the Alps to the crystalline deposits of Calabria.

We must pay attention above all to the more or less known granitic crystalline structures with particular regard to those of the Ercinic period which show pegmatitic, pneumatolitic and hydrothermal veins.

For these reasons, here only mentioned, geological uranium surveys had to be turned, at first, to the crystalline outcrops of the Graie and Pennine Alps (Northern Piedmont), the Sila (Calabria) and Sardinia, even though in this last region the chemical nature of the granitic magmas seems unfavorable for research. It is, however, advisable to consider the paragenesis of the mineralized veins of the Sarrabus and their relation with uranium mineralization.

Particularly in the western Alps the surveys should be directed toward the numerous granitic-gneissic areas of Dora-Val Maira, Gran Paradiso and Mt. Bianco. These investigations should include the overlying or interbedded Permo-Carboniferous. The porphyries are considered only when they occur in the Ligure-Piedmontese group. Their progressive metamorphism has long been a subject of investigation.

Other interesting igneous formations of this type, occur in the Canavese, the region of Mt. Bianco and in the eastern and Apuane Alps. It would be worthwhile to have more detailed geological and geophysical information on these areas.

Surficial deposits are not likely to occur in Italy, however some of the bituminous and asphaltic areas of Sicily should be examined as well as the phosphatic formations and thorium-uranium sands of the Tyrrhenian littoral.

Italian uranium occurrences are mainly in low percentage "diffusion" layers. This type of deposition is common in other parts of the world.

Data on the presence of uranium mineralization is scarce and although radioactive areas are frequently found, they have never been studied with particular care. Some of these localities lie near pegmatite outcrops in which some uranium ores have been found recently. In this connection it is worthwhile to mention the Monteschemo, Devio, Colico, Piona and Olgiasca pegmatites of the Northern Piedmont and Lombard Alps.

It is interesting to note the 1912[1] discovery of autunite at Lurisia (Cuneo) in schists which are probably upper Permian. Geologic and preliminary chemical studies were published later.[2] It is interesting to note that since then a rather optimistic opinion on "the possibility of mineral diffusion on a much larger horizon than the porphyroids" was foreseen, and that it was considered "probable that a primary mineral could be traced to numerous igneous formations or an underground metalliferous vein."

A more recent discovery is the radioactivity in the Tyrrhenian littoral. An investigation of the nature and percentage of the thorium-uranium minerals in the sands is a part of the future program of the National Committee for Nuclear Research (Comitato Nazionale per le Ricerche Nucleari).

ACTIVITIES OF THE C.N.R.N.

In 1952 the National Committee for Nuclear Research was founded in order to coordinate and increase the national activity in uranium surveys and exploration.

The first task was therefore that of studying the research methods adopted in other countries of similar geology in order to choose suitable methods for the geological features of our territory.

Research Method

The study of the French Organization of D.R.E.M. (Direction des Recherches et Exploitations Minières) of the Atomic Power Department, shows that the most efficient method for this type of research consists of systematic ground prospecting in zones previously chosen on the basis of fundamental principles or geologic studies. A more detailed description of the method used is found below. At the moment it is of great significance to point out that the preference given to the system adopted in France rather than to that followed in the USA is justified by the complicated geological and topographical structure

* Member and Secretary of the Comitato Nazionale per le Ricerche Nucleari.

of the Italian peninsula and by the limited area of the uraniferous formations. The efficiency of the American methods, for example the aerial observation of radioactive anomalies, is greatly reduced by the above conditions which also make them much more expensive.

The French research methods increase prospecting in known radioactive localities as well as starting exploration in completely new zones, in which the geology suggests the possibility of uranium. This systematic prospecting is carried out by "missions" of "flying squads" of geologists who obtain the following data: (i) gamma radioactivity measurements, at first widely spaced and then successively closer together; (ii) as detailed geological observations as possible; (iii) collection of representative samples for a subsequent petrographic and stratigraphic study; (iv) topographic correction for the localization of radioactive highs.

The information obtained from this first stage by radioactive prospecting, ground exploration and petrographic and chemical analysis forms the basis of the second research stage. In this stage it is possible to proceed to detailed prospecting by means of digging and drilling. If the locality proves favorable, underground mining can be assigned to industrial companies which are under the scientific direction of the Committee.

In Italy prospecting started, as in France, on areas in which the presence of uraniferous minerals has been established as in the Maritime Alps. Therefore geologists equipped with Geiger counter and rapid transportation have carried out the first stage of surveys or reconnaissance with satisfactory results. Based on these data the "detail stage" is now being planned.

At the same time in the field of low grade mineral occurrences, the Committee has focused attention on the Sicilian asphaltiferous layers, Sabatini volcanic tuffs, Tyrrhenian littorals, and the phosphatic formations of the Salentina peninsula. These surveys are however still in a preliminary stage.

Geological Surveys and Prospecting in the Maritime Alps

A geological investigation and a large scale radioactive survey was carried out in the Summer-Autumn 1954 on that part of the Maritime Alps which seemed most likely to contain uranium mineralization. This region is limited on the north by the Mondovi-Cava-Millesimo-Colle di Cadibona-Savona line, and on the south by the upper R. Tanaro, between Viozene and Garessio (Fig. 1).†

This area includes several favorable Permian formations: the quartziferous porphyries and their tuffs, the porphyry and porphrytic schists, and the white or greenish quartzite. Some schistose-slate and arenaceous *facies* of the Carboniferous (Viozene) were also taken into consideration, as they had shown previously radioactive characteristics.

This investigation was aided considerably by a large number of previous geologic studies. These include a paper on the petrology of the Rio Freddo which is being published. This paper shows that the mineralization of the Permian porphyric schists preceded the metamorphism which transformed and altered the primary structure. Therefore the alignment of the original mineralized bodies in more or less large lenses tends to follow the schistosity of the overlying rock. Microscopic studies confirm these conclusions on the nature of the uranium mineralization in the Rio Freddo.[3]

The preliminary ground observations outlined the Permo-Carboniferous formations in which the geophysical survey showed radioactive highs. In this way the different uraniferous outcrops are located precisely.

The "Boves" and "Albenga-Savona" sheets of the Italian Geological Map are the base maps for these surveys. The ground observations of this recent survey confirm the geology shown on the Boves sheet, although the petrographic interpretation is out of date. On the other hand the second "Albenga-Savona" sheet is not as accurate with regard to the Permo-Carboniferous of the earlier map. The conclusion reached on the basis of this investigation is that the gneissic *facies* of the eastern side of R. Tanaro, mainly ascribed to igneous Permian formations, belongs on the contrary to magmatic Ercinic inclusions which underlie a Permian-Carboniferous paraschist. It is believed that this will be confirmed by additional chemical and petrographic studies.

The Ercinic magmatism seems to be exclusively igneous in the Maritime Alps between the R. Tanaro and the Val Vermenagna where numerous anticlinal and synclinal ridges with east-west axes slope towards the Piedmontese plain. The principal tectonic feature is, however, the anticlinal structures in which thick fine grained porphyry outcrops in the centre, and porphyroid and porphyry schists along the flanks. The latter probably are derived from tuffs and arkoses which were discontinual in the uppermost porphyric formations, and now lie along the flanks of the anticlinals. As a result of their heterogeneous nature they have undergone strong dynamic metamorphism.

The porphyry schists have been studied extensively since they are important in the localization of uranium. The porphyric Permian probably consists of several extrusions with interbedded pyroclastic zones. It is not possible however, because of metamorphism to distinguish and map the different igneous rocks. While it is relatively easy to identify the primary igneous rocks from the slightly laminated porphyric masses, it is on the contrary very difficult to recognize them when the dynamic-metamorphism is more intense.

Microscopic examination shows that these dark green porphyries contain feldspar and quartz pheno-

† Figure 1 comprises the "Boves" and "Albenga-Savona" sheets of the Italian geologist map with scale of 1 to 100,000 —Nos. F° 91, 92 and 93, which cannot be reproduced here.

crysts in a homogeneous and compact groundmass. Strongly laminated facies have been found as dynamic metamorphism has destroyed the primary mass to form a schistose structure. These porphyroids are gray-green, and have more or less oriented phenocrysts which are less abundant than in the unmetamorphosed material. Some of the feldspar has altered to kaolinite.

It is not always possible to distinguish the porphyroids from the over-lying porphyric schists without microscopic examination. This area has been mapped since the geological survey by the Committee[4] for the M. Besimauda section, has shown that the pitchblende and sulphur mineralization are localized in this formation.

Microscopic examination of the most abundant of these schists shows a mixture of granular quartz, sericite and some chlorite. Structurally the material is schistose, slightly undulated and strongly folded. It varies from a green-yellow to gray-green colour. Relict phenocrysts are sometimes visible and a black greasy cover which probably is organic appears occasionally along the schistosity. Numerous lenses and quartzitic zones of variable thicknesses are interbedded with the thinner facies. This is accompanied by veins of kaolinitic material derived from feldspar alteration.

On the basis of the field study it has been found that the pitchblende and sulphur mineralization is mainly localized in the schistose layers which lie along the contact with the quartzite which in turn forms a transition zone to the lower Trias. These layers are generally observed below the schists, although stratigraphically they are above. This reversal is caused by the northern sloping of the ridges.

As stated previously, this mineralization which is known to be pre-metamorphic lines in lenses along the schistosity as a result of the alpine regional metamorphism. Therefore, as confirmed by the results shown in Fig. 2 (isoradioactivity map) these lenses are elongated at the surface to the west along a rather thin zone.

Along the margins of the mineralized zones numerous characteristic secondary minerals have been observed. These include torbernite and autunite, and mixtures with limonite the colour of which may mask the associated uranium-bearing red-orange minerals.

The pitchblende which is generally sooty is mixed with pyrite, chalcopyrite and occasionally carbonaceous material. Quartz, probably primarily, is characterized by a reddish colour.

Although microscopic and chemical studies are as yet incomplete, it is generally assumed that the paragenesis of the two main formations of R. Freddo and Bric Colmè, is very different.

It is important to note that some mineralization may be associated before metamorphism with pegmatitic phenomena, whereas some may be due to later deposition or to low temperature phenomena.

Specimens collected during the field study are being studied microscopically in order to determine the tectonic and stratigraphic genesis of the main facies. This study is in progress at the laboratory recently created by the Committee in Cuneo. This is located near uranium-mineralization.

The isoradioactivity map (see Fig. 2) is a graphic representation of the ground measurements determined during the geophysical survey. This map shows three progressively higher areas of radioactivity as follows: *Area A:* values lower than those of the Geiger scale, up to a maximum of 5 cps; *Area B:* values between 5 and 10 cps; *Area C:* values higher than 10 cps with maximum peaks of 100 to 150 cps. Although this map has certain limitations with respect to scale and count intervals it does show in this early stage of reconnaissance that the mineralized area corresponds with that of the upper Permian porphyry schists.

The radiometric surveys show that the uranium mineralization is concentrated within distinct areas. This is reflected in the abrupt rise or fall of the counts per second at mineralized outcrops and away from them. This agrees with the localization of mineralization in lenses.

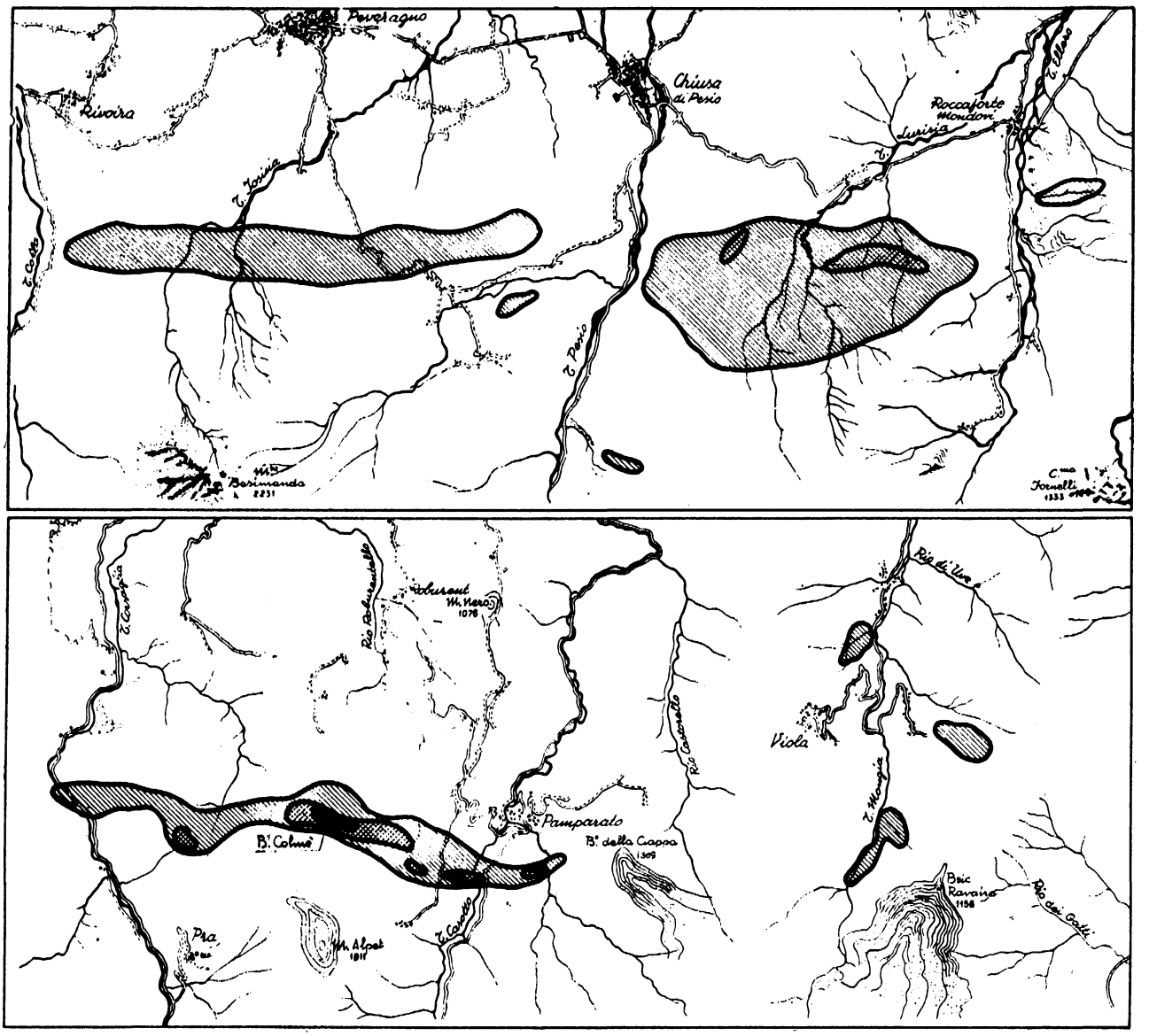
Preliminary Studies on the Thorium-Bearing Sands of the Tyrrhenian Littoral

The Committee has also considered the Tyrrhenian coastal sands which previous scientific research[5] has shown to be mixed with thorium-bearing materials. The Mineralogical Institute of Pisa University cooperated with the Committee in this study.

The investigation started with a series of qualitative determinations on material from the Nettuno, Ladispoli and Fregene sands, in which the presence of uraniferous thorite and monazite had been ascertained. Crystallographic and chemical studies led to the identification of "perrierite", a new silico-titanate of rare earths and thorium.[6]

A large part of the Tyrrhenian beach is derived from altered tuff much of which is found in south-central Italy where it forms a product of Quaternary vulcanism. The only sand, however, which is of particular interest as it is higher in thorium is that which occurs along the shore between the village of Nettuno (Roma) and the "La Banca" locality, about 1500 meters north of Torre Astura.

Radioactivity measurements have been made on the surface and underground material down to a depth of one meter, and the thorium-bearing minerals have been studied mineralogically. This material consists of perrierite, monazite and uranothorite. The total amount of thorium-bearing sand in the above mentioned zone is estimated as 444,000 tons. Based on the average ThO_2 content of 60 gm/ton, about 27 tons of ThO_2 would be present in 710 tons of 3.5% mineral. These figures may seem low, but a number of other useful minerals occur in the sand, and their extraction could lower the production cost of the thorium-bearing minerals. On the basis of the



Area with radioactivity values up to 5 counts per second

Area with radioactivity values between 5 and 10 counts per second

Area with radioactivity values higher than 10 counts per second up to a maximum of 100 to 150 counts per second

Note: The geophysical prospecting was carried out in 1953-54 by P. Baggio, G. Cevales and F. Silvestro, with supervision by F. Ippolito

Figure 2. Map of isoradioactivity

mineralogical composition of the Nettuno sand‡ we can assume that 44,000 tons of titaniferous magnetite, 10,000 tons of garnet, 4000 tons of zircon as well as small amounts of cassiterite and gold could be extracted.

It should be noted that only that part found on the shore is considered in these estimates, whereas a large amount of sand could be extracted from under the sea, at least for a short distance. A conservative estimate would be that the immersed area is at least equal to that of the emerged zone. This would then double the tonnage estimates.

Other Preliminary Studies

On the basis of the proved radioactivity of the tuffs at other localities, the tuff surrounding Lake Bolsena and much of the Viterbo has been radiometrically surveyed and found to have values which are above average.

The lavas and tuffs of Radicofani do not show any significant radioactivity.

Very small percentages of thorite occur in the sands near Bracciano, but economically they are not significant.

These preliminary studies have been made by the General Chemistry Institute of Rome University, which also has begun an investigation of the Miocene phosphate deposits at Puglia.

Preliminary studies are in progress in Southern Sicily on the asphaltic formations of Ragusa, which are believed to be middle and lower Miocene. This investigation is being made by the Mineralogical and Physical Institute of Palermo University.

PROSPECTING AND UNDERGROUND WORK BY MINING COMPANIES

Prospecting for radioactive minerals in Italy was begun in 1947–48 by two mining companies: the Montecatini and the Società Mineraria e Chimica per l'Uranio (Uranium Mining and Chemical Company). These firms focused their attention on zones in the Piedmont Maritime Alps. On the basis of the aforementioned guides a geophysical survey with Geiger counters was initiated in areas where current mining laws granting prospecting permits were in force. Last year, in addition, the AGIP Mineraria organized a Centre for Radioactive Mining Research. The results of this research to date are summarized below and the writers extend grateful acknowledgment to these companies.

Soc. Montecatini

The company expanded its prospecting in 1948 to include the large area from Chiusa Pesio (northern branches of M. Besimauda) to the French boundary along Val Roia and Val Vermenagna. Detailed exploration was extended to the Lurisia region, to the Permian "besimauditiche" formations and included the waters of the numerous local streams and lakes.

The above-mentioned areas were considered favorable for prospecting by the company geologist who postulated that the uranium mineralization is related to the nearby Argentera granitic mass. Traces of this material previously had been found in the Vallauria and Vinadio pegmatite and in the region near Terme di Valdieri. Later, geophysical exploration was extended to the eastern zones of Lurisia and to the Carboniferous formations near Viozene (valley of R. Tanaro), west of Col di Nava.

As a result of these investigations the company has found many uraniferous formations on the northern slope of the M. Besimauda group. The most significant of these are: Rio Freddo, Pradeboni, Rio Argentina, Valle dei Morti and Ciarma.

Since 1949 the Montecatini Company has concentrated on the Rio Freddo. A drilling program was carried out in order to locate the primary mineral which was responsible for the large amount of secondary uranium mineralization at the surface.

The shafts and drifts show that two mineralized formations exist. They have a variable thickness, which never is over 40 cm. These are separated by one to four meters of barren rock. At certain depths folding and faulting make mineral exploration difficult. The uranium mineral appears as a black powder which is associated with organic matter and dark red quartz. Preliminary studies carried out by the writer on Rio Freddo samples since 1952, show the presence of *amorphous pitchblende*. At the same time underground exploration continued in other favorable areas.

At Ciarma di Predeboni and Rio Argentina underground work seems to confirm the presence of strong mineralization as evidenced by abundant autunite and torbenite which appear at the surface. A more complete summary of the recent investigations by the Montecatini Company is shown by the following data: (1) explored hectares 79,665; (2) shafts lm. 590; (3) drifts lm. 1579; and (4) stopes lm. 302.

Società Mineraria e Chimica per l'Uranio

This company started systematic surveys in the spring of 1947. They began in an area just west of Lurisia where the upper Permian schistose vein was traced as some uranium-bearing phosphate had been noticed.

The company technicians succeeded in discovering the Fiolera (Val Pesio) layer in which underground and surface work ascertained the presence of a gray-blackish uranium oxide which is associated with pyrite and quartz.

Further surveys on the area between Val Corsaglia and Val Casotto to the east of the well known Lurisia area, show similar mineralization along the schist outcrops. Among these, it is particularly worth while to mention Bric Colmè, the area adjoining the Cardin locality, Assunta of Val Casotto and Val Limona, near the hamlet of Pamparato.

‡ According to the data of the Mineralogical Institute of the Pisa University, the sand composition should be as follows: pyroxene, 69.7%; magnetite and ilmenite, 12.4%; feldspar, 7.3%; garnet, 4.4%; quartz, 3.3%; calcite, 1.5%; and zircon, 0.9%.

In these localities digging was necessary in order to remove the heavy overburden which obscured the mineralization. The attention of the company however was focused at Bric Colmè which appeared more promising as underground work confirmed the presence of uranium mineralization. At this locality also the uranium minerals are gray-black and are associated with pyrite, manganese oxide, quartz and decomposition products which form "dark yellow ochres".

AGIP Mineraria

The AGIP Center for Radioactive Mineral Research first considered the organization of the technical staff, then the assembly of necessary equipment for ground operations as well as for the physical laboratory plant. Preliminary investigations have been carried out in the following zones: (*a*) Apuan Alps, in the zones north of Pietrasanta and near the town of Massa in November 1954; (*b*) Calabria, in the zones of M. Poro and of Delianuova in January and February 1955; and (*c*) Sardinia, in the zone of Sarrabus in January and February 1955.

The lack of staff and the climatic conditions have made it difficult to obtain reliable data for these zones.

Surface exploration is based on the work carried out by two groups: the first group has been working for several months in Calabria where gneissic formations cover pegmatite near Reggio Calabria. A gamma survey is carried out systematically along lines which are 10 m apart. These are fixed with the aid of a tachometer. About 40 km² have been explored. The second group has been at work since May, 1955 in the Maritime Alps. Geologic studies and systematic prospecting with the gammascope is being carried out by this group near the town of Ceva. The results obtained by these two groups are not as yet sufficiently confirmed by chemical and physical analysis to be considered reliable or encouraging.

A third group is being organized to be sent to Sardinia as soon as the agreement which is in progress with the Government of the Sarda Region is concluded.

CONCLUSIONS

At present the results in Italy in the field of uranium exploration by the Committee and private companies acting in accord with the Committee, seems satisfactory.

The previously explored areas are, as a matter of fact, very limited compared with those which may be investigated in the future. To this it must be added that significant mineralization has been discovered where previous opinions had excluded it.

The program developed by the Nuclear Research National Committee in the Maritime Alps, has been described. Their preliminary results are as follows.

Geologic investigation and the geophysical prospecting carried out during the summer of 1954 has shown that the igneous lavic formation has a much smaller area than that given by the official geologic the contrary mainly an intrusive gneissic facies which map. In fact the western Tanaro formation, which should consist of schists and Permian porphyry, is on is covered by an older, varied paraschist.

The results of these investigations show conclusively that the uraniferous mineralization is restricted to a well defined horizon, namely the upper Permian porphyry schists. It is therefore considered unwise to extend research to the other Carboniferous and Permo-Triassic formations.

The committee of geologists focused particular attention on these schists in order to determine the cause of the localization of the mineralization. The northern branches of the Maritime Alps are divided into three zones, each of which differs structurally.

The first and largest zone, located near the village of Peveragno (Cuneo), extends from Val Colla to Val Pesio. This includes from west to east the prospects at Tetti Meni, Rio Freddo, Eretta, Ciarma, Valle dei Morti, Valle del Malinverno and Rio Argentina. South of this alignment, in the middle of Val Pesio there is a small area which contains the prospects of Tetti Ruggero (near the village of S. Bartolomeo), Tetti Corda, Tetti Marat and Fiolera, near Vigna.

The second, smaller area includes the light porphyry schists which lie south of Lurisia. In this zone significant radioactivity is noted at Testa di Radeschi, Tetti Nuvola, Case Blot, and Rio S. Luca.

The third zone extends from Val Corsaglia to Val Casotto, just upstream from Pamparato. It consists of the prospects at Volpi, Bric Colmè, Case Furù, Assunta, Ravino and Val Limona. Just east of the latter locality the mineralized schistose horizon disappears due to the tectonic forces near the intrusive body which have transformed this material into gneiss.

Other uraniferous manifestations have been found in Carboniferous phyllite schists of the upper Val Mongia, near Tetti Lignoli. This mineralization is characterized by the presence of lenses and small quartz veins, of oligist iron (hematite) and limonite.

The field results of the geophysical survey by the Soc. Montecatini and the Società Mineraria e Chimica per l'Uranio have been summarized in this paper. It is, however, significant to mention here in conclusion that although the mining work has been mainly exploratory, it has produced a certain amount of ore which has been analyzed for uranium. For example, at Rio Freddo the pitchblende which is indicated at the surface by abundant autunite, occurs at a depth of 10 to 15 meters. Here, the Montecatini mined about 300 tons of ore with a uranium content which varies from 2 to 5%.

The Società Mineraria e Chimica per l'Uranio on the other hand mined the following amounts of material at Bric Colmè and Fiolera (this last locality actually is not in operation): (*a*) ore with 3 to 6% uranium = some tenths of tons; (*b*) ore with 1 to 3% U = over 100 tons; and (*c*) earth with as much as 11% of U = great quantities.

In general, the early radioactive surveys by the National Committee for Nuclear Research, may be considered successful as the more important mineralized areas in the Maritime Alps have been recognized. We may therefore conclude on the basis of these results and of those which are being reached by private companies, that the research and development of uranium in Italy does not justify pessimism. Results of laboratory investigations are encouraging.

In conclusion the writer particularly wishes to thank the directors and technicians of the Montecatini, of the Società Mineraria e Chimica per l'Uranio and of the AGIP Mineraria for their very generously given data. Grateful acknowledgment is given to Prof. S. Bonatti and Dr. G. Marinelli of the Mineralogical Institute of Pisa University who studied the thorium-bearing sands of the Tyrrhenian shore. The author also wishes to thank his colleagues at the National Committee for Nuclear Research, P. Baggio, G. Cevales, F. Silvestro, for their enthusiastic cooperation. It was this cooperation which made it possible for these results to be obtained in such a short time.

REFERENCES

1. Lingio, G., *Sull'autunite di Lurisia,* Rend. Acc. Scienze of Turin (1912-1913).

2. Franchi, S., *Nuove osservazioni sul giacimento del minerale radifero (autunite) di Lurisia,* La Miniera italiana (January 1923).

3. Ippolito, F. and Nicotera, P., *Contributo alla conoscenza del giacimento uranifero del Monte Besimauda (Alpi Piemontesi),* Rend. Soc. Mineral. It., year IX, (1953). See also "La Ricerca Scient." 22, No. 10 (1952).

4. See Ippolito, F. and Nicotera, P., *ibid.,* and Cevaltes, G., *Il giacimento a pechblenda e solfuri di Rio-Freddo-Peveragno,* Boll. Soc. Geol. Ist., Vol. LXXIII (1954).

5. Bonatti, S. and Galitelli, P., *Sulla torite di Nettuno,* Att. Soc. Toscana of Nat. Science, Memorie, Vol. LVII, Series A, Pisa (1950).

   Gottardi, G., *La sabbia di Nettuno (Roma),* Att. Soc. Toscana of Nat. Science, Memorie, Vol. LIX, Series A, Pisa (1952).

6. Bonatti, S. and Gottardi, G., *Perrierite, nuovo minerale ritrovato nella sabbia di Nettuno,* Att. Acc. Lincei, Rend, Series VIII Vol. IX, p. 361, Roma (1950).

Natural Occurrence of Uranium and Thorium in Japan

By the Geological Survey, Japan

INTRODUCTION

Uranium and thorium minerals in Japan have been found in granitic pegmatite regions (accompanied by feldspar, silica stone) and sometimes in tin placers. They were seldom mined for production purposes; in most cases, they were merely the object of scientific research or collection of minerals.

During World War II, however, researchers for industrial utilization of uranium and thorium minerals were stimulated and urgent survey and prospecting were carried out in the principal localities. Some of the ores produced as a result were employed in various experiments and researches, but were not practically used in industry until the end of the war.

Most of the uranium and thorium minerals hitherto known in Japan are associated with each other and have a close relationship to granitic pegmatites. Their modes of occurrence can be classified into the following three types:

1. Accessory Minerals in Granitic Rocks

Zircon, monazite, allanite and others are sometimes present as accessory minerals in granitic rocks. The quantity of such component minerals, however, is very small and, in most cases, the content of uranium is far less than that of thorium.

2. Minerals Present in Granitic Pegmatites

Monazite, euxenite, allanite, xenotime, fergusonite, samarskite, thorogummite, autunite and other radioactive minerals sometimes occur in druses, or as inclusion in micas, being associated with feldspars and micas in part of the graphic structure in pegmatites. Well-formed crystals of such minerals have been found so often that mineralogical and chemical studies have been made of them.

3. Minerals Present in Residual or Placer Deposits Derived from the Above Two Types

In the regions of granitic rocks and pegmatites mentioned above, residual materials produced on the land surface contain uranium and thorium minerals derived from the disintegration of the granitic and pegmatitic rocks due to weathering. These products are transported and sorted by running water and sometimes form placer deposits filling up the neighbouring river valleys.

Numerous localities of uranium- and thorium-bearing pegmatites have been known throughout the country. A few examples described as follows:

Ishikawa-Machi and Vicinity, Fukushima Prefecture

Ishikawa-machi is situated in the southwestern part of the Abukuma Mountainland, a noted plateau for swarming pegmatite veins. One hundred and twenty to one hundred and thirty or more pegmatites are found in an area some 8 kilometers from north to south and 5 kilometers from east to west.

Feldspar and silica stone of excellent quality are mined in some pegmatite veins. The size of the pegmatites so far known is less than 10 meters wide and some 40 meters long. This region consists chiefly of biotite granodiorite and coarse-grained biotite granite intruded in the former. Most of the pegmatite veins have a general trend of N20°W or N60°E.

Monazite, euxenite, allanite, xenotime, zircon, samarskite, fergusonite, uraninite, autunite, etc. are found in the pegmatite.

Owing to the general topographical feature of this region as shown by the predominance of low-lying hills, the residual materials and surface soil have a considerable thickness, and numerous small-scale placer deposits derived from the former are found along shallow river valleys.

Suisho-Yama, Fukushima Prefecture

One of the largest pegmatites in the Abukuma Plateau occurs in granodiorite or coarse-grained biotite granite at Suishō-yama, Iisaka-mura, Date-gun, Fukushima Prefecture, in the northwestern part of the plateau. The pegmatites here are irregularly pipy or lenticular in form. Fergusonite, uraninite, abukumalite, thorogummite, yttrialite, etc. are comparatively abundant in certain parts of the veins. Thorogummite is found often between the cleavage flakes of lepidomelane or at the boundary of lepidomelane and feldspar. Researches on the mineral components and chemical composition of this pegmatite are now being carried out.

Naegi-Machi and Vicinity, Nakatsugowa City, Gifu Prefecture

This district is famous for the locality of various minerals in connection with pegmatite.

Fine-grained biotite granite, quartz porphyry, granite porphyry, and the Tertiary formation overlying these rocks are the chief constituents of this district. Diluvial formations which form the river terraces and alluvial deposits are also present along the river valleys.

* Geological Survey, Ministry of International Trade and Industry.

The pegmatites are drusy, in general occurring in fine-grained biotite granite. They are distributed in an area 6 kilometers from north to south and 8 kilometers from east to west. Each of them has a cross section smaller than 5 by 3 meters and is lenticular, spindly or irregular in form. Numerous crystals of feldspar, quartz, micas and other minerals, within 5 centimeters in diameter, are crystallized out inside the druse cavities. Monazite, allanite, fergusonite and other rare-element minerals are often discerned in the druses by the naked eye.

The occurrence of such minerals in this district, however, is marked in placer deposits formed along the valleys by the sorting and transportation of running water. These deposits for the most part are the weathered products of the fine-grained biotite granite containing drusy pegmatites. Various rare-element minerals are contained in the sand and gravels deposited along the streams in this area. Among these minerals are monazite, fergusonite, samarskite, enalite, naegite, zircon and allanite. In addition, cassiterite, magnetite, ilmenite, quartz, topaz, beryl, corundum, tourmaline, wolframite, etc. are present. Cassiterite is especially abundant. Tin placers in this area were worked from the 17th century to the beginning of the 20th century. According to recent investigations, the content of radioactive minerals in the crude sand, for example, ranges roughly from 100 to 300 grams per cubic meter.

The occurrence of uranium and thorium known in Japan was previously confined to minerals originating in granitic rocks and pegmatites. A kind of uranium mineral contained in metallic ore deposit was found for the first time in 1954 in the Miyoshi mine at Haratsu, Kurashiki City, Okayama Prefecture.

In this area, quartz veins occur in biotite granite, having trends roughly parallel to each other. The ore deposit consists of quartz veins accompanying wolframite and cassiterite, 10 to 20 centimeters in width. The ore is of rather low grade, containing molybdenite, chalcopyrite and arsenopyrite as its minor constituents. Some 5 to 10 centimeters of both sides of the quartz veins are greisenized.

The uranium mineral is zeunerite, often found along the cracks in the vein and greisen. Primary uranium minerals have not been found as yet.

As mentioned above, uranium and thorium minerals that deserve special mention for the present in Japan are refractory minerals related to pegmatite. They consist of phosphates, tantalates, niobates, silicates, titanates, etc. Uraninite and other oxide minerals are rare. If such deposits are to be exploited, the complexity of their component minerals must be taken into account.

It may be expected that these deposits might prove to be workable when the exploitation is carried out in connection with the mining of feldspar and silica stone on one hand, and the utilization of beryllium, zirconium, niobium, tantalum, cerium, etc. as well as uranium and thorium is contemplated successfully on the other hand.

Prospecting of uranium and thorium deposits in Japan after the war was only started in 1954, and the work completed so far is no more than part of a preliminary survey for rare element mineral resources. The outcome depends entirely upon the progress of survey and research to be carried out hereafter.

Occurrence of Uranium and Thorium in South Korea

By Tong Suk Yun,* Korea

Geologically, Korea is characterized by the wide distribution of granite: pegmatite occurring in connection with this granite is found to be closely associated with radioactive minerals.

As primary deposits, columbite inbedded in pegmatite and allanite in basic rocks are the most important.

As secondary ore deposits, monazite, fergusonite and samarskite are only found in Korea together with gold as a part of placer heavy sand. Of these three minerals occurring in the placer deposit, fergusonite and samarskite are the more important due to the high content of uranium. The quantity of these two minerals, however, is very small.

According to the Mining Bureau of the Korean Government, the number of applications submitted for registration of mine sites of radioactive minerals is approximately five hundred (500) and has been increasing yearly. Of such sites, thirty (30) have been granted registration and can start operation in the immediate future.

Columbite deposits, located in the Kumwha-Chulwon area of Kangwondo and in the Muju area in Cholla-pukto, are currently being mined. The operation of columbite mines is still in the development stage: one ton of columbite concentrates was produced by one month's operation in 1953.

The monthly production of monazite, however, considerably exceeds one hundred (100) tons and thorium resources can easily be developed to produce a very substantial quantity if markets become available.

The following table shows the content of radioactive minerals contained in Korean black sand, viz.

	Samarskite (%)	*Monazite* (%)	*Zircon* (%)	*Ilmenite* (%)
Alluvial zone				
Sukchon	0.3	46.0	22.5	20
Sunan	0.1	28.0	44.0	22
Chonan	8.2	20.0	—	40

OCCURRENCE OF RADIOACTIVE MINERALS

Allanite: H Ca (Al, Ce, Fe)$_3$Si$_3$O$_{13}$

Allanite occurs inbedded in such rock formations as gneiss, limestone or basic rocks: it also appears in an alluvial deposit.

This mineral is widely found in South Korea in such formations. It shows a glassy luster and has a black prismatic crystal structure.

* College of Engineering, Seoul National University, Seoul, Korea.

Important Occurrences

Ichuk-myon, Ansong-gun, Kyunggi-Do.
Oedong-myon, Kyongju-gun, Kyungsang-Pukto.
Anak-myon, Anak-gun, Hwanghae-Do.
Bunyong-myon, Bunyong-gun, Hamgyong-Pukto.
Pyongang-gun area, Kangwon-Do.

Chemical analysis of a sample from Ansong-gun: SiO_2, 34.7; FeO, 17.0; Al_2O_3, 11.0; R_2O_3 + ThO_2, 21.0; MgO, —; CaO, 12.4; TiO_2, —; MnO, 3.4; and total 99.5.

Carnotite: $K_2(UO_2)(VO_4)_2 \cdot 3H_2O$

This mineral, which is yellow in color, is found in pegmatite, particularly in red feldspar accompanied by columbite.

Important Occurrences

Oenam-myon, Sakju-gun, Pyongan-Namdo.
Chokchang-myon Muju-gun, Cholla-Namdo.
Kumwha-gun area, Kangwon-Do.

Columbite: (Fe, Mn) (Nb, Ta)$_2$ O$_6$

Columbite is the most widely distributed radioactive mineral in Korea: it occurs in pegmatite and in placer deposits. It has a platy or brachy crystal structure and has a black sub-metallic luster. Occasionally, single crystals of columbite weighing more than 1300 grams are found.

Important Occurrences

Oenam-myon, Sakju-gun, Kangwon-Do (Dyke).
Kwalmal-myon, Cholwon-gun, Kangwon-Do (Dyke).
Chokchang-myon Muju-gun, Cholla-Pukto (Dyke & placer).
Hari-myon, Kumche-gun, Cholla-Pukto (Placer).
Ripchang-myon, Chonan-gun, Chungchong-Namdo (Placer).
Tanyang-myon, Tanyang-gun, Chungchong-Pukto (Placer).

Chemical Analysis:

Sample from Muju (chokchang-myon)

Ta_2O_5, 19.30; Nb_2O_5, 56.85; SnO_2 +WO_3, 0.67; TiO_2, 0.99; SiO_2, 0.70; UO_2, 0.05; ZrO_2, 0.40; $(Ce, Y)_2O_3$, trace; Al_2O_3, 1.05; FeO, 13.14; MnO, 5.52; CaO, 1.90; MgO, 0.34; and total 100.91%.

Sample from Sakju (Oenam myon)

Ta_2O_5, 10.81; Nb_2O_5, 68.06; SnO_2, 0.32; TiO_2, 0.30; SiO_2, 0.00; UO_2, 0.09; Th + R, 0.00; Al_2O_3, 0.17; FeO, 7.31; MnO, 12.19; CaO, 0.00; MgO, 0.29; H_2O^-, 0.15; H_2O, 0.07; total 99.76; and sp.gr., 5.37.

Fergusonite: (Y, Ce) (Nb, Ta) O_4

This mineral occurs in placer deposits, together with monazite, titanite, samarskite, zircon, xenotime, columbite, tantalite, wolframite, rutile, topaz and garnet. It has a black platy crystal structure and exhibits no luster because of weathering.

Important Occurrences

Haewol-myon, Yonback-gun, Hwanghae-Do.
Ripchang-myon, Chonan-gun, Chungchong-Namdo.
Kumsan-myon, Kumche-gun, Cholla-Pukto.

Samarskite: (Fe, Ca, UO_2)$_3$ (Y, Er, Ce)$_2$ · [(Nb, Ta)$_2O_6$]

Samarskite is one of the highest grade uranium minerals in Korea. It appears together with the heavy sand in placer deposits. It is prismatic or platy, yellowish gray and its larger grains are 10–14 mm long, 5–10 mm wide and 4–9 mm thick.

Important Occurrences

Chonan alluvial zone, Chungchong-Namdo.
Kumchae alluvial zone Cholla-Pukto.

0.79; CO_2, 0.23; and total, 99.93. Content of U, Th, and Ra: U, 0.094; Th, 8.46; and Ra, 3.21 × 10^{-8}.

Tantalite: (Fe, Mn) (Ta, Nb)$_2O_6$

This is one of the most important radioactive minerals in Korea. It is always accompanied by columbite and occurs particularly in pegmatite or alluvial deposits. Nb and Ta form a solid solution in this mineral and that found in Korea is richer in Nb than Ta. Since most of the occurrence of Nb containing minerals are listed under the columbite subheading (see above), only placer deposits are listed below.

This mineral has platy crystals with a submetallic luster. The size averages 3 to 6 mm in thickness.

Important Occurrences

Ripchang-myon, Chonan-gun, Chungchong-Namdo.
Chokchang-myon, Muju-gun, Cholla-Pukto.

Chemical Analysis of a sample from Chonan: Ta_2O_5, 54.06; Nb_2O_5, 24.96; TiO_2, 0.83; SiO_2, 0.94; Al_2O_3, 1.64; R. Earth, 0.07; FeO, 9.17; MnO, 5.62; CaO, 2.77; and total, 100.08.

	Ta_2O_5	$Nb_2O_5 + SiO_2 + SnO_2$			TiO_2	Al_2O_3	$Ce + Y + ThO_5$		
No. 1	16.14	32.42			1.97	1.50	9.75		
No. 2	16.47	33.55	0.16	0.73	1.57	1.67	2.23	5.93	0.92

	UO_2	UO_3	FeO	MnO	CaO	MgO	PbO	Total	Sp. gr.
No. 1	24.26	0.36	10.58	1.80	—	—	—	98.78	5.95
No. 2	22.84	0.35	10.08	0.64	0.67	0.54	0.40	99.77	6.05

Monazite: (Ce, La, Di) PO_4

Monazite is widely distributed throughout South Korea. It is found together with placer gold or heavy sand. Ordinarily, it is yellowish brown, transparent and has a glassy or resinous luster. Large lump monazite with diameters of more than ten (10) cm occurs in Cholsan-gun, Pyongan-Pukto.

Important Occurrences

Chonan Alluvial Zone, Chungchong-Namdo; Bonyong-gun Coastal Area, Chungchong-Namdo; Chongwon-gun Placer Mineral Zone, Chungchong-Pukto; Kumchae-gun Alluvial Zone, Cholla-Pukto; Kuregun Placer Mineral Zone, Cholla-Namdo; Kosung Coastal Area, Kangwon-Do; Pyongwon-gun Placer Mineral Zone, Pyongan-Namdo.

Chemical analysis of samples:

Sample from Chonan: CaO, 0.53; Al_2O_3, 1.36; Fe_2O_3, 1.35; Ce_2O_3, 24.67; R. Earth (Ce group), 31.16; R. Earth (γ-group), 2.31; ThO_2, 5.47; ZrO_2, 1.05; TiO_2, 0.19; (Nb, Ta)$_2O_5$, 1.50; SiO_2, 4.08; H_2O, 0.68; and total 100.26. Content of U, Th, and Ra: U, 0.494; Th, 5.86; and Ra, 16.80 × 10^{-8}.

Sample from Pyongwon: CaO, 0.53; PbO, 0.09; Al_2O_3, 0.28; Fe_2O_3, 1.65; Ce_2O_3, 28.25; Nd_2O_3, 27.87; Y_2O_3, 2.47; ThO_2, 9.49; SnO_2, 0.15; SiO_2, 1.85; UO_3, 0.15; P_2O_5, 26.07; Sb_2O_5, 0.06; H_2O,

Torbernite: $Cu(UO_2)_2\ P_2O_8 \cdot 12H_2O$

Korean torbernite occurs in pegmatite, particularly in muscovite aggregates accompanied by columbite. It has a fresh green minute crystal.

Important Occurrences

Chokchang-myon, Muju-gun, Cholla-Pukto.
Kumwha gun Area, Kangwon-Do.
Oenam-myon, Sakju-gun, Pyongan-Pukto.

Uranophane: $CaO.\ 2UO_3.\ 2SiO_2. \cdot 6H_2O$

The occurrence of this mineral is similar to that of carnotite. It is yellow in color and is found in pegmatite, particularly in red feldspar.

Important Occurrences

Same as Carnotite, see above.

Xenotime: $Y_2O_3\ P_2O_5$

This mineral is found in paragenesis with samarskite in placer deposits or in gold bearing quartz veins accompanied by manganstanolite. That found in placer deposits is the more important. It has tetragonal pyramid features.

Its grains are generally from 0.5 mm to 1.5 mm in diameter.

Important Occurrences

Ripchang-myon, Chonan-gun, Chungchong-Namdo.
Konbuk-myon, Kumwha-gun, Kangwon-Do.

The Occurrence of Uranium and Thorium in Norway

By T. Siggerud,*. Norway

Early in the last century mineralogists became interested in Norwegian pegmatites. The reason was first the large and well-formed character of the minerals. Later a large number of very rare minerals was discovered, many being first described from these pegmatites. Some of the minerals contain the elements uranium and/or thorium.

This thorough investigation has resulted in an over-estimation of the occurrence of uranium and thorium minerals in Norway, even among geologists. In reality the occurrence of uranium and thorium minerals is very rare and in most pegmatites rare minerals are not found.

In Norway there is much mining of the pegmatites for feldspar and quartz. Each year more than 100,000 tons are mined. Some sales of the rare minerals have also taken place, specially to mineral companies and museums. This has helped to make the Norwegian uranium/thorium pegmatites well known.

The following uranium and/or thorium bearing minerals were first described from Norwegian localities: pyrochlore-scheteligite; euxenite-polycrase; blomstrandine-priorite; polymignite; pitchblende (crystalline) with the varieties cleveite and bröggerite; thorite; tritomite; and caryocerite. Many other minerals with contents of uranium and/or thorium are also found. The two most important rock types for these minerals are the Granite-pegmatites and the Nepheline-syenite-pegmatites.

THE GRANITE PEGMATITES

The granite pegmatites are found in great numbers all over the country, but it is nearly only in the Pre-Cambrian gneiss areas that the uranium- and the thorium-bearing minerals occur. As the minerals are so widely distributed in the gneisses the age determinations show great variations: from 300 million years to 1100 million years. The youngest must be a mineralisation which is younger than the Pre-Cambrian rocks.

The main minerals in the pegmatites are the minerals of granite, viz., feldspar, quartz and mica, with accessory minerals.

The most important uranium mineral is pitchblende. A variety called Bröggerite has a thorium content, and Cleveite has also some rare earths. Taken together the pitchblende is found in 48 different localities.

Another group of uranium/thorium bearing minerals are the niobates and tantalates. These have a lower content of the radioactive elements, usually from 10% and down to traces. Among the minerals are: samarscite, fergusonite, euxenites, betafite, and blomstrandines. The uranium content of these minerals varies greatly from one locality to another.

Thorite is especially found in the granite pegmatites of the so-called Bamble formation in the Pre-Cambrian south of the Oslo Region. These thorite-bearing pegmatites were mined before the recovery of thorite from monazite sand started. A yellow thorite has been called an orangite.

Zircons often contain comparatively much uranium and thorium. They are then called alvite. Most zircons from Norwegian pegmatites have to be looked upon as alvite. Alvite has been shown to be a not uncommon accessory mineral in some rocks too, both basic and acid.

Orthite (allanite) with thorium contents is known from several localities.

Some pegmatites have been worked for uranium, both for production of radium, and in later years for uranium itself. There has been no profit as the deposits are too small and poor. At one pegmatite locality there is comparatively much euxenite but it is unusually poor in uranium.

NEPHELINE SYENITE PEGMATITES

The nepheline syenite pegmatites are mostly found in the Langesund area, in the southern part of the Oslo Region. The pegmatites are genetically connected with the igneous rocks in this region.

As an average it can be said that thorium-bearing minerals are not uncommon as accessory minerals.

Pyrochlor minerals with a thorium and uranium content occur in different types of rocks in several localities in this area.

Allanite containing thorium is found in aplitic dikes in the undersaturated rocks in the southern part of the igneous rock province.

The conclusion to the question on the mining of pegmatites for uranium and thorium is the following: the content of the radioactive elements (especially uranium which is best explored) is of the order of 0.005% U, in the volume which has to be mined at a deposit; and concentration by mechanical treatment can be done fairly easily, but the percentage of recovery is low. In the mill and esperially during washing much uranium is lost, because the uranium minerals flow away with the mica.

* The Geological Survey of Norway, Oslo.

The calculated total uranium content in each pegmatite is very small. Calculation for thorium content has not been done. The pegmatites will never be important for uranium production, but uranium may become a useful byproduct of feldspar mining.

URANIUM-BEARING CAMBRIAN SHALES (ALUMSHALES)

The greater part of Norway was covered by the Cambro-Silurian ocean. Sediments from this ocean are still found almost all over the country. Most of these deposits have taken part in the Caledonian orogeny during the Ordovician and Silurian age. Only in the so-called Oslo Region in the south-eastern part of the country are the sediments located in the periphery of the area which underwent mountain folding. In Permian times a large number of lava eruptions took place; the lava which still covers the sediments protected them from erosion.

The Oslo Region also slid down along large faults to make a "graben". The result is that while we in this part of the country mostly find precambrian gneisses, we find the younger sediments in the Oslo Region.

The large permian eruptions contact-metamorphosed some of the sediments.

All the sediments are more or less folded and have been through a strong diagenesis, with some recrystallisation (pyrite). In the southern part of the Oslo Region (south of Oslo) the sediments are almost flat and undisturbed. Going northwards one finds that the pressure from squeezing out and pushing together of various layers of the sediments caused the sediments to become more and more folded. The thickness of the series is therefore a function of tectonic movements more than of the primary sedimentation.

In the Cambro-Silurian is found a Cambrian series with more or less bitumen. The question of genesis is not settled but it has been suggested that it is a sapropelic mud. On the other hand some of it is, without doubt, of shallow water origin (beach conglomerates).

These bitumeneous shales (called alumshales) contain differing quantities of uranium. The uranium must be looked upon as a secondary deposit, precipitated in or with sediments, from solutions of the weathered Pre-Cambrian granites and gneisses. The same type of rocks are found in many places on the earth (Sweden, Baltic, USA, Canada, etc.).

The thickness of the sediments in primary deposits is 50–150 meters (greatest to the north). Part of the series is limestone, and in the shaley parts are found limestone concretions.

As mentioned above the uranium content differs greatly. The investigations carried out by Forsvarets Forskningsinstitutt (Norwegian Defence Research Establishment) show some relation between the uranium and bitumen-contents. But in the northern folded areas this is not found, possibly due to some concentration of the bitumen during the tectonic processes. The greatest uranium content is found in the zones with the fossils Eurycare and Peltura, in the upper Cambrian. The thickness of the beds is between 10 and 15 meters, with as much as 50% limestone. The maximum uranium content is 170 ppm with an average of 100 ppm in the shales of this rich zone. In younger layers the uranium content soon disappears, and in older layers it is very rarely more than 50 ppm.

Secondary pyrite crystals contain no uranium. The whole rock is so fine-grained that most of the minerals are in semi-colloidal form. Autoradiographs indicate the absence of discrete particles of radioactive minerals. The contact-metamorphism makes no difference to the occurrence of the uranium or to the grains of the rock. Natural enrichment of the uranium as in the well-known Swedish deposits, the Kulm, is not found in Norway.

Uranium production from the shales depends on a chemical metallurgical treatment of the whole rock. The Forsvarets Forskningsinstitutt in 1945–1948 investigated a number of such processes. But up to now no method is known which will produce the uranium cheap enough. Even if it were possible to get all the uranium out of the shales, one long ton alumshale would only give uranium oxide valued at 5 sh. (at a price of 50 sh. for 1 kg U_3O_8).

Areas with outcrops of the bitumeneous uranium-bearing shales cover hundreds of km². But because the thickness of the layers with maximum uranium content is not great, the uranium content itself is small, and the shales do not contain other elements of economic interest, the alumshales have no value as a uranium ore at present. If the uranium prices rise greatly, or new and cheaper methods for production of uranium from the shales are found, great possibilities for atomic energy production are buried in the bitumeneous Cambrian shales of the Oslo Region.

The great deposits of Cambrian shales and schists outside the Oslo Region have only been investigated to a small extent for uranium.

RENDALSVIK GRAPHITE-MICA-SCHIST

At Holandsfjord in Nordland country in northern Norway, radioactive elements were found in an old graphite mine. In 1952 a geological exploration of the area was carried out.

The locality with the radioactive elements is situated in the Caledonian-mountain-folding-chain. The rocks are metamorphosed sediments: limestone, mica-schist and quartzites. There is strong evidence for a granitisation of the schists, for large areas with granite are found.

The mica-schist contains layers rich in graphite, and it is in these graphite layers that the radioactive elements occur. The proportions of the minerals in the rock are approximately: quartz—35%, feldspar —15%, mica—35%, graphite—7%, ore—8%. The radioactive element is uranium oxide in discrete minerals. The genesis of the uranium-oxide minerals has not been proved, but it is suggested that the rocks

are regionally metamorphosed alum sediments (i.e., bitumeneous Cambrian shales as in the Oslo Region). During the orogeny the uranium content was concentrated as uranium oxide.

The uranium content in ppm is small. Many institutions have done the analytical work. The results differ somewhat but on the average are 140 ppm U in 350,000 tons graphite-mica schist and 35 ppm in 2 million tons of the same schist. Outside the graphite bearing layers the uranium content is negligible.

As the uranium in the graphite-mica-schist occurs in minerals, it is relatively simple to concentrate them by gravity methods. The ore is ground and washed, and the uranium oxides are concentrated together with the heavy minerals (mostly pyrrhotite). The pyrrhotite can be separated from the other heavy minerals by magnetic methods. The rest is a non-magnetic fraction with 0.5% uranium. How great the percentage of recovery will be in an industrial plant is not known.

The price of the uranium today gives a value of 5 sh for the uranium in 1 ton of the richest layers. The main products will therefore be the mica and the graphite. Uranium is only a byproduct, and the production will depend upon the market for the main products. A plant for production is already at the blueprint stage, but not yet built.

Some reconnaissance work in other localities with the same type of graphite deposits in this Caledonian zone has been done, but without positive result.

THE INVESTIGATIONS FOR URANIUM AND THORIUM

Norwegian Law (Bergloven 1842) has the main theme that all ores may be claimed for private profit by the man who first finds the ore. This is valid for all ores in which the ore mineral has a greater specific gravity than 4. This is even valid if the ore is found in privately owned ground, if this is not cultivated.

There are a few exceptions to this law. One of them is for the elements, uranium and thorium. All occurrences which contain the elements, uranium and/or thorium, can only be acquired or mined by the Government or the one who acts on behalf of the Government.

A law as this was natural in the first years after 1945. At present the law prohibits the private interest in uranium and thorium prospecting. The Institutt for Atomenergi (Joint Establishment for Nuclear Energy Research) and Norges geologiske undersökelse (Geological Survey of Norway) have therefore asked the Government to repeal this law and replace it by one giving the Government the right to be the only buyer of Norwegian produced uranium and thorium ore.

What is known at present of the occurrence of uranium and thorium is therefore the result of investigations carried out by geologists from the universities or other institutions.

As mentioned above the pegmatites were first examined by university geologists from a purely scientific point of view. Later on they were studied in connection with the exploration of the pegmatites as feldspar and quartz mines. This investigation was mainly done by geologists from Norges geologiske undersökelse. The uranium content of the pegmatites has been sought by Forsvarets Forskningsinstitutt and later on by the Institutt for Atomenergi. Both of them are in close contact with Norges geologiske undersökelse. The investigation of the uranium content of the bitumeneous shales in Oslo Region has been done by Forsvarets Forskningsinstitutt and Norges geologiske undersökelse. The graphite mica mine in northern Norway was explored by Norges geologiske undersökelse.

In 1954 Norges geologiske undersökelse started a systematic search for occurrences of uranium and thorium in Norway, to assess the possible supplies available for Norwegian atomic energy production. This work will take some years to complete.

Instruments were bought both for field and for laboratory work. The investigation is still in a period of experiment and development.

Up till now most of the work has been to conclude the investigations in the bitumeneous shales in the Oslo Region.

An examination of 8500 specimens of ores and rocks has been done in the collections of the Geological Museum, University of Oslo. A few of the samples were radioactive to a greater extent than the ordinary rocks. The radioactive elements are probably both uranium and thorium. Future work will be to prospect in the areas where these samples were collected.

Certain features are of great importance to the prospecting for radioactive elements in Norway, and should be mentioned. The surface of Norway is very rugged, not only on a regional scale with the high mountains and deep valleys and fjords, but also in every small area. The greatest part of the country is therefore difficult of access, except by foot. Measuring the radioactivity from the air or from a car will be of less importance.

Furthermore the search for radioactive elements is complicated by the fact that Norway was covered by ice during the latest ice age. The weathered zone of earth which usually covers the rocks in unglaciated area was transported by the ice and deposited elsewhere. What is important is that the sediments have no genetical connection with the rocks they cover to-day. The uranium in the sediments was leached out during the transportation. In addition the climate of Norway reduces the length of the field season.

THE POSSIBILITIES OF FINDING URANIUM AND THORIUM IN NORWAY

The possibility that the search will result in a really big workable deposit of uranium is not easy to evaluate. During the last 150 years a fairly good survey of the geological build of Norway has been worked out. Parts of the country are also mapped in detail

by modern methods. On the other hand experience from other countries shows that even mapping in 1/100,000 may overlook uranium deposits.

When it comes to geological areas which should be favourable for uranium and thorium deposits, two main parts of Norway may be considered: one is the Norwegian part of the Fennoscandian shield, with its Pre-Cambrian rocks, and the other is the Caledonian mountain chain which forms the western part of the country, along the border of the Pre-Cambrian shield. The Caledonian mountain chain is eroded down to different levels ranging from the nappes to the root zone. Both in the Pre-Cambrian rocks and in the Caledonian rocks occur a lot of mineral deposits.

In the pegmatite areas in the Pre-Cambrian it may be possible to find more uranium-bearing pegmatites. But this is thought to be less promising, due to past experience with those already found. As also mentioned there are radioactive anomalies in specimens from about 40 mineral deposits, but the field prospecting has not yet been done.

Really big deposits of high grade ore are not expected but the possibility of finding small deposits or deposits with low grade ore cannot be excluded.

Lastly, there is also a question of the price for the uranium and thorium, and how much there will be on the market. The deposits here in Norway which were of some interest a few years ago are of no interest today.

Uranium Deposits in the Philippines

By Amando Clemente and Edgardo Reyes, Philippines

The possibility that commercial quantities of uranium are present in the Philippines was reported by Puttuck and Stafford, Division of Raw Materials, United States Atomic Energy Commission. The report was based on the results of the preliminary reconnaissance which they have undertaken jointly with Gematero, Quema, Samaniego, and Teodoro of the Philippine Bureau of Mines in 1953.

In their unpublished report entitled "Search for Uranium in the Philippines" Puttuck and Stafford describe briefly the physiography, climate, and the general geology of the Philippines and of the various areas surveyed. They also conclude from the data they obtained that the most interesting deposits are those at Baguio, the Paracale-Mambulao stock, the Masbate gold district, the Jotafe Copper Deposit, the eastern cordillera of Mindanao and possibly the Pan-Philippine Mine at Lobo, Batangas. Deposits of moderate amounts are Looc load-silver mine in Batangas, the Minerals Resources Mining Company deposit and the Pauli prospect in Marinduque. Mention is made that areas of ultrabasic rocks, such as in Zambales ranges, and probably high temperature replacement deposits are unlikely sources of uranium.

On the basis of their observations in this survey, the following recommendations are made:

1. Reconnaissance in areas of acidic igneous rock and detailed mineralogic studies of mineralized outcrops, prospects, and the ores of operating mines in such regions, to determine the possibilities of ore zoning and its relationships to radioactivity.

2. Investigations of the possible occurrence of uraniferous marine black shales, marine phosphorites, or terrestrial sandstones, and oil drilling areas, the known oil seeps, the asphaltite deposits, and the various coal occurrences.

Aside from the interest shown by the Philippine Bureau of Mines in surveying uraniferous deposits, not much systematic work on locating uraniferous deposits has been done in the country.

Recently, however, the Philippine Iron Mines, Larap, Camarines Norte, reported discovery of a uraniferous ore in the Paracale-Mambulao district. A sample of ore material from this deposit, composed of mica, magnetite, apatite, molybdenite, chalcopyrite, and pyrite, furnished by the Soriano Mining Laboratory in Mandaluyong, Rizal province, was subjected to analyses. The following is the result of the chemical analysis of the sample on a moisture-free basis:

		Per cent
Uranium, U_3O_8		0.01
Silica, SiO_2		37.32
Antimony, as Sb_2O_3		.04
Molybdenum, as MoO_3		.12
Total Iron, as Fe_2O_3		31.35
Manganese, as Mn_2O_3		0.24
Alumina, Al_2O_3		10.84
Calcium oxide, CaO		4.30
Magnesium oxide, MgO		7.64
Sodium oxide, Na_2O		3.01
Potassium oxide, K_2O		1.93
Fluorides, as F		0.96
Chlorides, as Cl		0.06
Sulfur, as S		0.90
Phosphoric Anhydride, P_2O_5		1.51
Total		100.23
Less O for fluorides	0.40	
Less O for chlorides	0.01	0.41
Total		99.82

The spectroscopic analyses of ore samples made in the laboratories of the Bureau of Soil Conservation and the Department of Chemistry, University of the Philippines, revealed no uranium lines. However, tests made with Geiger counters showed the ore to be radioactive and the presence of uranium in it was definitely established by the positive result of the sodium fluoride bead test.

A quantitative determination of uranium by the SC-IC autoscaler (Tracerlab, Inc.) using as a standard for comparison a simulated iodine-131 standard of 2.44×10^{-5} millicuries was made. On the basis of the assumption that 40% of total radiation is caused by uranium alone, the analysis shows that the ore contains 0.029% uranium.

According to an executive of the Philippine Iron Mines, the firm has made about four hundred drillings in their Larap claims. Samples of ores they collected, sent to the United States for assay have been verbally reported to contain from 0 to 1.5% uranium.

The foregoing preliminary data are mentioned to show that commercial uraniferous deposits may be found in the Philippines. A more systematic geological survey is, however, necessary to determine the extent and establish the commercial possibilities of the most promising deposits.

Uranium Prospecting in Portugal

By Rogério Cavaca, Portugal

The main purpose of this paper is to give information on the prospecting plans which the Junta de Energia Nuclear proposes to carry out on the Portuguese territory.

By way of introduction, we present this abstract on the metallogenic and geologic conditions in the principal uranium bearing regions known to date, taking, as a basis, results of research, by government departments, or by private enterprise.

METALLOGENY OF URANIUM

The occurrence of radioactive minerals—particularly of uranium—has been mentioned, both in the Metropolitan territory and in the overseas provinces of Angola and Mozambique.

Metropolitan Portugal

The discovery of the first uranium deposits in Portugal dates back to 1907. Mining of some of them, for radium, was started in 1911, and reached peak production in 1926 when Portugal was fourth among the world producers. Despite the heavy competition from the Belgian Congo and Canada, mining continued until 1939, but it had to surmount tremendous difficulties.

From 1945, with the development of the uses of uranium, new horizons soon were opening up for Portuguese minerals, and in 1946, the first detailed studies of the old deposits were started, which, until then, had been worked only in the supergene area.

Since 1950, a private company has been carrying out systematic prospecting of the concessions it controls, centered about regions with known structural and metallogenic characteristics, including a large area in the central region of the country in which there are a great many occurrences of uranium.

The most important deposits in the Metropolitan Area are concentrated in the Hercynian granitic mass of Douro and Beiras, which consist essentially of granite porphyries with two micas of which biotite largely predominates. There are variation facies of medium and fine granites, granulites and greisens. There are a great many doleritic and basaltic veins which cut the ancient massif, the clay bearing schists of Beiras (probably Algonkian) and the Silurian anthracolitic formations. These basic emissions range from pre-Hercynian to post-Hercynian, and are related to the initial phase of the alpine tectonics. These basic veins have a variable orientation, from north 10° west to north-south, passing to north 30°–45° east, and less frequently to east-west.

Evidence of the Caledonian and Hercynian movements is shown clearly by the northwest-southeast orientation of the Silurian outcrops, as well as in the complex of argillaceous schists of the Beiras, which shift from a north-northwest—south-southeast orientation to north-south, in the north of Portugal; to northwest—southeast and even west-east in the Province of Beira Baixa, as one goes eastward.

The alpine orogeny is reflected in the resistant ancient massif and is made apparent by fractures and epirogenic movements which have structural orientations north-northeast–south-southwest to north-south, and caused a rejuvenated relief, with axes usually oriented along Hercynian directions and parallel to the Betic Chain.

The uranium bearing veins are nearly exclusively in the granite porphyries and they form a metallogenic province of three distinct mineralization zones in which the primary deposits of cassiterite, wolframite and sulphides, which are so frequent in other zones, generally are scarce or non-existent.

Until now, the occurrence of radioactive mineralization in sedimentary formation had not been noted. The main characteristics of the three mineralized zones are described in greater detail as follows:

"A" Zone

This includes the most important deposits now being exploited in the country, in the region of Viseu-Nelas-Carregal do Sal.

The main structure is a series of regional fractures with lateral "shears" orientated between north-south and north 60° east. These are related to the alpine movements which caused the "horst" of the Serra da Estrela, at the center of three mineralized zones. Among the regional shears there is a very complex system of tension fractures which are oriented east-west and north-south.

In the final phase, which is contemporaneous with the mineralization of the structures by uranium, horizontal movements caused adjacent tension fractures which were favorable for the deposition of pitchblende in the strongly brecciated zone.

The veins are simple fillings of faults in brecciated areas which contain micro-crystalline white quartz, brown or reddish jasper, microbotryoidal pitchblende of colloidal origin in a matrix of fine granular quartz, pyrite, galena, sphalerite and, somewhat more rarely, chalcopyrite.

Original language: French.

There is clearly a direct relation between mineralization by uranium and the size of the fractures, the hematitization of the feldspars, the sericitization of the alumino-silicates and the silicification of the wall rock in the vicinity of the veins.

The granite close to the veins, very often shows dispersed uraniferous mineralization of the "stockwork" type, as a consequence of its intense mylonitization.

"B" Zone

This includes the region of Guarda-Belmonte-Sabugal. The fractured zones are very large and are filled with mineralized veins and diabasic dikes, the orientation of which varies between north 5°–50°, and north-northwest–south-southeast.

The tension fractures included in a structural system with azimuths from north 40°–80° east to east-west, created at the intersection with the main "shears", a grid having zones of tectonic weakness, where the deposition of white, jasper-like or breccia-like quartz accumulated, as well as granular or finely veined pitchblende in the same matrix, and pyrite. Chalcopyrite occurs as speckles in the quartz or altered to chalcocite and covellite.

The deposits of the region show some evidence of compression, brecciation and silicification over large lenticular areas where the large fractures are sealed by jasperoid quartz and abundant pyrite concentrations. These show more recent tectonic activity, and are the cause of the disseminated mineralization.

Hematitization and sericitization of the host granites appear to be directly related to the distribution of the uranium deposits.

Association of the mineralization with the doleritic dikes is frequent, where it often occurs as fracture fillings.

"C" Zone

This includes the deposits of the Trancoso-Aguiar da Beira-Moimenta da Beira region. There are two fundamental types of structures which are well developed: one is a system of north-south "shears", the other, tension fractures which cover all the azimuths of the northeast quadrant and are subordinate to the lower "shears." We must draw attention to a peculiar characteristic of the zone, namely the existence of radial "shear" systems which are poorly developed, and oriented the last phase of the mineralization.

In the complex of the first two systems, the local tension fractures show variations in direction which cover the northeast quadrant. The mineralization is oriented north 10°–30° east, where the principal deposits are localized along veins of coarsely crystalline white and black quartz in brecciated areas, and in stringer-like open zones. The pitchblende and secondary minerals occur as veinlets in crystals, or again as microbotryoidal powder on quartz crystals, in geodes, or in vein fissures.

In the regional tension fractures, the direction favored by mineralization varies between 40°–50°.

In that zone, the distribution of the uranium ore is limited neither by special types of structure nor by the direction and dip of the veins; nor does it bear any relationship to the alteration of the deposit or wall rock.

Metallogenic Types and Paragenesis

Portuguese uranium deposits are the low temperature primary vein type and are characterized by the presence of quartz, jasper and chalcedony. The uranium occurs as the primary mineral—pitchblende—and as the secondary—phosphates, silicates, oxides, hydrates and sulphates, associated with pyrite, marcasite, galena, sphalerite, and chalcopyrite.

These are epithermal veins, with no high temperature minerals, the formation of which is correlated with the alpine orogeny.

Overseas Provinces

The known minerals overseas are of the "refractory" type and very complex in composition; as an exception pitchblende (Mozambique) has been found, as well as torbernite (Angola).

From 1952 to 1954, the Portuguese Government undertook, with the cooperation of the E.C.A., some important mineral-geological explorations in an area of 140,000 square kilometers in these two overseas territories as well as all the regions where, until then, occurrences of radioactive minerals had been noted.

The immediate objective of the research was the eventual discovery of mineral deposits, as well as that of supplying the cartographic and geological data to serve as a basis for later detailed reconnaissance of radioactive mineral deposits. The technique used included: (*a*) an aerial survey at an approximate scale of 1:40,000 with the help of existing geodetic triangulation; (*b*) assembly of uncorrected aerial photo-mosiacs; (*c*) photogeological interpretation together with (*d*) geologic reconnaissance by special field parties who investigated large areas first and then the smaller, in more detail. (*e*) petrographic, mineralogical and analytical studies.

We are reaching the conclusion of the final reports which will make it possible to establish the future plan of investigation.

Angola

Until 1950, all that was known here were traces of secondary uranium mineralization in rare pegmatites (Dande) and quartz veins (Caala). From then until 1954, radioactivity measurements were made in all the known mineral deposits, and prospecting was actively extended in the zones of more favorable metallogenic characteristics.

This first investigation, however, included a very limited area and only confirmed the occurrence of other types of radioactive mineralization which constituted a starting point for more detailed research.

The pegmatitic veins of Dande are enclosed in the gneiss of the basement complex and have been worked exclusively for muscovite and beryl; they contain, as accessory minerals, garnet, pyrite, chalcopyrite, epidote, chlorite and torbernite, always

irregularly distributed and without sufficient concentration for economic development.

The Caala occurrence is located in a zone of large fractures near the contact with the extensive granitic dioritic massif of the Benguela Plateau with a complex of quartzites, sandstones and argillaceous schists of the Oendolongo system. This is a large quartz vein with a mineralization of pyrite, chalcopyrite, malachite, chrysocolla, native gold, and a few torbernite flakes.

The existence of traces of radioactivity was also mentioned in the large Benguela Plateau, in formations of the basement complex represented either by dolomitic limestone (Longonjo), or by finely granulated and intensely altered rocks (Bailundo); high radioactivity readings were noted at times.

A study also was made of the concentrates of alluvial gold which develop near the contact of the large granitic batholith with the surrounding formations of the basement complex, and form low grade vein or metamorphic deposits. The mineralization of these gold concentrates contains a large proportion of rare earths, thorite, columbo-tantalates and cassiterite.

In the zone between Cazengo and Malange there is a pegmatitic formation which cuts the ancient magmatic rocks and the gneiss of the basement complex, and which seems to be related to a more recent basic intrusion. In the constitution of these pegmatites, quartz and orthoclase are prominent, and as accessories, titano-magnetite and vermiculite veins; at times samarskite is present, always associated with quartz.

Even though the background count of the region is relatively high and constant, which must be ascribed to the radioactive nature of some elements which constitute the rocks, readings three times as high frequently were noted close to the pegmatite veins.

Mozambique

In the Province, we have two uranium bearing regions—in the northern part of the Tete, and in the Departments of Zambezia and Nyassa—each with different metallogenic conditions.

The discovery of uranium minerals at Tete dates back to 1947, and was purely by chance as a result of the active prospecting for corundum. In this region, the following formations are very well represented: (*a*) metamorphic complex of the ancient crystalline socle, formed by limey schists, amphibolite schists and crystalline limestone, probably Archean; (*b*) Gabbro-dolerite intrusive which seems partially to have digested the older complex belonging to the pre-Karroo period; (*c*) Karroo system, consisting essentially of argillaceous schists, sandstones and conglomerates, at times with intercalated coal; and (*d*) Granitic-syenitic intrusive, more recent, probably Tertiary.

The uranium deposits, represented by pegmatitic dikes and hydrothermal veins, are concentrated in the contact aureoles with the gabbro-dolerite complex which underwent strong tectonic pressures, as well as in strongly scapolitized zones.

The zones of crushed gabbro, where scapolitization is most intense, formed a favorable path for the circulation of mineralizing solutions of uranium and other metals.

From the geological standpoint, five types of primary uranium deposits may be mentioned: (*i*) mineralization disseminated in finely granular acid rocks which may reach 1% in uranium minerals; (*ii*) continuous and large pegmatitic veins, derived from the granite syenite magma; (*iii*) calcite veins, with "stringer" structures, of considerable extension and size; (*iv*) gabbroic pegmatite veins, pyroxene rich as a result of metasomatic alterations, always thin and short; and (*v*) impregnations of scapolitized bands of the gabbros, generally irregular and rather thin.

In the areas near these primary deposits, alluvial deposits frequently occur. They are of limited extent, very small and of uneven thickness, but nevertheless can be worked economically.

Uranium mineralization is mostly davidite, and, at times, samarskite and stibiotantalite; rarely, small deposits of massive pitchblende occur with the characteristic yellow alteration products.

Generally, these minerals are associated in variable proportions with pyrite, pyrrhotite, chalcopyrite, molybdenite, rutile, ilmenite, magnetite, calcite, apatite, tourmaline, scapolite and vermiculite.

In 1934, several pegmatite dikes were discovered at Ribaue (Nyassa), and at Alto Ligonha (Zambezia), which were amazing as much by their great extent and thickness as by their wealth and variety of unusual mineralization which consisted largely of micas, lepidolite, beryl, columbite-tantalite, stibiotantalite, bismutotantalite, samarskite, euxenite, monazite, bismuth, and also several semi-precious varieties of tourmaline, morganite and garnet.

Granite and gneiss predominate in the region, occurring between long bands of strongly metamorphosed rocks, seemingly remnants of synclines.

Some irregularly distributed granite bosses, not related to the structure, represent the intrusions which gave rise to the mineralization.

The pegmatite dikes have a tendency to be grouped around these granite bosses in the metamorphic bands, and to be surrounded by amphibolite schists. Generally, their dimensions are large; however, they vary in form and position and almost always have a zoned structure.

Columbite appears either on the walls, in the intermediate zones, or in the center; however, its distribution is very irregular.

Beryl occurs only in the intermediate zones, in masses which are spread at random. Samarskite, euxenite and bismuth always are found as accessory minerals, although in very limited quantities.

Lepidolite very often forms large masses.

The alluvial deposits are relatively abundant in the immediate vicinity of the large pegmatites which

give rise to them, hence a concentration by gravity of the dense minerals such as ilmenite, magnetite, garnet, zircon, monazite, samarskite and columbite; the latter is the only one present in economic amounts.

Elsewhere, alluvial deposits are relatively rare as a result of their high density, which does not allow transport for considerable distances from the primary source. Only a few deposits of low economic potential are noted in the terraces and thalwegs of some of the more important tributaries.

PROSPECTING PROGRAM

In March 1954, the Junta de Energía Nuclear was created in Portugal. This organization is under the direction of the Prime Minister, and among other obligations, it has that of undertaking over all the national territory the work necessary for an inventory of the occurrence of classified and radioactive materials as complete as possible.

At the beginning of its activities, the Junta decided it would carry out a large scale prospecting program in the metropolitan area and overseas. The courses for the training of technicians and auxiliary personnel which were organized were well attended and most successful.

Thereafter, the initial prospecting plan was made for a complete reconnaissance of the metropolitan area over 12,000 square kilometers, as shown in Fig. 1. This included all of the granite massif of Douro and of Beiras where the most important mineralization in the country is found.

Once the metallogenic conditions are established with certainty, research will progressively include other regions of similar geology and geomorphology.

Thus, it will be possible to show, in the least possible time, positive results of the prospecting, and there will be a better chance for the success of the undertaking, as well as a strong basis for future studies.

In the meantime, once the results of the preliminary reconnaissance in Angola and Mozambique are known, we shall make the final selection of the regions to be studied in those two overseas provinces.

The prospecting plan underway in the metropolitan area has for its main purpose the discovery of all radioactive ore deposits, particularly uranium, as well as the other minerals which happen to be associated with them. Exploratory work will be followed by sufficient investigation to define the extent, strength, content and other characteristics of those deposits, as well as the reserves.

The length of the project is estimated to be about four years and will include the following operations:

(*a*) Coordination of map and aerial survey data. For this work, use is made of excellent contour maps at scales of 1/250,000, 1/100,000, 1/50,000 and 1/25,000, as well as recent aerial photographs, at approximate scales of 1/30,000 and 1/15,000 which cover the whole country.

Air photograph mosaics were prepared at a scale of 1/25,000, which will serve as a basis for airborne scintillometer radiometric surveys. For certain regions, survey maps at scales of 1/5000, 1/2000 and 1/1000 will also be used.

(*b*) Geologic mapping. Due to the lack of detailed geologic maps of the region, it was necessary to resort to photogeology as the only means of providing within a reasonable length of time the geologic and structural maps on a scale of 1/25,000.

A photogeologic interpretation correlated with geologic field studies is in progress for the interpretation and completion of the results.

(*c*) Geologic and metallogenic study of typical mineralized areas. Since there are many uranium deposits which already are known in the country and on which important reconnaissance has been made as well as development and exploitation to great depth, the initial phase of the plan is to make geologic and metallogenic studies of typical mineralization, which doubtless will be of great use in the orientation of the prospecting program.

(*d*) General radiometric prospecting. The purpose is to select zones of highest radioactivity on the basis of measurements made on a relatively large grid.

As an experiment, simultaneous applications of three different methods are made: (*i*) radiometric prospecting with airborne scintillometers, at a height of 80 meters on a grid of 400 meters, which is normal to the predominant structural trend and gives a coverage of 25% of the terrain; (*ii*) reconnaissance with a high sensitivity scintillometer installed on an automobile which goes over all roads whether they be national, provincial, local or mere paths for a total length of 18,000 kilometers (the network of roads for the region is 9000 kilometers); (*iii*) Reconnaissance with a Geiger-Müller counter on an average grid of 1 kilometer.

It is impossible to predict which of these methods would be the most efficient and economical. Their simultaneous use over the same 3000 kilometers area indicates which will be most useful and appropriate. The decision on the method to be used in the future will be made on the basis of the results obtained.

(*e*) Regional Prospecting. This will be carried out mostly in the regions where, in the course of general prospecting according to the method described above, the most important radioactive anomalies are observed. This requires the measurement of radioactivity with a Geiger-Müller counter on an average grid of 100 to 200 meters. The results of this prospecting will be useful for isoradioactivity maps, in order to outline the zones where this value is double, triple, etc., the background.

At the same time detailed geological studies will be made which, on the basis of the map, will make it possible to select the most important mineralized areas for the following:

(*f*) Local prospecting. This consists of the application of the above methods to increasingly smaller regions down to a grid, which may be 5 meters or even 1 meter. The final result is an outline of

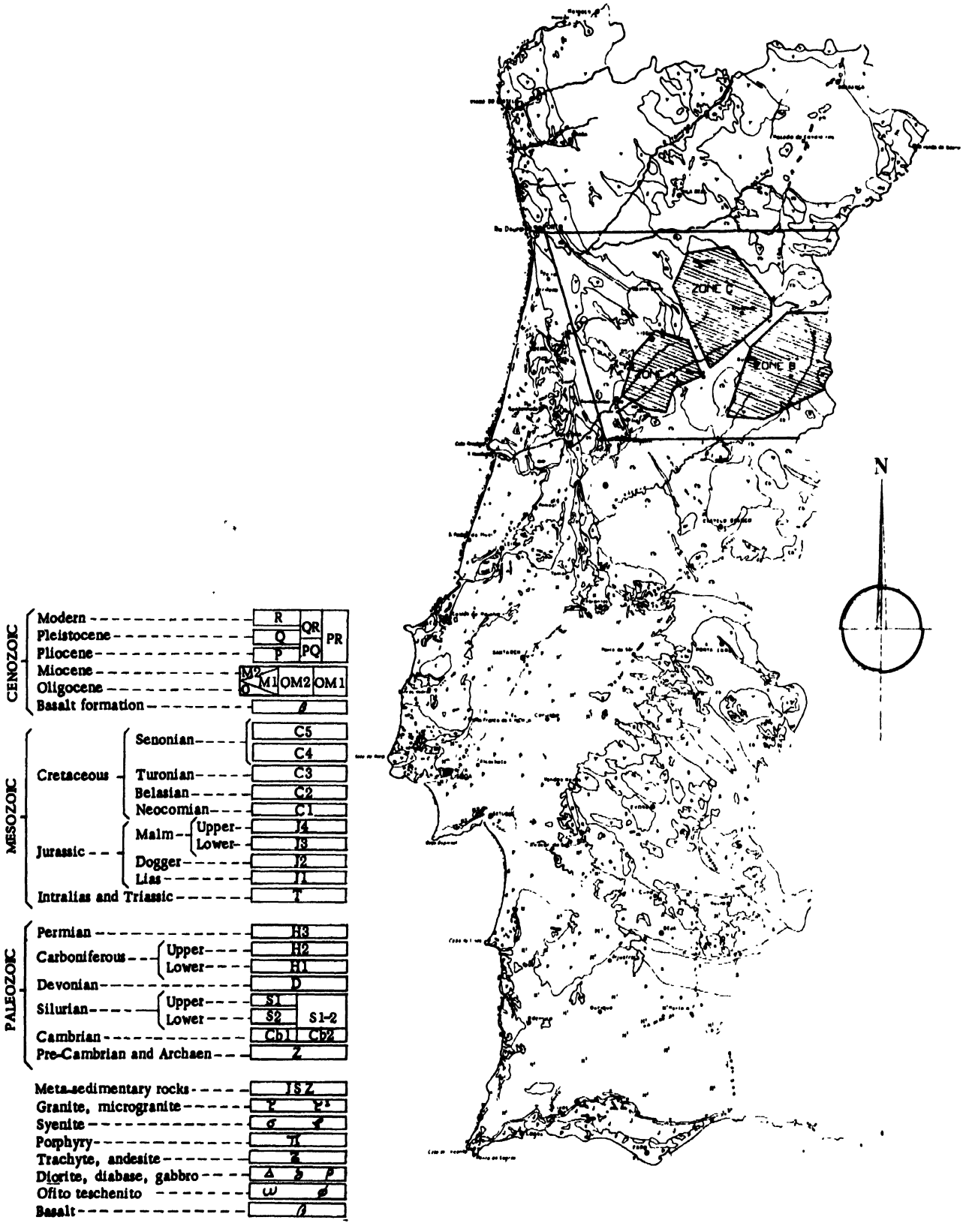


Figure 1. Position of the main uranium deposits in Portugal

the radioactive deposits. This work will be carried out in the same fashion as for isoradioactivity maps and will add to the detailed geological studies. Each operation from (*b*) to (*f*) will be followed by laboratory and office investigations, the results of which, as well as of the field work, will be presented in final detailed reports. The conclusions of these reports will serve as a basis for future investigation and research. The regional and local prospecting stages will be complemented by topographic surveys on large scales of 1/2000 and 1/500 respectively.

(*g*) Geochemical prospecting. For special cases, which are difficult to solve by other means, it will be necessary to try this method.

(*h*) Geophysical prospecting. Very few opportunities for use of other geophysical methods can be forecast for uranium prospecting, aside from those which depend on measurements of radioactivity. However, it is possible that, for the solution of difficult structural problems, it will be necessary to use other geophysical methods, particularly those of electrical conductivity.

(*i*) Surface examination. As the local prospecting develops, it will be necessary to investigate the surface, by means of trenches or shallow drill holes, arranged in such a way that it will be possible to check on the possible continuity of the outcrops.

All surveys must be recorded on the large scale topographic maps and will be the object of detailed geological study based on systematic detection of radioactivity, sampling and analysis. The geological cross sections will indicate distribution and type of mineralization, nature of wall rocks, faults, etc.

(*j*) Diamond drilling. This operation is one of the most important phases of the studies planned and constitutes the first step in the survey which the Junta de Energía Nuclear proposes.

The operations mentioned above have as their only purpose the definition and outlining of the mineralized zones, whereas the drilling will provide precise data on the characteristics of the deposit at depth, making it possible, with good core recovery, to undertake mineralogical, radiometric and analytical studies for quantitative information on the deposits which have been observed by this method.

All mineralization indicated by local prospecting will be the object of exploration and drilling; use will be made exclusively of rotary diamond drills.

The number of the drill holes, their inclination and depth, will be chosen for each case, on the basis of the preceding study.

A careful log of the radioactivity of the drill cores will be kept daily, and the general cross section will be estimated as to its radioactivity.

(*k*) Underground exploration. This work includes the drilling of shallow holes, trenches and galleries, and its purpose is to permit examination of the deposits at depth.

Underground exploration will be carried out on the basis of the drilling so that all future development and mining is integrated. Thus, it will be necessary to make frequent internal drillings which, in general, will be less steep and shallower than those at the surface.

(*l*) Metallogenic study. All underground work, both for exploration and for working, will be accompanied by very detailed geologic and metallogenic studies, particularly where faults affect the deposit; careful radioactive measurements and geologic cross sections will be made as the exploration proceeds.

(*m*) Computation of the reserves. This is the first operation which the Junta de Energía Nuclear proposes in order to make the survey which will depend upon systematic sampling and chemical analyses made by standard methods.

The reserves will be classified as follows: (*i*) *Ore Reserves*—quantity estimated on the basis of outcrops and geological concepts as to continuity and repetition; (*ii*) *Probable Ore*—quantity computed partly by statistical measurements, and partly by geological deduction; and (*iii*) *Possible Ore*—quantity which can be assumed by geologic extrapolation or by other types of deductions with few or no samples.

A comparative study of the technical and economic results of radiometric prospecting with an airborne scintillometer or one set up on a car will make it possible to select the most effective method for a logical selection of the areas for prospecting in the large overseas region.

Studies of Spanish Radioactive Minerals. Phosphates of Uranium-Calcium and Uranium-Copper of Venta de Cardena (Cordoba)

By R. Fernándes Cellini,* T. Batuecas Rodriguez* and J. Vera Palomino,* Spain

Since the Atomic Energy Council has found and described a certain number of radioactive uranium deposits in Spain, this paper will give data on the chemical composition and mineralogical identification of material from the Venta de Cardeña (Province of Cordoba) deposits.

CHEMICAL STUDY OF THE ORE

The analytical study of the crude ore was made on an average sample of 50 kg, in which observation by ultraviolet radiation (wavelength 3655 Å), reveals the presence of two components; one is canary-yellow and has strong yellow-greenish fluorescence, and the other is bluish-green and has weak fluorescence.

From the ore, these two crystalline components were separated mechanically under ultraviolet light, and subjected to the following identifying tests.

Spectrographic Analysis

The qualitative and semi-quantitative spectrographic analysis was made on an average homogeneous ore sample by using a high dispersion Hilger quartz spectrograph of the Littrow type, under the following experimental conditions.

Qualitative Spectrographic Analysis

The following methodology was used: slit, 15 microns; current, 140 volt dc; resistance, 1.8 ohm; electrodes, carbon (Johnson Matthey and Co. Ltd.); separation of electrodes, 2 mm; exposure, 30 seconds; plate, Ilford panchromatic; developer, Kodak D–19b; developing time, 4 minutes at 20°C; and fixing solution, F–5 Universal.

This shows: silicon, very abundant; aluminum, abundant; iron, abundant; magnesium, appreciable; phosphorus, appreciable; uranium, appreciable; calcium, small; titanium, small; copper, very small; manganese, trace; lead, trace; and sodium, trace.

Semi-quantitative Spectrographic Analysis

A method similar to that described by F. T. Birks[1] was followed, with slit, 15 micron; current, 145 volts dc; resistance, 12 ohm; current, 5 amperes; electrode, carbon (Johnson Matthey and Co. Ltd.); specimen mount, 0.8 mm deep, 5 mm diameter in the anode, pointed cathode; separation of electrodes, 4 mm; specimen, 2 mg; exposure, 30 seconds; plate, Ilford panchromatic; developer, Kodak D–19b; developing time, 4 minutes at 20°C; fixing solution, F–5 Universal; and washing, 20 minutes in running water.

The results were:

Sample	*Per cent*
SiO_2	40
Al_2O_3	6–20
Fe_2O_3	2–5
MgO	0.5–1.5
P_2O_5	0.1–0.5
TiO_2	0.5–1.5
CaO	0.2–0.5
CuO	0.12–0.4
MnO_2	0.05–0.015
PbO	0.01–0.03
Na_2O	Trace

We give this semi-quantitative spectrographic technique because it is consistently followed in this Department in order to get preliminary data and to serve as a basis for the analysis of ores, alloys, etc.

Chemical Analysis

The quantitative chemical analysis of the average sample gives the following, which represents the mean of three determinations:

Sample	*Per cent*
SiO_2	84.56
Al_2O_3	8.06
FeO	3.04
MgO	1.18
U_3O_8	0.75
P_2O_5	0.345
TiO_2	0.22
CaO	0.17
CuO	0.052
MnO_2	0.009
PbO	0.0071
Loss at 110°C	1.61
ThO_2	0.0006
Total	100.0031

These determinations were made as follows: a mixture of sodium carbonate and potassium carbonate (1:1) with a 1 gm specimen was analyzed gravimetrically for SiO_2, FeO, Al_2O_3 and MgO, and volumetrically for P_2O_5 and CaO. TiO_2 was determined colorimetrically by the titanate-peroxide method; MnO_2 was determined by oxidation of per-

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* Department of Analytic Chemistry of the Junta de Energia Nuclear (Atomic Energy Council), Spain.

sulfate to permanganate; CuO by the formation of the cuprotetramine compound, and PbO with dithizone. Uranium was determined: (*a*) volumetrically, by reduction to U(IV) with electrolytic cadmium and determined with permanganate; (*b*) calorimetrically, as uranyl carbonate peroxide; and (*c*) by extraction with ethyl acetate, reduction with cadmium and measured with cerium sulphate, and orthophenanthroline as an indicator. All of these methods gave similar results. Thoruim was determined colorimetrically with sodium salt of 1-arseno-2-phenylazo-3-6-disulphoric acid.

These colorimetric determinations were made with a Model B Beckman spectrophotometer.

Interpretation of Results

A consideration of the quantitative chemical analysis of the crude ore, as well as of the corresponding spectrographic analyses, shows an abundance of SiO_2 and appreciable Al_2O_3 and Fe_2O_3. This indicates that this is a deposit in which siliceous and argillaceous components predominate. They are associated with lesser amounts of uranyl phosphate, calcium, copper, and uranium disintegration products such as lead, thorium and radium.

Forjaz[2] notes uranium and zirconium ores in which the radioactive element occurs as a double phosphate. The qualitative spectrographic analysis of this material shows vanadium, barium, thallium, arsenic, tin and bismuth. This agrees with the theory of origin for these phosphate deposits which are associated with carnotite and zeunerite whereas these minerals are lacking in our ore. Various authors describe phosphate deposits and state their chemical analyses show arsenic as an impurity.[3] The presence of other elements such as zinc, tin and bismuth is reported.[4] Crystalline forms of autunite and torbernite were studied, and the presence of arsenic is confirmed[5,6] as an insoluble hydrated arsenate impurity. These elements, especially arsenic, as a possible substitute for phosphorus in the uranium compounds of the uranite group, have not been found in our deposits, no doubt due to a genesis which differs from that described by the above-mentioned authors. Occasionally, autunite and torbernite are associated with deposits of tungsten,[7,8] and this is verified by analyses. This relation does not exist in our ores which, as we have seen, are usually associated essentially with siliceous components and are free of sulphur. They are, therefore, different from the secondary uranium ores (autunite and torbernite) which other researchers have found as coatings in quartz-pyrite oxidized veins.[9,10,11]

Corradi,[12] in his study of a metamorphosed granite porphyry, finds as much as 2% uranium in the form of double phosphates. During the study of several torbernites[13] from a quartz vein in granite-porphyry in northern Portugal, U_3O_8 between 0.12 and 0.87% was found. This maximum amount is similar to the uranium content of our deposits. However, the copper concentration found by the above-mentioned author is much higher than the stoichiometric concentration of the uranium-copper double phosphates which, in our case, is practically identical with theoretical one.

Davidson and Atkin[14] analyzed phosphate minerals and rocks from various countries of which Spain was one. They note the low uranium content (0.001 to 0.007%) and correlate it with the low phosphate concentration of the samples. In the deposits of this study the low phosphorus content (0.345%) and U_3O_8 content of about 0.75% agrees with the stoichiometric value of the above-mentioned double phosphates.

Steinkuhler,[15] studying torbernite from Katanga, notes the high lead content (3%) of these ores. However, their uranium/lead ratio does not agree with that of our deposits.

Sometimes[16] autunite is conspicuous in fractures along the contact of intrusive rhyolite porphyry and alluvial deposits. These are associated with violet fluorite and limonite.

In a study of Bulgarian autunite,[17] Knaeff indicates the absence of thorium, barium and sulphur which also are lacking in our deposits.

The chemical analysis of our crude ore shows that the amount of phosphorus, as well as uranium, copper and calcium, is almost the same as the stoichiometric determination of the double phosphates which are identified in a predominantly quartz gangue (approximately 70%) with about 30% clay and ferromagnesian silicates, and very low concentrations of uranium disintegration products.

Strongly Fluorescent Yellow Component

This component occurs as scales and lamellae in the cracks and fissures of the gangue. In order to study it we made a mechanical separation under ultraviolet light. This gave us a concentrate from which we could isolate uncontaminated crystals for petrographic and X-ray examination.

Qualitative Spectrographic Analysis

The analysis of the concentrate was made using the same experimental procedure as with the crude ore. The results are as follows: silicon, very abundant; uranium, very abundant; phosphorus, abundant; calcium, abundant; aluminum, appreciable; iron, appreciable; magnesium, very small; lead, trace; titanium, trace; manganese, trace; copper, trace; nickel, trace; and cobalt, trace.

Semi-quantitative Spectrographic Analysis

It was made with the same concentrate and experimental procedure as with the crude ore. The results were:

Sample	*Per cent*
SiO_2	20–40
P_2O_5	5–10
CaO	3–10
Al_2O_3	1–3
Fe_2O_3	1–2
MgO	0.02–0.05
PbO	0.003–0.01
TiO_2	0.002
MnO_2	0.001
CuO	0.001

Chemical Analysis

The quantitative analysis of the major components of interest was made with the carefully selected sample in order to determine the possible stoichiometric formula.

The ore concentrate was subjected for two hours to a hot 1:1 solution of nitric acid. This was diluted, filtered, washed, and the residue was tested for the absence of uranium by fluorescence and chemical methods. In the acid solution much higher percentages of P_2O_5, U_3O_8 and CaO were found and a greater loss at 110°C, then in the crude ore. Pb and Th were determined by the method previously described. The results indicated below correspond to the average of three determinations.

Sample	*Per cent*
U_3O_8	32.49
P_2O_5	8.37
CaO	3.39
PbO	0.0052
ThO_2	0.0005
Loss at 50°C	4.34
Loss at 110°C	7.00

On the basis of this analysis, we derive a stoichiometric ratio which corresponds to the following formula: $Ca(UO_2)_2(PO_4)_2 \cdot 6.58H_2O$.

The water content was determined as the average number of moles with respect to uranium moles (6.72), P_2O_5 moles (6.60), and CaO moles (6.43). The loss at 50°C corresponds to 4.08 water molecules for each mole of anhydrous phosphate.

Dehydration Analysis

This analysis was made with a Chevenard dehydration apparatus. Figure 1 shows the curve obtained for temperatures between 25 and 220°C. The linear temperature increase from 25 to 220°C was made by the furnace in two and a half hours.

Figure 1 shows that at about 50°C, there is a slow loss of water. For this reason, in view of the heating rate, the results derived from the curve cannot be compared with those obtained in the oven in which the sample was kept for three hours at 50°C. Thus, the determinations at 110°C in the oven and in the dehydration apparatus are not comparable; in the latter case, it can be seen that a plateau is not reached until 135°C, after heating for about 80 minutes. However, in the oven the sample was kept at 110°C for three hours, and therefore the gravimetric loss in this case, may be compared with the dehydration results established within the range between 135 and 172°C.

From the dehydration curve, we can interpret the changes in the composition of the hydrated phosphate which begin at 49°C. The anhydrous compound is present between 135 and 172°C, and from the average value, we obtained the percentage of water in this phosphate.

We started with a sample that weighed 0.4713 gm. The loss of weight at 151°C (mid-point in the range) represents 6.60% H_2O, which is equivalent to 6.22 molecules of water per molecule of anhydrous phosphate.

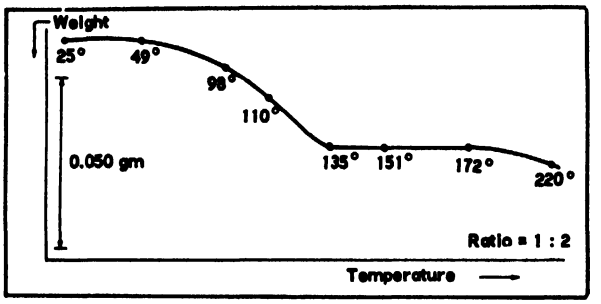

Figure 1. Dehydration curve of the yellow component

Petrographic Study

In order to carry out this study, we studied selected crystals which were observed directly with the microscope. This material is yellow, non-pleochroic along (001) and perceptible along (100), (010) and (110).

The crystals are biaxial negative. The show fine polysynthetic twinning which is parallel with the prism. There is uniform extinction when these planes are at an angle of 45 degrees with the polarizer.

Due to the twinning it is difficult to distinguish the indices $N\beta$ and $N\gamma$. For some specimens with comparatively large twin planes, the following values have been obtained by immersion method using sodium light at 26°C:

$$N\beta = 1.600_0 \quad N\gamma = 1.603_0 \quad N\gamma - N\beta = 0.003_0$$

Although the cleavage planes along the prism are evident, it is difficult to find laminae parallel to c, and therefore we have not been able to determine $N\alpha$.

X-ray Diffraction Study

This study of Debye-Scherrer patterns was made with the following experimental conditions: camera, Unicam; radius, 45 mm; voltage, 35 kv; current, 15 milliamperes; radiation, $K\alpha$: tube, copper; and exposure, 90 minutes. In Fig. 2 the Debye-Scherrer pattern is shown. This gives the data for Table I.

In order to determine the crystal system to which this compound belongs, we have applied the relation established by Hesse[18] and that of Stosick who have obtained satisfactory results with a number of substances. This material is established as tetragonal which is in agreement with Winchell.

Interpretation of the Results

In view of the chemical composition derived from the analyses of the concentrates which have strong fluorescence, it may be stated that this is a mineralogic species which belongs to the uranite group of minerals with the general formula $A(UO_2)_2(XO_4)_2 \cdot nH_2O$, where A may be: Ca, Cu, Ba, Mn, Fe, Na, K, Pb or Mg, and including Al and H in the mineral sabugalite which has been recently discovered in northern Portugal. This mineral is a uranium-calcium double phosphate, since these elements are in stoichiometric balance with each other and their content in the fluorescent material is high. Mg and Mn which are suggested as possible substitutes for Ca in the autunite lattice, are not present

Figure 2. Debye-Scherrer pattern of the yellow component

in this mineral, since these elements do not occur in appreciable quantities or are present only as traces in the analysis of the concentrate.

Water content characterizes the particular mineral among the possible varieties, and the thermogravimetric study shows that 6.22 water molecules are present in this compound. This figure, within the limit of experimental error, agrees proportionately with the value of 6.5 molecules as determined by heating to 110°C for three hours. As a final result, we give the mean of these values (6.40 water molecules), and believe this to be the variety metaautunite I.

Table I. Debye-Scherrer Powder Pattern of the Yellow Compound

No.	I/I_0*	*d*, Å
1	60	7.35
2	10	5.34
3	50	4.88
4	20	4.53
5	40	4.27
6	40	3.93
7	90	3.38
8	30	3.31
9	40	3.05
10	40	2.79
11	70	2.50
12	50	2.35
13	40	2.14
14	80	2.04
15	40	1.97
16	50	1.88
17	10	1.83
18	50	1.76
19	50	1.70
20	10	1.67
21	10	1.61
22	90	1.56
23	40	1.53
24	90	1.50
25	30	1.42
26	10	1.35
27	70	1.32
28	10	1.30
29	30	1.24
30	30	1.17
31	10	1.13
32	10	1.12
33	20	1.09
34	30	1.05
35	10	1.03
36	30	0.97
37	10	0.91
38	10	0.89
39	10	0.87
40	40	0.85
41	10	0.84
42	10	0.82

* The intensities are given in accord with A.S.T.M. standards.

The petrographic investigation was extremely difficult, since it was impossible to make thin section or study fragments which showed all the optical characteristics. However, since Stoces gives values which are lower than those found by us for the refractive indices of autunite (which implies a higher water content), our results confirm that this is a metaautunite which is, of course, in agreement with the chemical analysis.

Bluish Green Component with Weak Fluorescence

This component occurs as minute crystals which occur mostly in druses in quartz gangue. It is considerably less abundant than metaautunite I. Therefore, it was not possible to isolate enough material for determinations which required more than microscopic quantities of pure material. The mechanical separation and general method of investigation is, in every respect, similar to that of the previously described study.

Qualitative Spectrographic Analysis

The results are as follows: silica, very abundant uranium, very abundant; phosphorus, abundant copper, abundant; aluminum, abundant; iron, abundant; magnesium, very small; calcium, very small lead, very small; and manganese, trace.

Semi-quantitative Spectrographic Analysis

The results are as follows:

Sample	*Per cent*
SiO_2	20–40
P_2O_5	5–10
CuO	2–5
FeO	3–6
Al_2O_3	1–3
MgO	0.02-0 05
CaO	0.1–0.4
PbO	0.03–0.10
MnO_2	= 0.001

Chemical Analysis

The average of three similar determinations gives the following:

Sample	*Per cent*
U_3O_8	34.10
P_2O_5	8.63
CuO	4.38
CaO	0.34
Loss at 110°C	11.16

These results indicate that this is a uranium-copper double phosphate with impurities of uranium-calcium phosphate. When the above is given in moles per 10,000 we have:

Sample	*Moles/10,000*
P_2O_5	6.08
U	12.14
CuO	5.51
CaO	0.60

Figure 3. Debye-Scherrer pattern of the bluish-green component

Since the proportion of P_2O_5 and U are slightly altered by the contamination of uranium-calcium phosphate, we shall take CuO as a reference, and refer to it all other values, so that the following molar relations result:

Sample	
CuO	1
P_2O_5	1 + 0.103
U	2 + 0.205
GaO	0.109

The moles of CaO and the excess of P_2O_5 and U essentially occur in the proportions: P_2O_5:U = 1:2, and P_2O_5:CaO = 1:1. The values are found also in the proportions: P_2O_5:U = 1:2 and P_2O_5:CuO = 1:1. This indicates a uranium-copper double phosphate with the formula: $CuO{\cdot}2UO_3{\cdot}P_2O_5$. It is contaminated by the phosphate $CaO{\cdot}2UO_3{\cdot}P_2O_5$ in an approximate ratio of 10:1. This is based on the percentages of CuO and CaO in the analysis.

The water content, according to the chemical analysis, is 11.6%, which corresponds to 61.95 moles per 10,000. If the number of water moles per 10,000 is computed on the basis of CaO P_2O_5 and U which correspond to the contamination from metaautunite I, we find: 3.60 moles/10,000 of H_2O when CaO is taken as a basis; 3.48 moles/10,000 of H_2O when P_2O_5 is taken as a basis; and 3.39 moles/10,000 of H_2O when U is taken as a basis when deducted from the total (61.95) this leaves for this component, the following H_2O moles per 10,000: 58.35; 58.47 and 58.56. To their average value of 58.46 there correspond, stoichiometrically, 10.60 moles of water per mole of anhydrous phosphate, and the final formula is: $Cu(UO_2)_2(PO_4)_2{\cdot}10.6\ H_2O$

Petrographic Study

The crystals studied are uniaxial negative No distortion is observed in the optic axis with objectives of large numerical aperture in sodium light.

These crystals show distinct cleavage parallel with the prism faces, and clear pleochroism.

$N\epsilon$ = grass green

$N\omega$ = bluish green

The indices of refraction were determined on cleavage flakes parallel to (100) or (010). These are easily distinguished from those parallel to (001), as they are light between crossed nicols. They have rectangular extinction parallel to basal plane and the other prism face. These measurements were made with sodium light at 26°C by the immersion method:

$$N\omega = 1.592_6.$$

$$N\epsilon = 1.580_9.$$

$$N\omega - N\epsilon = 0.011_7.$$

X-ray Diffraction Study

This pattern was made with the same experimental conditions as for metaautunite I. Figure 3 shows the Debye pattern as obtained, and the corresponding data is given in Table II.

As with metaautunite I, it is proved that on the basis of the relations established by Hesse, this material is tetragonal, this also is in accordance with Winchell.

Interpretation of the Results

On the basis of the chemical analysis, we believe that this material belongs in the uranite group. It is a uranium and copper double phosphate which is contaminated with approximately 10% metaautunite I. This may account for the slight fluorescence of the crystals, as well as for the contradictions found

Table II. Debye-Scherrer Powder Pattern of the Bluish-green Component

No.	I/I_0	*d*, Å
1	70	8.02
2	40	5.09
3	10	4.75
4	10	4.42
5	10	4.18
6	100	3.57
7	30	3.38
8	40	3.14
9	10	2.99
10	30	2.88
11	40	2.49
12	40	2.32
13	30	2.17
14	30	2.09
15	80	2.02
16	80	1.95
17	10	1 82
18	80	1.75
19	90	1.62
20	10	1.57
21	100	1.53
22	50	1.40
23	80	1.35
24	40	1.32
25	40	1.30
26	90	1.22
27	10	1.10
28	10	1.06
29	10	1.04
30	10	1.02
31	30	0 97
32	40	0.94
33	10	0.91
34	70	0.89
35	40	0.88
36	80	0.85
37	90	0.84
38	50	0.82
39	70	0.81
40	40	0.80
41	10	0.78

in the literature on this property. Because of its water content, and in keeping with the findings of Cana, this component is identified as torbernite. On the basis of the crystallographic data and the indices of refraction which agree with those given in the literature, we arrive at the same conclusion. Therefore, the component of weak fluorescence is identified as torbernite which is contaminated with meta-autunite I.

DETERMINATION OF RADIOACTIVITY IN THE CRUDE ORE AND CONCENTRATES

The direct determination of uranium content by the measurement of combined β and γ activity with a Geiger counter, and the comparison of these figures with the activity of the ores in radioactive equilibrium is only valid when the ores also are in equilibrium. Consequently, when geologic processes occur which cause the loss of one or more elements of the corresponding radioactive family, at times recently enough for the ore not to be able to reach equilibrium, there will be a discrepancy between the chemical and radiometric results.

The determinations of radioactivity were made with the equipment and methods described below.

Equipment was as follows: Tracerlab scaler (Superscaler) on the basis of 1000; G.M. tube TGC-2; average background in lead case, 40 cpm; J.E.N. scaler on the basis of 64; G.M. tube TGC-2; average background in lead case, 30 cpm.

Samples were 0.2000 gm in holders with a diameter of 1 inch.

Standards (*a*) of ores in equilibrium were: ref. "C" of 11.80% in U_3O_8, and ref. "Ca 209-2" of 30.84% in U_3O_8; and (*b*) of U_3O_8 were ref. "U_3O_8-1": 10% in U_3O_8.

Table III summarizes the results of the various measurements.

Determination of Radium in the Crude Ore

The determination of radium in the crude ore was made with the emanation method.

Equipment included purified nitrogen and radon accumulation equipment which was designed and built in this department; cylindrical J.E.N. ionization chamber; and linear amplifier, detector and J.E.N. scaler on the basis of 1000.

Standard was a hydrochloric acid solution, prepared from barium-radium carbonate, of the Institut de Radium, Laboratoire Curie (Paris).

The result gave a content in RaA of 2.24×10^{-9} gm Ra/gm. The ratio $Ra/U = 3.52 \times 10^{-7}$.

Interpretation of the Results

In the crude ore (No. 1), there is considerable agreement between the concentrations of U_3O_8 determined chemically and radiometrically. This indicates that the ore is in radioactive equilibrium. In addition, the ratio Ra/U, which is slightly higher than the theoretical value for ores in equilibrium, seems to confirm this hypothesis.

In the uranium-rich concentrates (No. 2 and 3) there is a marked discrepancy between the uranium content as determined chemically and radiometrically.

For sample No. 2, the uranium content is between that of a mineral in equilibrium and the corresponding recently prepared U_3O_8. On the other hand, for sample No. 3 the uranium content is much closer to that of recently prepared U_3O_8.

It appears, therefore, that autunite and torbernite have not yet reached their radioactive equilibrium, and that they are associated with a gangue which has an appreciable radium content that might be derived from the primary ore.

CONCLUSIONS

1. The radioactive mineralization from the region of Venta de Cardeña (Province of Cordoba) is composed of uranium-calcium and uranium-copper double phosphates.
2. The uranium-calcium double phosphate is meta-autunite I with the formula: $Ca(UO_2)_2(PO_4)_2 \cdot 6.40\ H_2O$.
3. The uranium-copper double phosphate is torbernite with the formula: $Cu(UO_2)_2(PO_4)_2 \cdot 10.6\ H_2O$.
4. From the study of the Debye-Scherrer powder patterns of both components, and by application of Hesse's relations we conclude that they are tetragonal.
5. From the radiochemical study we infer that these phosphates have not yet reached radioactive equilibrium, and that they occur in a gangue which is enriched in radium.

ACKNOWLEDGEMENTS

We should like to extend our warm thanks to F. Alvarez, M. Roca, F. de la Cruz, G. Domínguez, J. Alonso and L. Gascó of the Department of Analy-

Table III. Radiochemical Determinations

Sample Ref. No.	Standard			Sample		
	Ref.	% U_3O_8	Cpm plus background	Cpm plus background	% U_3O_8 radiometric	% U_3O_8 chemical
1*	"C"	1.18	1088.0±4.2	721.2±3.5	0.782±.005	0.75
	"U_3O_8-1"	10.00	2897.9±7.6	721.2±3.5	2.490±.003	
2†	"C"	11.80	9520.8±40.1	11,126.5±16.0	13.790±.005	32.49
	"U_3O_8-1"	10.00	2541.0±12.3	11,126.5±16.0	43.788±.022	
3†	CA 209-2	30.84	23,691.7±45.4	18,239.0±28.0	23.474±.001	68.44
	"U_3O_8-1"	10.00	2541.0±12.3	18,239.0±28.0	71.778±.036	

* J.E.N. scaler used. † Tracerlab scaler used.

tical Chemistry, and to Mr. J. M. Fuster of the Higher Council of Scientific Investigations (Consejo Superior de Investigaciones Científicas) for their cooperation in this investigation.

REFERENCES

1. Birks, F. T., Report de la A.E.R.E. C/R 1177. Harwell, Berks (1953).
2. Pereira Forjaz, A., Comp. rend. 164, 102–3 (1917).
3. Love, J. D., US Geol. Survey Circ. No. *352,* 11 pp. (1954).
4. Porlezza, C. and Donati, A., Ann. Chim. applicata *15,* 518–34.
5. Francesconi, L. and Bruna, R., Gazz. Chim. ital. *64,* 650–2 (1934).
6. Francesconi, L. and Bruna, R., Ann. Chim. applicata, *23,* 534–46 (1933).
7. Toll, R. W., Mining Mag. *85,* 137–42 (1951).
8. Kaspárek, A. and Dusan Nemec. Mineralog. Abstra. 11, 434 (in Mineralog. Mag. 29 (1952).
9. Granger, H. C. and Baner, H. L., Jr., US Geol. Survey Circ. *189,* 1–16 (1952).
10. Gruner, J. W., Fetzer, W. G. and Rapaport, I., Econ. Geol. *46,* 243–51 (1951).
11. Sharp, B. J. and Hetland, D. L., US Atomic Energy Comm. *RME–2010,* 16 pp (1954).
12. Corradi, C., Periodico min. Roma, *4, 252–66* (1933).
13. Cotelo Neiva, J. M., Publ. museu e lab. mineral. e geol. e centro estudos geol. univ. Coimba, Mem e notic. no 32, 63–4 (1952).
14. Davidson, C. F. and Atkin, D., Geol. Survey (Gt. Brit.) and Museum, Atom. Energ. Div. Report no. 124, 16 pp. (1952).
15. Steinkuhler, W., Bull, soc. chim. Belg. 32, 270–2 (1923).
16. Vickers, R. C., US Geol. Survey circ. no. 286, 1–6 (1953).
17. Knaeff, T., Chimie et industrie, *31,* 727–30 (1934).
18. Hesse, R., Acta Cryst. *1,* 200 (1948).

Radioactive Deposits and Possibilities in Spain

By Manuel Alía,* Spain

Because of their geologic characteristics and history, the ancient "Plateau" region in Spain appears most promising with regard to radioactive possibilities. The Plateau is an ancient mass which contains a variety of minerals. Structurally, it is very similar to the French or Bohemian Central Plateau, in the western part of which the well-known and historic Portuguese deposits occur. This large area, predetermined by its structure and mining history, later was confirmed by the actual findings and so, today, most of the Spanish radioactive deposits and indications are situated within the boundaries of this Plateau.

The mountain ranges of the Alpine type, which are one of the main features of the Iberian Peninsula, have shown themselves so far to be areas of lesser potentialities, although within their boundaries, certain radioactive findings have been made. This is also true of Spanish regions in which Tertiary sediments fill depressions, as two Castiles and the Ebro fosse.

When we begin with the Plateau, the deposits that occur here represent various types: pegmatitic, hydrothermal, metasomatic and sedimentary.

The well-known deposits of Hornachuelos, in the Sierra Morena, are the pegmatitic type. In this region, there appears a unit of the lower Paleozoic which gradually becomes strongly metamorphosed. In these metamorphic regions, there is an abundant mixture of pegmatites of various types. These trend in NE and NW directions, which are determined by the dominant faults. The radioactive ores occur in pegmatites along with microcline and large masses of quartz which frequently pass to graphic forms. They also occur in pegmatites where smoky quartz is predominant. Concerning the ore, uraninite and brannerite, along with autunite and the radioactive ochers are usual. These formations are being worked.

Deposits of the hydrothermal type exist in various parts of the Plateau but in general, they show characteristics that are very similar. For this reason their description may be made by taking a specific example. Let us choose, for this purpose, the vein system which occurs in the large structure of the Sierra Morena further north of the pegmatites.

In this area there is a large massif mostly of biotite granite, although there is some granite which contains two mica species which, because of the peculiarities of its emplacement, must be considered later that the Hercynian folding. The massif is elongated in such a way that its longer axis parallels the hercynian northwestern direction, and it is cut by a series of fractures. Those of the most importance for radioactive mineralization run perpendicular to the Hercynian direction indicated above, i.e., northeast. These fractures are frequently injected by various mineral veinlets of hydrothermal origin in which a sequence of deposition took place which, in general, includes such minerals as white barren quartz, quartz with chalcopyrite and pyrite, calcite, quartz and oligist iron (hematite), and subsequent microcrystalline silicification. The radioactive mineralization mostly took place in the last period, along with local processes of reopening of the fractures and the mineralization appears as the epithermal phase. The radioactive minerals that have been identified are: torbernite, autunite, and radioactive ochers. At depth the possible existence of primary minerals is considered. The number of veins of radioactive ore in this region is high, and the average sample contains 0.75% U_3O_8. These vein deposits are important.

As an example of radioactivity associated with metasomatic deposits, we may mention those found in the northern mountains of León. In the Namur limestone which forms part of an imbricated structure, there are dolomite masses which contain mineralization, mostly cupriferous, of various sizes and locations. In the remains of the pocket which once was more extensive where copper and cobalt ores were mined, there are clear signs of radioactive ores and the presence of colloidal pitchblende has been recognized. Mineralization is hydrothermal, and it appears that the mineralizing solutions rose along the tension faults and associated brecciated fill. Metasomatic processes extended the mineralization until the final pockets formed.

Finally, as an example of sedimentary deposits in the Plateau, we may mention those that occur in the region of Despeñaperros. In these areas, the Ordovician outcrops. It is folded and consists largely of quartzite and slate, with some horizons of greywacke and sandstone; certain strata of these greywackes are radioactive. Their content is not very high, since their mean assay is 0.035% U_3O_8. However, there is a considerable expanse of these mineralized layers at the surface. Recently, further to the north, similar greywackes have been found. These have an average content of 0.07% U_3O_8.

Original language: Spanish.

* Council on Nuclear Energy, Madrid.

The various examples that have been mentioned show that the most important types of radioactive deposits occur within the boundaries of the Spanish Plateau. The detailed study of those that are known so far, and of those that will probably be discovered in the future will, no doubt, lead to interesting conclusions concerning correlation, the age or ages of radioactive mineralization through which the ancient massif may have gone, and its development in time and space. It already seems apparent from the current data that the radioactive mineralization occurred to a rather large extent contemporaneously with the initial phase or phases of the Alpine orogeny. We relate most of the magmatic deposits in the area of the "ancient land mass" to this mineralization; these deposits seem to be related closely to the tensile phases of these movements.

A different case is that of the sedimentary deposits of the Ordovician period, in which radioactive mineralization is syngenetic and appears to be the result of the erosion of still older deposits. In this respect one might ask if this Ordovician mineralization which was granitized during the Hercynian orogeny, did not supply part of the radioactive ores, afterwards intruded as veins, in the adjoining region.

In contrast with the Plateau, findings of radioactive ores in the Spanish regions of the Alpine cordilleran type have so far proved to be less abundant and usually less important. These occurrences seem to be localized in the periphery of the large structures.

For example, the occurrences in the Sierras of Cazorla and Segura may be mentioned. These Sierras are related to the main structure of the Andalusian mountains. One of these deposits is a replacement in Triassic limestone which contains copper and lead ore, in which the pitchblende occurs as a film on the copper ore. It appears that the radioactive mineralization is related to that which occurred during the initial phases of the Alpine movements.

In other cases, the radioactive deposits have a different origin, since they are in sedimentary formations. These occurrences are present at certain horizons of the Liassic carbonaceous limestone, which sometimes contain radioactive lignite. Many of the Triassic arkoses in the Andalusian Mountain Ranges also show some radioactivity.

In the Triassic formations of the northern regions, radioactive mineralization likewise has been found. This is present for instance in the lower continental facies of the southern Sierra de la Demanda region where certain arkosic horizons are mineralized by radioactive ores which frequently are accompanied by copper carbonates. Above these arkosic horizons, there are limestones, also carbonaceous, which are radioactive.

Of the large area occupied on the geologic map of Spain by Tertiary continental sediments, particularly Miocene, which are related to areas of structural depressions such as those of the two Castiles, or those of the Ebro and the Guadalquivir, radioactive findings are scarce and are restricted to syngenetic mineralization at certain stratigraphic horizons.

As an example of this type of mineralization, we might mention the type found in the Oligocene of the northern boundary of the Ebro depression. In this molasse, there are certain layers where nodules of malachite and azurite are abundant along with fossil carbonaceous remains. Locally, some of these fossil remains are radioactive due to the presence of autunite.

The deposits and occurrences mentioned in the foregoing are related to mineralization in which the most abundant radioactive element is uranium. In Spain, however, there also are deposits of thorium. These are mostly located in the coastal regions of Southern Galicia, and in some cases, they appear in placers and in other sites which are related to typical vein ores. Examples of this latter type of deposit are given by the thorium ores of the tantalite bearing pegmatites, or those that occur with wolframite and vein cassiterite, as well as rutile. It is interesting to note that in the majority of these deposits where the thorium ore is associated with other ore, the veins trend northeast, i.e., in the direction which, as formerly indicated, is followed by the majority of the Plateau tension fractures which were mineralized by uranium. The placers of thorium are related to various beaches of monazite sand which are situated in Southern Galicia.

In regions other than Galicia, thorium ores also occur, such for instance, as in the province of Salamanca, where they appear to be associated with tantalite, and in the province of Cordoba where monazite occurs.

Finally, beryllium has been found in a certain type of pegmatite which occurs in the radioactive region of Hornachuelos. These pegmatites consist of large crystals of quartz and muscovite, together with a smaller proportion of sodium plagioclase. The beryllium crystals which are sometimes large, are scattered and only in a small number of cases do they contain uranium. Beryllium can also be found in other parts of the Plateau, for instance in the province of Salamanca.

All the data given above, on the outstanding types of radioactive occurrences made so far in Spain, show, although only in general outline, the picture that the country presents at the present time as to actual and, above all, possible exploitation of radioactive ores. In view of the deposits already found and the accepted possibilities, it definitely seems that this picture is a favorable one.

A verification of these possibilities, as well as an investigation of the deposits already known, will be developed by the Council on Nuclear Energy by means of its geological prospecting and mining equipment. More and more interest is concentrated on prospecting on the basis of geologic evidence, and its activities have recently been increased. Private prospecting cooperates with Governmental prospecting, and the required laws are in effect.

The Occurrence of Uranium and Thorium in Sweden

By Erik Svenke,* Sweden

Present geological knowledge of the distribution of uranium and thorium in Sweden is mainly concerned with the uraniferous alum shales and with uranium and thorium bearing pegmatite minerals and thucholite. With the exception of the alum shales, the regional distribution of the other known types of deposits had only been very incompletely investigated until the last few years, during which preliminary work has been started on the regional distribution of the uranium and thorium bearing pegmatites and thucholite.

An extensive research and prospecting program covering this and also other types of minerals is now in progress.

THE URANIFEROUS ALUM SHALES

The uranium content of the alum shales has been known for over 50 years and already some years before starting the atomic energy program in Sweden these shales have been thoroughly investigated from other industrial points of view, especially for shale oil production. Consequently the raw material activities in the atomic energy program were also focused on this uranium bearing material, already well known. An extensive drilling program now going on in cooperation between the Geological Survey of Sweden and the Atomic Energy Company has further broadened the knowledge.

Important uranium content in the alum shales, reaching 100 grams/ton or more, is found in the strata beginning with the Olenus in the upper Cambrian and ending with the Dictyonema and the Ceratopyge in the region between Cambrian and Ordovician.

The Olenus shale is regionally distributed into all Cambro-Silurian districts in Sweden, except the northern part of Lake Siljan in Dalecarlia, i.e., in the provinces of Scania, Öland, Västergötland, Närke and Norrland.

The Dictyonema shales have a more restricted distribution and are found in Scania, Öland, Östergötland and Norrland and in the south-western part of the Falbygden district of Västergötland.

The Ceratopyge shale is developed as alum shale only in Öland and in the Bothnian Gulf.

Some districts are, however, of special interest, namely the Billingen-Falbygden district of the province of Västergötland and the province of Närke, where uranium contents from 200 grams/metric ton up to 400 grams/ton and even higher are found. The strata richest in uranium begin in the lower part of the Peltura Scarabæoides zone which also contains a coal-like substance "kolm" forming lenses or layers in the shale. The uranium content of about 3000 grams/ton in these concretions makes up about 5% of the total uranium content of the richest part of the Peltura Scarabæoides zone.

The uraniferous shale district of Billingen-Falbygden has been thoroughly investigated by core drilling. This district covers a triangular area of about 500 sq.km. The uranium-rich layer has a mean thickness of about 3 m and a mean uranium content of about 300 grams/ton. The uranium reserves in the Billingen-Falbygden district can thus be estimated to about 1 million tons, a considerable part of which is supposed to be minable.

The province of Närke has not yet been fully investigated. With the information collected from the well known Kvarntorp district where the uranium-rich layer is about 5 or 6 m thick, the uranium content about 200 grams/ton, and from the distribution of alum shale in other districts of this province, the uranium reserves can be roughly estimated to about 100,000 tons including the uranium content of "kolm".

From the economic point of view it is an important fact that the uranium-rich zone of shale in the province of Närke to a considerable part can be open pit mined, and that it covers a shale layer which yields about 5% oil, and which is now used in large scale production of shale oil. The uranium-rich shale in the district of Billingen, however, has mainly to be mined underground and the potential oil recovery from it and from surrounding layers of shales in this district is very low, about 1%.

PEGMATITES

So far the investigations carried out with regard to the Swedish pegmatites indicate that there are no deposits of uranium or thorium bearing minerals, worth mining. Euxenite and orthite minerals of a high grade have, however, been found in some places in West Sweden (about 10% U_3O_8 in euxenite). Also in the pegmatites in Central Sweden mined for quartz and feldspar there are comparatively large quantities of uranium bearing Cb-Ta minerals.

* Department of Chemistry, Aktiebolaget Atomenergi, Stockholm, Sweden. In cooperation with the staff of the Geological Survey of Sweden.

OTHER DEPOSITS

Interesting indications of uranium and thorium in thucholite have been found in Zn-Pb occurrences in Central Sweden. These indications have caused a certain optimism that deposits of this type may be worth mining for uranium and thorium.

There are also indications that larger deposits may be found in fine-grained pegmatites and in granites and veined gneisses, and a prospecting program including also these rocks has just set in.

Uranium Prospection in Switzerland

By P. Huber,* Switzerland

No systematic prospection for uranium has been made in Switzerland so far. The good geological knowledge of our country did not seem to indicate any deposition containing uranium worth mentioning. Therefore the prospecting work up till now has been merely accidental.

Prospection has been carried through in the Bergeller Massiv, in the region between Hinterrhein—Averserrhein and around the Mürtschenalp (Kt. Glarus). Then several samples of bituminous shales from the Berner Jura and from Merid as well as 400 samples from more than 100 Swiss lignitic layers and coal have been investigated. Those samples include lignites of the diluvium, tertiary and mesozoic brown coal, and samples of anthracite and bituminous shale. Finally some granite samples originating from different regions have been examined.

No deposition containing uranium worth mentioning could be found. The maximum content of U was around 100–200 gm U per ton of material, while in granite there was between 5 and 50 gm U per ton.

* Physikalische Anstalt der Universität Basel.

Natural Occurrence of Uranium and Thorium in Thailand

By The Delegation of Thailand

GEOLOGIC BACKGROUND

Mineral resources of Thailand are confined chiefly to tin and tungsten ores which occur in hydrothermal veins and pegmatites derived from granitic intrusions. The major geologic formations comprise Paleozoic schist, slate and quartzite underlying Permian limestone. These rocks are found both in continuous and scattered masses throughout the north, the east and the west central, and the south. Mesozoic sandstone and shale are exposed in confined area adjoining Malaya, while they underlie nearly the whole of the east and northeast Thailand, forming an extensive plateau in the latter case. The ore bearing area is limited to the Cretaceous granite which intrudes the sedimentary formations along northwest Thailand down south into Malaya, usually close to the western part. There are a few places where the granite came into contact with limestone resulting in a unique contact metamorphic tin deposit.

The price of tin is far more stable than that of tungsten, and its physical property is more favorable for the formation of easily mined placer deposits. Therefore, mining in Thailand has been more or less confined to tin. In washing to obtain a marketable tin concentrate of over 65% metallic content, the rest of the minerals including some irrecoverable tin is discarded as tailing.

The end of World War II saw a great change in the attitude of the mining people who became aware of the value of other minerals found along with tin, especially the radioactive minerals. Prospectors are on the alert to find new ores that would make the Geiger counter click. Tin miners are keeping watchful eyes on other heavy minerals that are found with cassiterite. Samples of minerals are sent to the Thai Geological Survey for investigation. It is from such samples that the occurrence of uranium-bearing minerals in the tin ground is discovered besides monazite, which has been known to be in association for a long time. Further investigations recently made confirmed the presence of substantial amount of such radioactive minerals in the tin tailings.

MINING BACKGROUND

The peninsular area from 12° parallel down to the southern border is rich in tine placers where cassiterite is concentrated in the foot-hill regions as a result of weathering. Mining methods can be classified into dredging, gravel pumping, hydraulic and ground sluicing. In some hilly areas where tin-bearing pegmatites occur, mining is carried out by hydraulicking or ground sluicing on the hillside. Regardless of the number of mining methods, the principles are the same; that is, the ground must first be broken loose and the dirt-carrying-tin must be preliminarily dressed at the mining place by gravity concentration either by sluices called "palongs" or jigs to separate heavy cassiterite from lighter materials. This brings the content of tin up to 20–50%.

Further dressing has to be done in the tin washing shed using a Willoughby washer (employing the principle of anticurrent separation) or lanchute (a special kind of sluice tapering at the lower end and worked by manual labour), and finishing up by hand jigging with a sieve. Owing to difficulties in separation of minerals of nearly equal specific gravity, a number of magnetic separators are used in some mines to take out such magnetic minerals as magnetite, garnet, ilmenite and monazite, leaving the non-magnetic tin ore intact. The finished product contains 85–95% tin ore, the rest being some adhering minerals which would be non-economical to completely eliminate. The discard, known as tailing, is composed of heavy gangue minerals and 2–5% tin content which is not worth recovering. These tailings are thrown into dumps behind the tin washing shed. Up to now only the management of the Kamunting Tin Dredging Limited (Phang-nga Section) made investigations on the possibility of exporting their tailings. Since 1936, action has been suspended because of the low economic aspects at that time. In some areas the tailing consists nearly wholly of ilmenite, while in other areas the presence of hitherto unsuspected valuable minerals promises an additional revenue to the mine owners.

OCCURRENCES OF RADIOACTIVE MINERALS

Detrital minerals present in the final tin tailings are ilmenite, monazite, garnet, tourmaline, zircon, topaz, rutile, tantalite-columbite, pyrite, arsenopyrite, native gold, molybdenite, quartz, some cassiterite which is left over, and uranium-bearing minerals which are not yet specified. Of these, the first four are the most common, especially ilmenite which is so common that it is locally called "tin excrement". Although tantalite-columbite minerals are quite valuable to mine operators, only the radioactive thorium and uranium-bearing minerals will be described in the following.

Thorium-bearing Minerals

Monazite is the only thorium-bearing mineral so far known in Thailand. It is found in appreciable amount in pegmatite veins, granite gneiss, and adjoining eluvial or alluvial area associated with tin ore along the west coast of the peninsula. Rich monazite sand deposits as worked in India have not been reported. The mineral is invariably lemon yellow or honey yellow with translucent resinous lustre. Sizing tests of the alluvial monazite show that they are mostly subrounded equidimensional, of —40 to —60 mesh size. Coarser grains are rare, which is one reason why megascopic recognition in fresh rock materials is extremely difficult. However, its unique colour and configuration enables instant identification in alluvial residues.

Marketable monazite concentrate has never been accomplished in Thailand, owing to difficulties in ore dressing techniques due to the multiplicity of associated minerals which render present separation methods ineffective. Therefore the following analysis made by I.C.I. Technical Service Staff, London, on a sample of tin tailing in Phang-nga is tentatively quoted to indicate basic nature of the monazite in that area:

Sample	*Per cent*
ThO_2	4.05
Ce and R.E. oxides	45.00
P_2O_5	19.00
SiO_2	1.60
$(Ta, Nb)_2O_5$	16.70
FeO	3.42
MnO	3.74
SnO_2	1.65
ZrO_2	Not detected
Al_2O_3	1.00
TiO_2	1.15

Mineralogical examination of the sample revealed approximately 70% monazite and 20% tantalite-columbite, the rest consisting of predominant ilmenite and cassiterite. On such basis, the thorium oxide

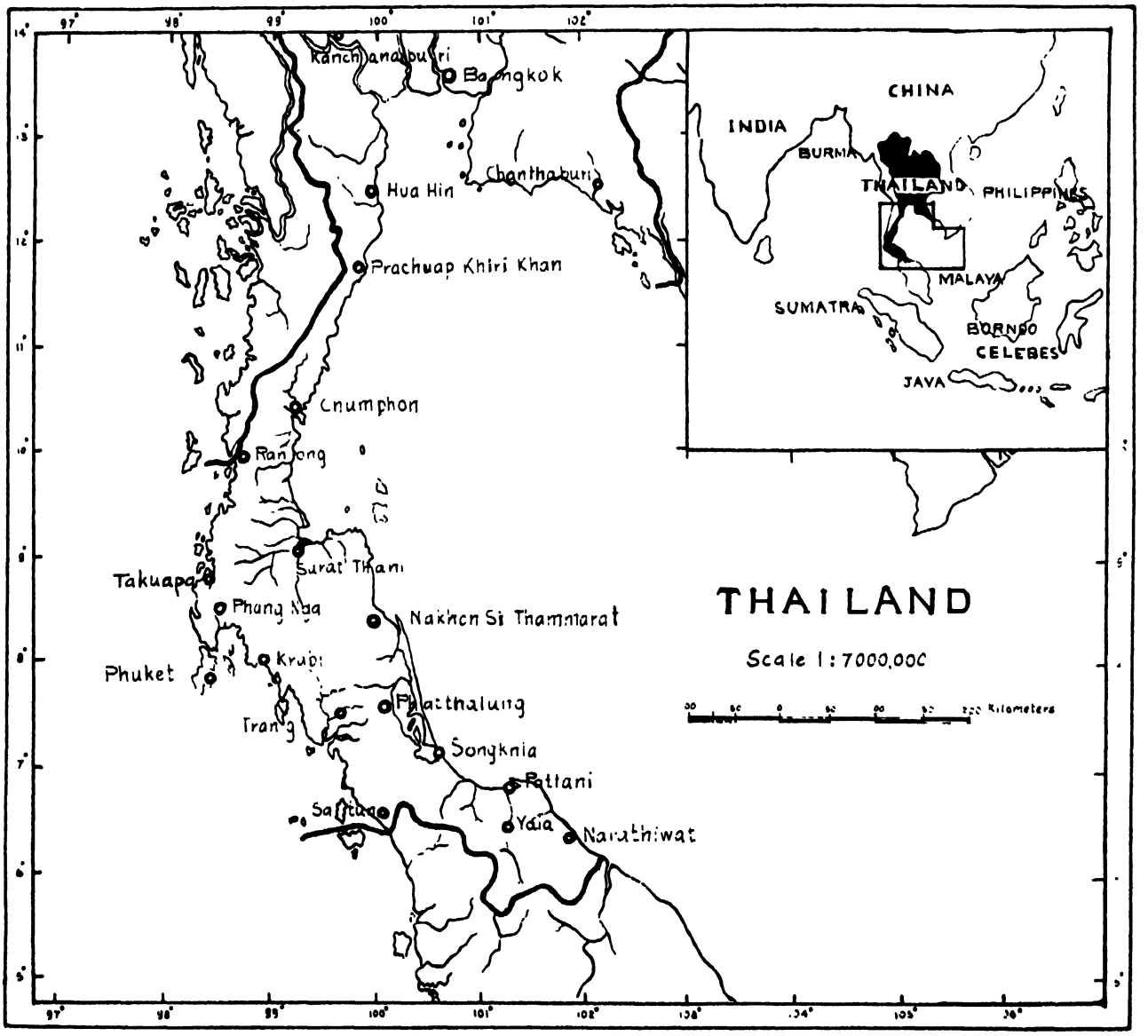

Figure 1. Map of Thailand

content in dressed monazite concentrate would be about 5.7%, a figure well below the Indian beach sand deposit.

Uranium-bearing Minerals

These comprise only the refractory minerals containing an appreciable percentage of uranium oxide. In 1953 the presence of uranium was discovered in the tailings of Kamunting Tin Dredging Ltd. (Phang-nga Section) consisting of 3% cassiterite, 2% euxenite, 2% columbite, 1% monazite, the rest being ilmenite, pink garnet and quartz. Since then requests have been sent out to mine owners to send tailing samples to the Royal Department of Mines where the scintillator was used to detect the presence of radioactive content. It turned out that nearly 40% of the mines along the west coast of the Peninsular provinces, from Ranong down to Phuket, show variable amount of radioactivity. Mines nearer to the granite body are richer than those farther away.

Hand sorting revealed the minerals to be euxenite and a supposedly new mineral which is described below. This mineral predominates all other radioactive minerals and will certainly be of economic importance in the future.

This mineral is usually coarse-grained, the largest piece being about two centimeters long and equally broad. It is crystalline but crystal faces are missing due to water-worn effects with all edges and faces rounded off. So far only one small crystal has been found from tailing in Kanchana Buri and is undoubtedly orthorhombic. The colour is slightly variable usually nearly opaque brownish black with a glassy fracture. Optical character cannot be determined by the microscope because of the very weak transmission of light. Hardness is 5.5–6 and the specific gravity 5.8–6.0. The following are some analyses of the mineral taken from Teen Pet Mine in Phang-nga.

	1	*2*	*3*
Cb_2O_5 }	27.10	26.30	15.61
Ta_2O_5 }			15.29
ThO_2	1.30	1.7	1.27
U_3O_8	13.20	16.30	7.00
RE_2O_3	4.20	3.20	Not analysed
TiO_2	25.30	20.30	7.30
FeO	9.10	10.60	Not analysed
MnO	6.50	6.50	Not analysed
CaO	2.70	1.90	Not analysed
MgO	0.03	0.01	Not analysed
SnO_2	3.50	2.60	Not analysed
WO_3	3.60	3.10	Not analysed
SiO_2	1.60	5.10	Not analysed

RE = Rare earth metal.
1 & 2 = Analyses by the Thai Geological Survey, Royal Department of Mines.
3 = Analysis by the US Geological Survey.

It is this chemical property which led to the controversy as to real nature of the minerals.

Whereas the primary mineral has no cleavage, its alteration product, pinkish honey brown or yellowish brown in colour, invariably shows good cleavage. Although its nature is again not definite, there is no doubt at all about its being a secondary product. Specimens showing various stages of alteration from merely a thin coating on the black vitreous primary material to a total homogeneous substance with nothing or a few tiny specks of the original are common.

These minerals are heavy enough to make separation from the cassiterite by usual gravity concentration very difficult and some new ore dressing method has to be sought.

FUTURE POSSIBILITIES OF URANIUM AND THORIUM MINERAL PRODUCTION IN THAILAND

As stated previously the radioactive minerals in this country are always found associated with tin and tungsten minerals. Therefore, processing and subsequent production under the present economic condition must depend entirely on the fluctuation of market prices and production figures of the two ore minerals, which would directly determine the amount of tailings. Besides, aggregation of such heavy tailing minerals, valuable or otherwise, had in the past caused great difficulties in efficient processing either by gravity concentration, flotation, or magnetic separation. The Royal Department of Mines is trying to solve this concentration problem on the line of electrostatic method or an economical partial chemical extraction of the required materials to assist the mines in earning more income.

CONCLUSION

1. An unknown mineral containing 7–16% uranium oxide is found in tailings of tin and tungsten mining areas on the west coast of the Peninsular Thailand. This mineral also contains valuable columbium, tantalum and thorium, and occurs in such quantity that will have economic influence to the mining industry in the near future.

2. Its real nature and new ore dressing methods will be immediately determined by the Royal Department of Mines in cooperation with any interested learned agencies.

3. Monazite is the only thorium-bearing mineral found in Thailand. It is also common in the tin tailing and can be separated in appreciable amounts if the price justifies the processing.

4. Other common radioactive minerals have not yet been found anywhere in Thailand.

The Radioactive Mineral Resources of Great Britain

By C. F. Davidson,* UK

As long ago as 1815, a paper was read to the Geological Society of London entitled "On the oxyd of uranium, the production of Cornwall".[1] In this publication William Phillips records the discovery at various times since 1805 of green "oxyd of uranium" (torbernite or meta-torbernite) accompanied by black "pecherz" (pitchblende) in the mineral veins at Tincroft, Tolcarne, and other Cornish localities. The mineral province of South-West England, which has yielded in total more than two million tons of tin and which during the first half of the nineteenth century supplied over forty per cent of the world's copper, was then approaching its heyday; and during the mining and prospecting operations of the last century and a half, close on a hundred occurrences of uranium mineralization have been found in Cornwall and Devon. Although none of these is of significant economic potentiality under modern conditions, the accumulated knowledge on the geology and geochemistry of these deposits is of much scientific interest.

A Geological Survey monograph on the mining district of Southwest England, from which part of the following information is taken, is at present awaiting publication.[2] The region is formed predominantly of slaty shales and mudstones with subordinate grits and conglomerates, all of Devonian-Carboniferous age, these sedimentary formations being known to the local miner by the name of "killas." Basic lavas and tuffs with penecontemporaneous dykes and sills of diabase ("greenstone") are sometimes present. In Permo-Carboniferous (Hercynian) times granites were intruded into the sediments to form the cupolas of Dartmoor, Bodmin Moor, St. Austell Moor, Carnmenellis, Land's End and the Scilly Isles, each of which has its aureole of thermally metamorphosed killas. At a late stage in the granitic injection, fissures opened up along an ENE trend were filled by quartz-porphyry dykes or "elvans", and emanations from the solidifying granitic magma gave rise to lode mineralization, predominantly along this same ENE trend but with some veins ("caunter" lodes) in an ESE direction. For simplicity these two groups of mineral veins are referred to as the E-W lodes. Low temperature mineral lodes in cross-courses trending N-S post-date the principal mineralization. More than 1500 mines in the district are known by name; and although some of these were no more than prospects and the sites of many of the old workings have long been forgotten, it has been found possible to compile records of very varying completeness for over 1100 properties. Only three mines, two for tin and one for wolfram, are in operation at the present day.

In the mineral lodes both the metallic and gangue minerals have a zonal distribution, those formed at higher temperatures and pressures occupying the deeper parts of the mineralized fissures. The order of deposition of the principal ores from below upwards is tin, copper, zinc, lead, iron. The tin and copper zones may each reach as much as 2500 feet in vertical range, and the zinc-lead zone about 1500 feet. In many E-W veins, a tin mineralization in the granite gives place to copper mineralization in the killas; but there are frequent exceptions to this simplification, and stanniferous lodes have been found in killas far removed from the granite contact. The primary uranium mineralization in these E-W veins usually occurs in or close to the copper zone; it is present only exceptionally and where found is always in pockets of no great size, most frequently occurring at intersections with cross-courses and where the wall-rock is greenstone. Some of the better-known occurrences of pitchblende mineralization are described below. Secondary uranium minerals such as zippeite, torbernite, autunite, zeunerite and bassetite are less localized but are usually present only in specimen amounts.

At Wheal Trenwith, an old copper-tin mine at St. Ives, mining was carried out from 1909 to 1915 in search of pitchblende, the ore being derived principally by stripping the walls of stopes and from hand-picking of dumps. The uranium mineralization was found in shoots of chalcocite, bornite and chalcopyrite, associated with some blende, galena and molybdenite, usually occurring as lenses from two to twelve inches wide along the walls at intersections with cross fractures. The distribution of ore was found to be closely controlled by the nature of the wall rock, the lodes being productive in greenstone and hard killas but not so in soft slaty shales. Some pitchblende was found in the country rock, in one instance as far as forty feet from the copper veins. As the lodes entered the granite in depth they became mineralized with tin and tungsten and lost copper-uranium values. In total these mining operations yielded no more than six tons of uranium oxide in six years, and they were closed down because sufficient ore capable of being concentrated to

* Geological Survey of Great Britain.

one per cent grade could not be found. A very similar occurrence in the old copper-tin mine of Wheal Edward near St. Just has at various times yielded a few hundredweights of uranium ore. Here again the uranium mineralization occurs in haematitized quartz and jasperoid veins along greenstone wall rock in the copper zone, "uranites" and uraniferous iron ochres being present near the surface and pitchblende at some depth. The one uranium-bearing shoot accessible above sea level (below which the mine is flooded to 100 fathoms) contains no more than a ton or so of oxide. At Wheal Providence, Carbis Bay, there was a similar token production of uranium from the shallower levels, and fragments of killas and greenstone veined with pitchblende, mispickel, and copper sulphides can be found on the old mine dumps and in beach pebble beds derived from this spoil. Specimen amounts of pitchblende can also be collected readily, with the aid of a Geiger counter, from old dumps at Trewavas Head mine near Breage, Wheal Leeds, Wheal Sheep, and St. Aubyn and Grylls mine near St. Hilary, Wheal Bray near Altarnun in Devon, and many other localities. Gunnislake old mine on the Cornwall-Devon border is well known as the source of the finest torbernite in European museum collections, large books of green mica-like flakes having been found here a century ago in a copper lode close to the granite-killas junction. At none of these places is there any reason to believe that the uranium mineralization is present underground other than in pockets much too small to merit the cost of dewatering the old workings. A small lens of pitchblende in a narrow pyrite-bearing quartz lode, accompanied by a little native bismuth and by copper and nickel arsenides, occurs in a prospect adit at Kingswood near Buckfastleigh; but this too is of no more than academic interest.

In each of the two tin mines still active in Cornwall small shoots of pitchblende are found, there being a general antipathetic relationship between tin and uranium. At Geevor the investigation of some 6½ miles of gallery on the lower levels has revealed the presence of uranium mineralization of sub-ore grade at many localities where the lodes are open, brecciated and vuggy. The uranium is almost invariably associated with an increase of the sulphide content in the siliceous leaders—notably of mispickel, chalcopyrite, covellite and chalcocite. The upper levels of the mine, initially more rich in copper but now exhausted and inaccessible, probably contained richer pockets of uranium ore. At South Crofty, pitchblende ore, of fair grade has been found on the No. 4 lode at depths of 260–290 fathoms, principally in granitic ground which is unpayable for tin near to the killas junction. The extent of the mineralization appears to be insufficient in itself to warrant extraction, though it could probably provide tribute ore if discoveries elsewhere in Cornwall merited the erection of a treatment plant.

One of the N-S lodes which post-date the E-W fissures has given rise to the only mine in Britain that has been worked exclusively for uranium. This, the South Terras property near St. Stephen, was once a mine of some importance, which before the discovery of Shinkolobwe ranked next to Jachymov and Urgeiriça as the third most productive source of uranium in the world. Its past output of uranium oxide, almost all obtained from one high-grade ore-shoot, amounted to between 70 and 90 tons. The uranium lode, known as the Jim lode from the abundant occurrence of "Green Jim" or metatorbernite, was encountered in 1873 in underground workings on an iron vein. It is a well-developed fissure filling with quartz gangue, the width of which ranged from ½ to 3½ feet and averaged about 2 feet. The wall rock is principally Lower Devonian killas, but greenstone is locally present. About a mile to the north, the killas is intruded by the St. Austell granite. The uranium leader had good continuity, ranging in thickness from a knife edge to local swellings of seven or eight inches; and the mineralization consisted of metatorbernite, autunite and zippeite at shallow depth, with pitchblende as the principal ore below twenty fathoms. Accessory pyrite, chalcopyrite, mispickel, galena, and cobalt-nickel arsenides were present in small amounts. This lode was worked at various times between 1878 and 1909, down to the 40-fathom level, most of the ore being shipped to Germany in a concentrate ranging between 3 and 10 per cent, for use in the glass and pottery industries. Between 1913 and 1929 two later attempts were made to work the property, the output being used to maintain a small radium factory in France and another at the mine; but in each case production was derived mainly from stope fill and from the old dumps, practically no new mining being done. The mine was sampled by the Geological Survey in 1929 just before it was abandoned and allowed to flood for the last time; and it was found that no significant part of the ore-shoot had been left unstoped. More recently, in 1952–53, a programme of diamond drilling was undertaken to explore for new ore-shoots laterally and in depth; but the only mineralization found consisted of occasional irregular stockworks in the wall rock, with insufficient continuity to warrant development. The surface dumps and the stope fill are of a grade which would merit their treatment as tribute ore, but they are insufficient in themselves to support an extraction plant. Another uranium-bearing N-S lode is found at St. Austell Consols mine nearby; but here the radioactive ore-shoot was of insignificant size and produced only a few tons of uranium ore, with some nickel and cobalt.

Elsewhere in Britain uranium-bearing mineral lodes are very rare, only two occurrences being known. At the lead-zinc mine of Laxey in the Isle of Man, a thin band of so-called "anthracite" was found in 1860 along the wall of a chalcopyrite shoot on the 100-fathom level; and recent examination of specimens of this hydrocarbon has shown that it consists of a complex of thucholite with pitchblende, the former presumably having been formed by the

polymerization or condensation of hydrocarbon gases through the agency of alpha radiation. From the old records and from a study of the mine dumps it appears that this uranium mineralization was no more than a small pocket. At Tyndrum in Perthshire a minute cross-course fissure cutting a lead-zinc lode has recently produced specimen amounts of kasolite.

Uranium mineralization is not rare in the sedimentary rocks of Britain, but nowhere does it reach an overall grade sufficient to merit commercial exploitation. Radioactive vanadiferous nodules are sparsely distributed in Permian-Triassic marls at many localities, notably at Budleigh Salterton in Devon where concentrically-banded specimens several inches in diameter contain up to 0.4% U_3O_8 and 6.5% V_2O_5. Thin, unworkable, uraniferous coal seams have also been found, one example in Warwickshire yielding 0.08% uranium in the coal ash; typically these radioactive coals form the topmost seam of a sequence overlain by red beds, from which the uranium is apparently leached by downward percolating waters to become adsorbed with other heavy metals as the waters pass through coaly matter. Except where rich in calcium carbonate, all British phosphates and phosphatic shales are uraniferous, carrying from 0.01 to 0.10% U_3O_8; but the deposits are again too small to be workable. As in the coals, the uranium content of the phosphates is apparently due to adsorption from acid meteoric waters. A more feeble tenor is found in some non-phosphatic shales, such as the Upper Cambrian rocks at Dolgelley in North Wales and various marine horizons of the Carboniferous strata of northern England.

There are no known thorium resources in the British Isles. Monazite occurs as an accessory mineral in the Cornish granites and derived sediments, but only in traces; and thorite with orangite has been recorded as a mineralogical curiosity from Ben Loyal in Sutherland. Some of the Archaean granite-gneisses in the Isle of Lewis, Outer Hebrides, are rich in allanite, but this is of a variety very low in radioactive elements.

The likelihood of finding important new uranium and thorium deposits in the United Kingdom seems rather remote. The Geological Survey of Great Britain, which has been in existence since 1835, has mapped the country in greater detail than any other part of the world of comparable size; and the extensive information available offers no hopeful grounds for future prospecting. The best possibilities lie in the west of England mining region; but this is without doubt the most fully explored mining field in the world, where important new discoveries are improbable. So far as can be foreseen, the British atomic energy effort cannot therefore be other than wholly dependent upon supplies of mineral from overseas.

REFERENCES

1. Phillips, W., *On the oxyd of uranium, the production of Cornwall*, Trans. Geol. Soc. London, 3, 112–120 (1816).
2. Dines, H. G., *The metalliferous mining district of South-West England*, Mem. Geol. Surv. Great Britain, H.M. Stationery Office, London, 2 vols., circa 800 pp. (1955).

Radioactive Minerals in the Central African Federation

By C. F. Davidson,* UK

The Federation of Southern Rhodesia, Northern Rhodesia and Nyasaland occupies close on half a million square miles in Central Africa. It is a country rich in mineral resources. Within the post-war decade 1945–54 the value of the output of minerals derived from Northern Rhodesia has been £508 million, and from Southern Rhodesia £131 million. In Nyasaland there are as yet no important mines. Radioactive minerals have not so far been produced within the Federation, but one small deposit of uranium ore is at present being developed in Northern Rhodesia and many uneconomic occurrences are known which give promise of useful discoveries being made in the future. Extensive prospecting is at present being undertaken, mainly by British mining houses.

The principal known mineral resources lie in the Copperbelt of Northern Rhodesia; and, together with the adjacent heavily-mineralized region of Haut Katanga in the Belgian Congo, this forms one of the greatest mineral fields in the world, through the midst of which the political boundary is drawn without relation to geological structure. The known reserves in ore of workable grade within this single metallogenetic province aggregate to close on 100 million tons of copper and a million tons of cobalt (metal content). Uranium mineralization is found in conjunction with the copper-cobalt ores, the association of the three elements being so intimate that it cannot be doubted that they are all of like origin. On the Congo side of the frontier the small but very rich mine of Shinkolobwe has produced more uranium than any other ore-field in the history of mining.

The mineralization of the Copperbelt province is of two kinds. The greater tonnage of copper and cobalt is present as disseminated deposits of irregular distribution within sedimentary strata, the host-rock of this disseminated mineralization in Northern Rhodesia being dominantly the calcareous shale and arkose of the Lower Roan formation in the Katanga System, whilst in the Congo it is the dolomite, dolomitic shale, and carbonate-rich strata of the Séries des Mines (Upper Roan formation). The richer but smaller ore-bodies, however, occur as veins, lenses, or chimney-like masses of high-grade mineral cutting across these same sedimentary strata. It has been suggested that the disseminated deposits are of syngenetic (perhaps bacteriogenic) origin whilst the high-grade ores are of epigenetic (hydrothermal) derivation, may be concentrated from the former by secondary migration in a period of diastrophism. This view is difficult to maintain, for the primary uranium mineral (uraninite and pitchblende), where dated by mass spectrographic assays, is always contemporary with a period of granitization in Tanganyika to the east, with an age of about 612 million years. It would therefore seem that all the ore is of hydrothermal origin, the richer deposits marking structural traps that existed at the time of initial mineralization.† If this is so, disseminated ores may be found at many more stratigraphical levels than those at present thought to be hospitable. (In the somewhat similar geochemical conditions of the Colorado Plateau, presumably epigenetic uranium mineralization of Cainozoic age has now been found at no less than 32 stratigraphical horizons of sandstones, shales and limestones ranging from Pennsylvanian to mid-Tertiary, 22 of these carrying ore.)

In Northern Rhodesia the absence of topographic relief and the frequent presence of a thick soil cover is a serious obstacle to prospecting work, and as yet the only uranium minerals found at the surface have been worthless occurrences in pegmatites. Nevertheless many outcrops of secondary copper ores found in former explorations perhaps merit reinvestigation with modern radiometric equipment.‡ Underground, however, each of the large copper mines—Nkana, Nchanga, Mufulira, Roan Antelope, Chibuluma and Kansanshi—has been found to possess discrete uranium mineralization of some slight extent, though not necessarily in workable amount. Recent work by Rhodesian geologists, notably W. G. Garlick, has shown that the disseminated ores tend to exhibit a lateral and vertical zonary distribution of iron, cobalt and copper sulphides, with uranium present in greatest concentration on the edge of the copper zone where the copper and cobalt values fall below cut-off grade. Such zoning, perhaps representing a chromatographic partition, is by no means invariably present; but the distribution of most of the occurrences of uranium mineralization is in agreement

* Geological Survey of Great Britain.

† For recent discussion on the origin of these ores, see *Bull. Inst. Min. Metall.*, London, 1953–54, *passim.*

‡ A list of these occurrences is given by Guernsey, T. D., *A Prospector's Guide to Mineral Occurrences in Northern Rhodesia* with geological maps (1:750,000), British South Africa Company (Salisbury, S.R.), 1950.

with this concept. In the Mindola section of Nkana mine, for example, a significant discovery of uranium mineralization was made in 1952 at the "No. 4 shaft barren gap", where earlier development had shown the sandy dolomitic ore shales to become unpayable for copper. Alone of the several uranium discoveries yet made in the copper mines, this uraninite-bearing ore-shale is present in sufficient tonnage to merit the erection of a small treatment plant, now in course of construction. All other occurrences, whether of disseminated uraninite ore, veinlets of pitchblende, or secondary accumulations of uranium ochres along joints and fissures, are too small to permit selective extraction under the working conditions necessarily obtaining in these great copper-mining operations. The likelihood of making further worthwhile finds seems strong, however, particularly in view of the use now being made of radiometric equipment for the gamma logging of exploration drill holes. Nearly all the normal copper-cobalt sulphide ores have been found to be feebly radioactive, with about 0.005–0.01% U_3O_8, and intersections of the ore horizons by diamond drill holes may thus be detected electronically. Unfortunately this feeble tenor of uranium is not significantly concentrated at any stage of the metallurgical processes for copper or cobalt extraction, and the high carbonate content of the ores prohibits its recovery by acid-leaching of the tailings.

Mineralization, very like that of the Copperbelt, has long been known in the rocks of the Lomagundi system in the Sinoia district of Southern Rhodesia. At the Molly Mine in this region, where the ore consists of copper sulphides disseminated throughout pre-Cambrian arkoses, weakly radioactive zones have been found in which there is a sparse dispersion of grains of uraninite, the copper and uranium showing a somewhat antipathetic relationship. In the oxidized zone of this mine secondary concentration of uranium in the form of torbernite and uranophane may occasionally be seen along fissures and joint-planes. These known occurrences of radioactive mineral are quite devoid of economic value, but their presence suggests that the Lomagundi sediments form a geological environment which is particularly favourable for prospecting.

On present knowledge it would seem that, just as happens with copper, the gneisses, granites and pegmatites of Central Africa are somewhat less favourable to payable uranium mineralization than are the pre-Cambrian sediments, though high-temperature lode deposits both of uranium and thorium could well be found in these formations. Many of the granitic-pegmatitic complexes are noticeably uraniferous. Thus some granites of the Matopo hills south of Bulawayo give a brilliant fluorescence when they are examined in the dark by ultraviolet light, due to traces of uranium adsorbed in the abundant secondary silica. At Beitbridge on the Southern Rhodesian-South African border migmatites are widely mineralized with thorite, allanite and euxenite. Radioactive tantalite, microlite and other tantalum-niobium minerals are of frequent occurrence in the pegmatites of the Bikita tinfields and of the Enterprise district near Salisbury. Small pockets of betafite have been mined from various mica-pegmatites, especially in the Fort Jameson-Lundazi district of Northern Rhodesia. None of these occurrences is of more than academic interest, but there is certainly no reason to be pessimistic about future exploration.

Radioactive mineralization of quite a different type is found in the carbonatite complexes which of recent years have been discovered in Central and East Africa. These intrusive masses of carbonate rock are usually rich in apatite and other phosphates, including some monazite; but it is the almost ubiquitous presence of the niobium mineral pyrochlore which makes them of economic interest. The best-known occurrences in the Rhodesias and Nyasaland are apparently of less interest as a potential source of by-product thorium and uranium than are the carbonatites of Tanganyika, Kenya and Uganda. Although the *terra rossa* soils overlying these deposits are significantly radioactive, most of this activity is due to thorium and to daughter elements of the uranium series adsorbed on iron hydroxides, the parent uranium having been leached away. The pyrochlore at Chilwa Island and Tundulu Hill in Nyasaland has a very variable radioactivity, ranging from 0.83 to 4.5% equivalent thoria, but with a urania content of no more than 0.01%. That of Nkumbwa Hill near Isoka in Northern Rhodesia is only very feebly radioactive. The monazite of both occurrences is almost devoid of thorium. Several other carbonatite complexes have only recently come to light, and there is a possibility that one or more of them might prove to be a source of uranothorianite, which is present in a carbonatite ring structure at Palabora in the Transvaal.

Although monazite and thorite are present in the alluvial sediments of most of the Rhodesian rivers which drain granitic country, no deposit of a grade and size that would merit consideration being given to dredging operations has yet come to light. The content of monazite in the sediments is only rarely as high as 2 lb per cubic yard. In the Tambani region of Nyasaland, however, alluvial river sands have recently been found to carry an unusual variety of radioactive minerals. Of 40 samples studied mineralogically, 39 contain monazite, 25 thorite, pyrochlore and/or betafite, and 11 uranothorianite. There would thus seem to be a fair possibility that radioactive minerals are widely distributed in the syenite or other bed-rock from which these placers are derived.

The "Gold Belts" of Southern Rhodesia, unlike the gold deposits of the Witwatersrand to the south, have not as yet been found to be a promising source of uranium mineralization. During an examination carried out in 1953 on more than fifty working and derelict mines with auriferous, polymetallic, quartz lodes, only three small uranium occurrences, none of

any commercial importance, were found at widely scattered localities. At the R.A.N. mine in the Mazoe district and the Pool mine near Que Que a slight radioactivity is locally present due to a feeble dispersion of uraninite in the ore. At the Skeleton mine, Que Que, a small isolated pocket of brecciated rock in the vein wall, in which uraninite is associated with haematite, has given specimen amounts of good grade uranium mineral; and fragments of rather similar uraniferous limonite have been found more recently in the gossan at the Cactus Poort mine in the same district. Considering the widespread distribution of polymetallic lodes in the schist belts of Southern Rhodesia, the sparseness of these discoveries is somewhat disappointing.

Among other discoveries of radioactive material in the Federation, carbonaceous phosphates present in the Karroo sediments at Livingstonia in Nyasaland merit brief comment. The richest material, originally logged as a three-inch band of coal, was discovered in a bore-hole core. It consists of a coaly phosphorite with 0.73% uranium oxide and 27.1% volatile matter. Surface radiometric traverses over the Karroo arkoses in the same neighbourhood has established the presence of at least one band to which anomalous radioactivity is imparted by fine laminae of uraniferous phosphatic material along the bedding planes. The uranium content of these phosphates has presumably been adsorbed from percolating waters in the arkoses; and there is thus a possibility that some of the uppermost coal seams in the Karroo Coal Measures may have soaked up uranium in the same manner.

Radioactive accumulations of very recent date are to be found around hot springs in the Kasempa district of Northern Rhodesia. A calcareous sinter from one such deposit affects a Geiger counter as strongly as a high-grade ore—but chemical analysis shows uranium to be completely absent, the radioactivity being due entirely to radium and other elements that are its daughters.

Radioactive Minerals in the British Colonies

By C. F. Davidson,* UK

No uranium deposits of economic significance have as yet been found in any of the British Colonies, Protectorates, Protected States and Trust Territories. Occurrences of uranium minerals in pegmatites and migmatites are far from rare, and various attempts have been made to work such rocks for uraninite in the Uluguru Mountains of Tanganyika, and for euxenite or samarskite at Nanseke in Uganda, at Rupununi in British Guiana, and near Mbabane in Swaziland. At the best these efforts have supplied no more than a few hundredweight of concentrate at a prohibitive cost. Lode occurrences of uranium are not known in the Colonies apart from an occasional very small pocket of metatorbernite in some tin veins in Malaya and in fissures in the copper-cobalt ores of Kilembe, Uganda. Volcanic ashes at Ndale near Fort Portal in Uganda carry betafite, but the overall grade does not exceed 0.01% U_3O_8 and 0.04% ThO_2. All of these discoveries are of no more than academic interest. A commercial value may, however, one day attach to very extensive deposits of albite-riebeckite-granite at Kaffo in the Liruei-n-Kano hills of Northern Nigeria, which carry 0.33% Nb_2O_5, 0.012% U_3O_8, 0.03% ThO_2. In these rocks the active mineral is pyrochlore with 41.1% $(Nb, Ta)_2O_5$, 3.1% U_3O_8, 3.3% ThO_2; and output of the radioactive elements will be possible if and only if the deposit can be worked for niobium.

* Geological Survey of Great Britain.

The known sources of thorium ore are more plentiful. In common with other placer tin-fields throughout the world, the tin-mining operations in Nigeria and Malaya are capable of yielding by-product thorium if the need arises. In Nigeria the resources lie partly in monazite and partly in thorite, the latter mineral being more common than generally realized. The current throughout at the tin dressing sheds totals about 75 tons thoria per year contained in crude tin ore averaging about 0.40% equivalent ThO_2, and the reserves of thoria that will be mined with the tin over the next twenty years amount to between 1000 and 2000 tons. At the present price of monazite and thorite, however, it may not be possible to recover more than a small part of these tonnages as by-product, and even for a small yield of thorite considerable modifications of milling practice are likely to be necessary. The aggregate reserves in Malaya exceed those in Nigeria, but differ in character in that the thoria is present almost wholly as monazite. Other potential sources of thorium are to be found in possible by-production from the pyrochlore-bearing carbonatite deposits of Kenya, Uganda and Tanganyika, which are now being explored as a source of niobium; and from such beach sand deposits in East and West Africa as may be worked for ilmenite. The sand-bars and beaches now being investigated for titanium in Sierra Leone are a likely source, since the hinterland carries many migmatites rich in thoria-high monazite.

Natural Occurrence of Uranium in the United States

By Staffs of the US Geological Survey and the US Atomic Energy Commission, USA

Uranium, discovered by Klaproth in 1789, has a remarkably wide geographic and geologic distribution. From 10 years of intensive study since 1945 by thousands of workers in the United States, uranium is now known to occur in all major geologic environments, except those typified by ultramafic and plateau basalt igneous rocks and certain marine sediments. It is impossible to summarize adequately here all facets of uranium occurrence or to give adequate credit to all scientists who have contributed to this fund of knowledge. This paper, though it summarizes only those papers submitted to this Conference, nevertheless gives a brief, but complete, account of all important data available in the United States for use by others in the search for source materials of atomic energy.

Exploitable deposits of uranium result partly from original inhomogeneities in the earth's crust and partly from the interplay of cyclic orogenic and geochemical processes. In the generation, differentiation, emplacement, and crystallization of magma during an orogenic cycle, original inhomogeneities in the crust can be accentuated. Uranium is concentrated in the final fractions of the magma, and from some magmas the last igneous rocks to crystallize or the residual fluids, or both, are uranium-rich. Tectonic events during the final stages of crystallization may determine whether the uranium crystallizes in pegmatites or in other small differentiated granitic or alkalic plutons, or escapes in hydrothermal solutions and forms veins or other epigenetic deposits.

Uranium may be concentrated further during the subsequent period of weathering, erosion, and sedimentation in and adjacent to a uranium-rich orogenic belt. Complex multiple oxides rich in uranium are relatively insoluble and may accumulate in placer deposits. Uranium from soluble minerals enters the surface and subsurface water and may be deposited in a great variety of environments; that not entrapped reaches the sea and ultimately may be concentrated in black shales and phosphorites. These deposits, through subsequent burial and action of igneous heat and hydrothermal solutions, may be modified to various degrees. Reincorporation of uranium-rich sedimentary rocks in magma and recycling and perhaps reconcentration of uranium are possibilities. Thus uranium-rich provinces, once established, continue through long periods of geologic time.

We group uranium deposits in the United States according to their host rocks or their controlling structure, as deposits in igneous rocks, veins, terrestrial clastic rocks, precipitates and evaporites, lignites, coal, and asphaltic materials, marine black shales, and phosphorites. Most of the ore deposits of uranium occur in the orogenic belt between the 100th and 120th meridian of west longitude; a few occur elsewhere.

Some igneous rocks contain much more uranium than most granites; none is a present source of this metal. Complete studies of four plutonic, one hyperbyssal, and one volcanic igneous magma series, and incomplete investigations of five alkalic intrusive complexes and one lava series show that the uranium content of the mafic rocks is about 0.3 parts per million (ppm), rising steadily in the intermediate rocks to about 2.0 ppm, and reaching a maximum in granite of about 5 ppm. Some late K-rich—Ca-poor porphyries contain as much as 140 ppm. Results of sampling of 116 widely separated rhylitic and dacitic, glassy to partly glassy, volcanic rocks in the Cordilleran region of western United States suggests a provincial grouping of uranium content with certain other trace metals. Recent discoveries of ore-grade deposits, probably epigenetic, in Nevada and California, are in those volcanic provinces of high-uranium content.

The uranium in igneous rocks occurs as discrete uranium minerals, disposed in the structure of the rock-forming minerals by diadochy and in structural defects, in cation exchange positions, adsorbed on surfaces of grains, and dissolved in fluid inclusions and intergranular fluids. The uraniferous intergranular fluids are leachable in dilute acid and may offer a very low-grade, exploitable source of uranium for the future.

Uraniferous vein deposits in the Western States are mainly Tertiary in age. Most economic deposits are in crystalline rocks of Precambrian, Mesozoic, and Tertiary age. Occurrences in eastern United States, mostly undated, are mainly in rocks of Precambrian age. Pitchblende, associated with base metal sulfides or with fluorite, is the principal uranium mineral in vein deposits at depth. Supergene secondary uranium minerals occur in some deposits, but are not abundant. Uranium is mined from veins in Colorado, Arizona, Montana, Nevada, and California, but principally from those near Marysvale, Utah.

Felsic extrusives and intrusives are the most common host rocks of uraniferous veins; less common are the orthoschists and gneisses, quartzite, metavol-

canics, and arenaceous sediments. The vein minerals, for the most part, fill open spaces and were deposited under epithermal conditions; a few, as in Central City, Colorado, may have been formed in mesothermal environments. Replacement bodies are rare. Hydrothermal alteration of the wall rocks includes silicification, sericitization, chloritization, argillization, and alunitization. Hypogene red hematite zones adjacent to veins are very common. Uraninite, the most prominent ore mineral, probably is precipitated from hydrothermal sulfate- and carbonate-rich solutions through reduction caused by hydrogen sulfide, sulfur dioxide, or ferrous iron; decrease in temperature and pressure; or through chemical reaction with host rocks.

Similarities in primary mineral assemblages in various veins of ore grade allow the following classification: Type A—uranium, iron, and silica oxides; Type B—uranium oxides and Fe, Pb, and Mo sulfides with abundant silica and fluorite; Type C—uranium oxides, Co, Ni, base-metal sulfides, and native silver with abundant carbonate gangue; Type D—uranium oxides, iron sulfides, and native gold with abundant silica gangue; and Type E—uraniferous hydrocarbons.

Veins of Type A contain sooty pitchblende with some uraninite and pyrite; quartz and fluorite gangue are sparse. The Moonlight mine, Humboldt, Nevada, is an example of this type, though most of the uranium oxides have been altered to autunite, torbernite, and gummite (?). The brecciated rhyolite wall rock of Miocene age has been altered, in part, to clay minerals.

Type B veins may contain uraninite, iron and copper sulfides, galena, sphalerite, and molybdenite associated with abundant quartz and fluorite. The deposits at Marysvale, Utah, are typical examples. An extreme variant of this type are the uraniferous fluorite deposits of the Thomas Range, Utah.

The veins of the Marysvale district, Piute County, Utah, are in Tertiary quartz-monzonite and the unconformably overlying latitic and andesitic volcanic breccia, tuffs, and flows of early Tertiary age, and the rhyolitic flows and tuff breccias of late Tertiary age. Post-rhyolite, normal and reverse faults and shear zones of diverse orientation contain ore bodies as much as 800 feet long and 700 feet in vertical extent. Ore shoots occur at intersections of faults and points of change of fault-strike. The primary minerals pitchblende, quartz, or chalcedony, dark purple to black fluorite, pyrite, and adularia, occur over a vertical range of 2000 feet; calcite, jordisite, hematite, magnetite, marcasite, and molybdenite have a more limited vertical range. Hydrothermal alteration is marked by alunite, which preceded the uranium minerals, and by later clay minerals, chlorite, local silicification, and hematite. The hematitic alteration is absent in depth. Alteration of pitchblende, to depths of 400 feet, has resulted in many secondary phosphates, silicates, sulfates, sulfo-carbonates, vanadates, and perhaps oxide (sooty pitchblende).

Uraniferous fluorite pipes, veins, and disseminated deposits in the Thomas Range, Juab County, Utah, though in part of uranium ore grade, are mined for fluorite. The ore contains 65 to 95 per cent fluorite and resembles brown, white, or purple clay. It is in soft pulverulent masses or boxworks. The fluorite is associated with montmorillonite, quartz, chalcedony, opal, dolomite, and calcite. Except for a few specimens of carnotite near the surface no uranium mineral is visible; autoradiographs show a uniform distribution of uranium suggesting that it is held in the lattice of the fluorite. As a result of secondary enrichment, the uranium content of the fluorite pipes is highest within 30 feet of the surface: the content is as much as 0.33 per cent. These deposits are in dolomitic wall rocks and are closely related in age to topaz-bearing intrusive and extrusive rocks.

Veins of Type C are characterized by the presence of nickel, cobalt, and native silver with pitchblende in a gangue dominately of carbonate, but with minor silica and barite. The Sunshine mine, Shoshone County, Idaho, is a typical example.

Type D veins contain uraninite with gold-bearing pyrite and quartz associated with lead, copper, and silver sulfides. Deposits of this type are represented in the Central City district, Gilpin County, Colorado, and probably in the Boulder batholith region, Montana.

In Gilpin and Clear Creek Counties, Colorado, pitchblende-bearing veins occur in gneisses and granitic rocks of Precambrian age, associated with potash-rich dikes of Tertiary age. The veins are fillings in faults of Laramide age that formed at intermediate temperatures and pressures. Hypogene mineral zoning exists in this district. Pitchblende is a local constituent of ores of all zones but is most abundant in galena-sphalerite ores and the composite ores between the galena-sphalerite and pyritic gold ore zones. Pitchblende, characteristically showing colloform texture, was the first mineral to form; it is contemporaneous with quartz, and closely followed by pyrite, chalcopyrite, sphalerite, tennantite, and galena. Carbonate minerals locally form part of the gangue. The pitchblende is in shoots, small pods, or lenses that are systematically arranged in some veins and erratically distributed in others. The shoots are small but contain ore of 1 to 65 per cent U_3O_8.

In veins of the galena-sphalerite type, where supergene solutions were only slightly acid, torbernite and other secondary minerals occur in the lower part of the zone of oxidation as disseminations in biotite gneiss and amphibolite wall rocks that have been largely altered to montmorillonite.

Similar veins in Jefferson County, Colorado, indicate that pitchblende ore shoots may preferentially form adjacent to wall rocks in ferrous minerals.

In the Boulder batholith region uranium minerals occur both in chalcedony veins and in veins mixed for silver, lead, zinc, and gold. The silver-lead veins occupy faults cutting quartz monzonite and granodiorite, which have been silicified and sericitized. The

vein minerals are galena, sphalerite, tetrahedrite chalcopyrite, pyrite, quartz, chalcedony, and carbonate minerals. Only minor quantities of sooty pitchblende have been found in these veins; however, uranium ore has been produced from the associated chalcedony veins. The chalcedony veins contain pitchblende, and its yellow alteration products, in at least three generations of black to gray chalcedony and microcrystalline quartz. Minor pyrite and chalcopyrite occur in the veins. The granitic wall rocks are silicified, sericitized, and argillized outward from the veins.

Type E veins contain uranium-bearing hydrocarbons in gangues of calcite and barite together with a variety of metallic sulfides. Near Placerville, Colorado, veins of this type occur in faults cutting sandstones, limestones, and shales of Mesozoic age. The mineralogy is complex and includes at least three stages of mineralization. Calcite, pyrite, and barite are followed by uranium-bearing hydrocarbons, which in turn are followed by chalcopyrite, barite, tetrahedrite-tennantite, galena, sphalerite, fuchsite, and minor molybdenum and cobalt sulfide. The hydrocarbons are associated with minor autunite and uranophane. X-ray analysis of the hydrocarbons detected coffinite and pitchblende. Analyses of the ash of the hydrocarbons show as much as 9.8 per cent uranium.

The principal source of uranium in the United States is in terrestrial sandstones, mudstones, and limestones in which the uranium minerals occur as pore fillings and impregnations. The largest and most numerous of these deposits are in rocks of Mesozoic age on the Colorado Plateau, but similar deposits also occur in Mesozoic and Tertiary rocks on the fringes of the Plateau in Arizona, New Mexico, Utah, and Colorado; and in Texas, North and South Dakota, Wyoming, Montana, Nevada, and California. Uranium occurs in Paleozoic sandstones on the Colorado Plateau, and in Texas, New Mexico, Oklahoma and Pennsylvania. In all, 37 sedimentary units have yielded uranium; 18 have furnished at least 1000 tons of ore averaging over 0.1 per cent U_3O_8.

The Cordilleran Foreland in Colorado, Wyoming, Montana, and the Dakotas, east of the main folded and thrusted belts of the Middle Rocky Mountains is becoming an increasingly important source of production from sedimenatry rocks. This area is characterized by simple folded mountains alternating with broad, asymmetric basins. Most of these structures appear related to vertical block movements in Precambrian basement rocks. Most uranium deposits in the region show a spatial relationship to the tectonic pattern on both a large and small scale.

In the Black Hills of South Dakota and Wyoming the uraniferous districts are on major structural terraces on the Precambrian surface and individual deposits are on similar minor structures in Cretaceous sandstones. Likewise in the Colorado Plateau, regional structures, such as uplifts, faults, joints, and igneous masses appear to influence the distribution of ore deposits, although sedimentary structures are the dominant control.

The uranium-vanadium-copper deposits of the Colorado Plateau region form a group of deposits with a wide distribution and many common geologic characteristics. They are in rocks of late Paleozoic to early Tertiary sedimentary rocks that in places are invaded by moderate-sized stocks and laccoliths of early Tertiary or Late Cretaceous age. Laramide deformation is expressed by several broad folds, flexures, and faults, but in most of the region the beds are nearly horizontal.

Chemical, mineralogic, and geologic evidence indicates that the well known carnotite ores have been derived by progressive oxidation of primary black vanadium-uranium ores. The primary ores contain uranium in uraninite and coffinite, and vanadium in montroseite and roscoelite. Minor amounts of copper, iron, lead, and zinc sulfides are abundant; arsenides and selenides are less common. Calcite and gypsum are commonly present; gypsum is rare in primary ore. Most uraninite and coffinite replace or impregnate coalified wood or other carbonaceous material. Primary vanadium minerals occur also in intergranular space of sandstone.

On oxidation, jet black montroseite alters to paramontroseite and another unknown vanadium oxide, then to blue-black, greenish black, and purplish corvusite group minerals. The primary uranium minerals oxidize and combine with vanadium to form rauvite. As oxidation continues carnotite and tyuyamunite develop. These changes are closely controlled by the pH conditions existing at the time of oxidation; this in part is dependent on ground water conditions. The non-vanadiferous primary ores contain more abundant copper sulfides with uraninite and on oxidation yield a wide variety of secondary hydrated oxides, carbonates, sulfates, phosphates, arsenates, and silicates. Comparison of the unoxidized Plateau ores in Triassic and Jurassic rocks and those of Eocene age in the Gas Hills of Wyoming show similar mineralogy and paragenesis, but vanadium is absent in ores of Eocene age. In the Texas Coastal Plain tuffaceous rocks, uranium phosphate and silicate minerals are associated with arsenic and molybdenum.

Uranium ore bodies in clastic rocks range from small masses only a few feet across to deposits several hundred feet across. The large ore bodies are mainly tabular, forming layers a few feet to as much as 20 feet thick; the long axes of these layers lie essentially parallel to bedding, but the layers are undulant and cut across the beds in places. Many ore bodies in sandstone are slightly elongate parallel to the trend of the stream that deposited the sandstone. On the Colorado Plateau significant production is mainly from the Shinarump conglomerate and Chinle formation of Triassic age and the Todilto limestone, Entrada sandstone, and Morrison formation of Jurassic age. Major deposits in the Shinarump conglomerate are mined in Monument Valley, Arizona and White Canyon, Utah. Deposits of equal importance

are in the Chinle formation in the Big Indian Wash-Lisbon Valley area and at Temple Mountain, Utah; and near Cameron, Arizona. Both Shinarump and Chinle formations contain varying proportions of fluvial conglomerates, sandstones, and mudstones in which plant debris is abundant. Copper, copper-uranium, and vanadium-uranium deposits, both oxidized and unoxidized, have been found in both formations; uraninite is the chief ore mineral in most deposits. Exploitable ores as at Monument Valley and White Canyon are restricted to the sides and bottoms of channel fillings in swales in the lower part of the Shinarump conglomerate. Ore bodies in the Chinle formation are not restricted to channels or to any particular stratigraphic unit; most, however, are in sandstones or coarse clastics in the lower part of the formation.

The Entrada sandstone in Colorado, New Mexico, and Arizona is a massive, crossbedded, fine-grained sandstone of probable eolian origin. It contains several large vanadium deposits (with minor uranium) in western Colorado. One of these deposits, at Rifle, is also partly in the underlying Wingate sandstone.

A very large part of the United States' production of uranium has come from the deposits in the Morrison formation. The Salt Wash member in Colorado and Utah and Brushy Basin member in New Mexico are the most favorable horizons; minor deposits occur in the Recapture and Westwater Canyon members in northwestern New Mexico. Vanadium-uranium deposits, having 1 to 20 parts V_2O_5 to 1 part U_3O_8, predominate in the Morrison formation. These deposits are commonly in belts, such as the Uravan mineral belt, elongated at right angles to the trend of individual deposits. The deposits appear to be localized in the thicker parts of the sandstone lenses by sedimentary structures, such as channels, lenses, and intersections of crossbeds. Many of the deposits are characterized by "roll" ore bodies; layered ore deposits in sharply curving forms that cut across bedding. These deposits are common in the upper part of the Salt Wash sandstone member, but are less common than tabular bodies. They occur at the base of thick sandstone units near numerous, thin, well-defined mudstone layers. The rolls may be several hundred feet long and the long axes parallel current lineation, festoon bedding trends, and scours.

Criteria which lead to the localization of ore deposits within clastic rocks of the Colorado Plateau have received much attention because of their use as guides in drilling. Studies of transmissivity on Outlaw Mesa, Mesa County, Colorado, in the upper ore-bearing sandstone of the Salt Wash member show that these carnotite deposits are largest and most frequent where the uppermost layer is most transmissive, greater than 100 meinzer-feet; they are uncommon where the rocks are less transmissive, below 50 meinzer-feet. The smaller deposits are in rocks having transmissivity of 50–100 meinzer-feet. Determinations of regional transmissivity do not appear to correlate with the position of deposits within a particular fluvial host rock.

Sedimentary structures from which direction of flow of paleostreams can be determined are of considerable aid in predicting favorable areas for uranium deposits. Such structures have apparently guided the flow of ore-forming solutions to local environments favorable to precipitation. As a result elongation of ore deposits can be predicted as parallel to channels and other structures. Thickened parts of sandstones and their trends are of interest because in many districts the thicker parts are more prolific. Associated with these structures are variations in grain size, color, mudstone abundance, and content of carbonaceous material. These features can be correlated with the degree of favorableness of ground for ore deposits, and various types of maps showing their interrelationships have been prepared as guides in exploration.

Alteration zones are common in the mudstones below ore-bearing clastic rocks and their thickness can be correlated with the presence of deposits in many places. This is particularly true in the Morrison formation where the red mudstone is altered to green or gray rock for several feet below ore deposits. In the Temple Mountain area, Emery County, Utah, uranium deposits in asphaltic sandstones are associated with collapse structures in strata above the Sinbad limestone member of the Moenkopi formation and Kaibab limestone. The breccias and adjacent rocks have been highly bleached and altered. Dolomite and iron oxide impregnated zones formed in the Wingate sandstone during this process. Similar collapse structures are known in the southern part of the Plateau and in the Black Hills of South Dakota.

Although most uranium deposits are in the coarse clastic units of terrestrial beds, ore has been produced from mudstones and siltstones in most of the known uranium districts in western United States. These finer clastics are most favorable where they contain large quantities of organic material, as in some of the paludal shales of Cretaceous age in northwestern New Mexico.

Large ore deposits occur in lacustrine Todilto limestone of Jurassic age near Grants, New Mexico. Smaller deposits are known in the Kaibab limestone of Permian age in Arizona and Utah and in its equivalent in New Mexico; in the calcareous and arenaceous portions of the Bidahochi formation of Pliocene age in the Hopi Buttes area, Arizona; and in the algal limestones in the Browns Park formation in southern Wyoming. Occurrences of uranium minerals in limestones also are known in western Texas, northern Wyoming, and northern Utah. Calcareous caliche also is uraniferous in places.

The deposits in the Todilto limestone appear to be confined to intraformational, anticlinal folds in the troughs of shallow synclines. These synclines plunge away from the axis of the Zuni uplift and show a rough alignment with faults. The ore bodies are long and narrow; the trends follow the reticulate joint

and fold pattern. The primary ore minerals are uraninite, fluorite, pyrite, barite, hematite, and calcite, all of which replace limestone. Oxidation produces tyuyamunite, metatyuyamunite, uranophane, limonite, and manganese oxides that fill joints and vugs, and coat bedding surfaces.

The ore in the Kaibab limestone, Temple Mountain, Utah, contains galena, arsenopyrite, and other sulfides associated with realgar. Most of the other occurrences of uranium in limestone are of secondary minerals, although uranium minerals are not visible in the freshwater limestone of Tertiary age at Myton, Utah.

The upper part of the Todilto limestone grades eastward into gypsum derived from anhydrite evaporite. This gypsum apparently does not contain concentrations of uranium, although minor occurrences are known in gypsum beds in northwestern Nebraska. As a rule evaporite deposits contain only trace amounts of uranium.

In semiarid regions terrestrial clastic rocks at the surface may contain caliche-type deposits such as the schroeckingerite deposits of the Great Divide Basin, Wyoming. These are rarely of ore grade, but may serve as indicators of buried deposits.

Coals interbedded with the clastic terrestrial sediments commonly contain minor concentrations of uranium; more rarely these are of ore grade.

URANIUM IN COALS

Coals, in the eastern United States, of Mississippian, Pennsylvanian, and Permian ages, bituminous to anthracite in rank, average about 0.001 per cent uranium; more rarely they contain 0.005 per cent or more. Exceptionally in central Pennsylvania they contain as much as 0.019 per cent. Some shales and underclays associated with average coals contain from 0.002 to 0.005 per cent uranium; one in Illinois contains 0.017 per cent. Coals of Cretaceous and Tertiary ages in western United States are more uraniferous. In Colorado and in North and South Dakota parts of some coal beds may contain several per cent uranium; some deposits have been mined as ore. Subbituminous coal of the Wasatch formation (Eocene) in Sweetwater County, Wyoming, ranges from 0.001 to 0.05 per cent uranium; the average is 0.003 per cent. Cretaceous coal of the same rank in Sandoval County, New Mexico, contains up to 0.1 per cent uranium.

Widespread lignites in the Ludlow, Tongue River, and Sentinel Butte shale members of the Fort Union formation (Paleocene) in northwestern South Dakota and adjacent parts of North Dakota and Montana range from 0.001 to over 10 per cent uranium. At Cave Hills, Harding County, South Dakota, 600 tons, assaying 0.4 per cent U_3O_8, have been mined.

The differences in the uranium content of coals of differing ranks is not entirely a consequence of the availability of uranium. Laboratory experiments demonstrate that peat, lignite, and subbituminous coal extract from aqueous solutions 98 per cent of the contained uranium, while bituminous coal and anthracite capture less than a fifth and slightly more than a third respectively. Investigations have further demonstrated that over 90 per cent of uranium in lignites is in organo-uranium compounds associated with the organic matter of lignites rather than with the extraneous inorganic matter which includes analcite at some localities, jarosite, quartz, gypsum, calcite, and clay minerals.

Uranium itself is one of the several inorganic epigenetic constituents of coals and although its concentration is in large part dependent on the nature and quantity of various humic constituents, other factors exercise control. Slightly impure coal is generally richer in uranium than is the pure coal and carbonaceous shale associated with it. Commonly, no uranium minerals appear in coals containing less than 0.1 per cent uranium; carnotite, autunite, torbernite, metazeunerite, and coffinite are rare in western lignites and subbituminous coals.

One of the most carefully studied subbituminous B-rank coals is in the Great Divide Basin, Sweetwater County, Wyoming, where uraniferous coal of Eocene age underlies more than 750 square miles. Deposits of schroeckingerite occur in a graben near the northern edge of the coal field. The thickest coal beds, as much as 40 feet thick, underlie a relatively narrow belt in the trough and on the west side of a syncline; those coals containing the most uranium are on the east side and are thinner. The syncline coincides with a zone of intertonguing highly permeable, coarse-grained arkosic sandstone beds and less permeable clay, shale, siltstone, fine-grained sandstone, and oil shale. Most of the coal contains less than 0.003 per cent uranium; some as much as 0.051 per cent. The ash of most of these beds contains 0.003 to 0.023 per cent uranium. The highest concentrations are in coals overlain by gravels of Miocene (?) age. In general the uranium content increases toward areas of greater permeability. Ga, Ge, Fe, Mo, Pb, V, and rare earths appear to have a similar distribution as uranium.

The uranium-bearing lignites in western North and South Dakota and eastern Montana occur throughout 2000 feet of fluviatile deposits of early Tertiary (Paleocene) or Late Cretaceous age. Above a marked regional unconformity are 250 feet or more of mildly radioactive tuffs and bentonitic clays of Oligocene and Miocene age. Lignites near this unconformity are markedly radioactive; they contain 0.005 to 0.02 per cent uranium and average about 0.008 per cent. Locally there are significant tonnages of autunite- and metazeunerite-bearing lignite containing as much as 5 per cent uranium.

The uranium in these coals and lignites is believed by many geologists to have been leached from overlying tuffaceous rocks.

URANIUM IN MARINE SEDIMENTARY ROCKS

Widespread uraniferous marine sedimentary rocks include principally phosphatic rocks of Permian age

in Idaho, Montana, Wyoming, and Utah, and of Tertiary age in Florida; and the Chattanooga shale of Devonian and Mississippian age, and some black shales of Pennsylvanian age in the Central States. The uranium content generally is less than 0.02 per cent. Marine sandstones, conglomerates, mudstones, and limestones rarely contain concentrations of U.

Many of the 200 or more black shale units of Precambrian to Tertiary age in the United States have been sampled. The most uraniferous ores are rich in organic matter (mainly plant debris), pyrite, and phosphatic matter. They are low in $CaCO_3$ content and yield oil by destructive distillation.

The Chattanooga shale and its equivalents average about 50 feet in thickness over much of eastern and central United States and contain 0.001 to 0.035 per cent uranium. One of the most uniform areas is in eastern Tennessee where the uranium content is from 0.005 to 0.008 per cent.

In the northern Rocky Mountains and Great Plains regions black shales of Precambrian to Late Cretaceous age contain 0.005 to 0.01 per cent uranium; those of Mississippian age are consistently about 0.005 per cent over wide areas.

Marine phosphorites commonly contain 0.005 to 0.03 per cent uranium. The uranium content increases roughly with increasing phosphate content but is generally low in rocks that contain more than a few per cent CO_2. Aluminum phosphate deposits that have been derived from the weathering of marine phosphorites and phosphatic nodules in some marine black shale formations contain similar amounts of uranium. Most of the uranium in these materials does not occur as a separate mineral phase but substitutes for calcium in carbonate-fluorapatite or crandallite. A few occurrences of tyuyamunite and torbernite have been reported from highly weathered marine phosphorites, however, and these and other secondary uranium minerals, such as carnotite and autunite, are most uncommon in fossil bones and teeth that have been exposed to uranium-bearing solutions after burial. Because the marine phosphorites are of wide extent they contain large tonnages of uranium, some of which can be recovered, under favorable conditions, as a byproduct of the manufacture of triple superphosphate.

Phosphate deposits in the Phosphoria formation occur in an area of 135,000 square miles in Idaho, Montana, Utah, and Wyoming. Nearly all the phosphatic beds are uraniferous with a content range from 0.001 to 0.065 per cent uranium; beds that are more than 3 feet in thickness and that contain more than 31 per cent P_2O_5, generally contain from 0.01 to 0.02 per cent uranium.

The land-pebble phosphate district of Florida covers an area of more than 1000 square miles. The lower phosphorite part of the Bone Valley formation and the upper residual part of the underlying Hawthorn formation, both of Tertiary age, are mined for phosphate. Samples have shown that the coarser phosphate particles are higher in uranium and lower in phosphate than the finer-grained material. The coarser material contains 0.01 to 0.02; the finer is 0.005 to 0.015 per cent uranium. The Bone Valley formation has been leached by acid ground waters and a zone of aluminum phosphate minerals has formed that contains 0.01 to 0.15 per cent uranium. Carbonate-fluorapatite, the primary mineral, has been leached and crandallite, wavelite, and millisite formed.

URANIUM IN PETROLIFEROUS ROCKS

Some Paleozoic and Mesozoic rocks in the South-Central and Western States contain uranium-bearing petroliferous substances. Concentrations of these substances great enough to form uranium ores are rare.

About 200 asphalt-bearing rocks from western United States were analyzed for uranium and found to contain as much as 0.376 per cent uranium in the ash of extracted oil. Other investigations show that uranium is generally enriched in seep oil and in the heavy surface-active fractions of petroleum that adhere to the rocks as compared to the crude oil fraction of petroleum that is produced at the well head. Some concentrations of metalliferous asphalt pellets found in reservoir rocks in Oklahoma and Texas contain uraninite, coffinite, and thorite with an unidentified uranium-bearing compound that may be a metallo-organic complex. Radium, radon, and helium are found in such reservoirs.

ORIGIN

Comparisons of $Pb^{206}/U^{238} < Pb^{207}/U^{235} \gg Pb^{207}/Pb^{206}$ ages of minerals and determination of ratios of oxygen isotopes in uranium oxides have provided data concerning the absolute age of uranium deposits. As a result many hypotheses accepted in the past have been re-examined. Detailed geochemical studies have supplied data useful in explaining the mechanism of formation of deposits. As a result most geologists accept an epigenetic origin, with one or another modification for the ores being mined today; low grade or potential ores are in a large part syngenetic.

Uranium Provinces

By M. R. Klepper and D. G. Wyant,* USA

As with many other metals, most of the world's important uranium deposits are clustered within broad, indefinitely defined areas or provinces. The initial concentration of uranium in these broad areas probably occurred during the formation of the earth's crust. Subsequently, owing to the interplay of geochemical and orogenic processes, the uranium in the original areas of concentraton has been redistributed and in part concentrated to exploitable deposits.

A uranium province is here defined as a broad and generally indefinitely bounded area in which uranium deposits and uranium-rich rocks are relatively abundant. Commonly, the deposits are of several types and of more than one age. Most of the world's important uranium deposits are clustered in a few such areas; notably the broad belt in and adjacent to the Rocky Mountains, from New Mexico and Arizona to the Dakotas and Montana; the western and southern part of the Canadian shield; the northeastern part of the South African shield; parts of the Australian shield; the Erzgebirge and vicinity in central Europe; and probably the Ferghana-Kara Tau region in Russia.

In contrast there are broad areas in which uranium deposits, other than low-grade syngenetic concentrations in phosphorite or black shale, are sparse or lacking. For example, in the eastern third of the United States, in and adjacent to the Appalachian Mountains, no important uranium deposits are known, though there are low-grade syngenetic concentrations in black shale and scattered pegmatites, and a few small epigenetic deposits of carnotite in sandstone.

The main geologic features of the uranium-poor Appalachian region are in many respects similar to those of the uranium-rich Erzgebirge and Rocky Mountain regions. Each of these areas is a strongly deformed geosynclinal belt, intruded by granitic plutons of various types; each is flanked and in part covered by erosional debris from orogenic mountains. The Triassic basins and the plateaus underlain by Pennsylvanian nonmarine rocks in the Appalachian region are comparable to the plateaus and intermontane basins within the adjacent to the Rocky Mountains and to the Triassic and younger basins and plains marginal to the Erzgebirge. Nevertheless, in the Appalachian region, uranium concentrations are few, low grade, and mostly of syngenetic origin (black shale and pegmatite), whereas in the Rocky Mountain region, important epigenetic deposits of several types occur in many districts. In the Erzgebirge region, veins have been an important source of uranium for many years,[1] and strongly uraniferous coal has recently been reported.[2]

Similarly, the geologic histories and features of the Canadian shield, the South African shield, the Fennoscandian shield and the Brazilian shield are roughly similar, but the first two certain important uranium deposits whereas the second two contain virtually no known deposits.

GEOCHEMISTRY OF URANIUM

Data on the uranium content of rocks and fluids are relatively sparse, and estimates of the abundance and distribution of this element in the earth's crust are consequently approximations, though probably of the correct order of magnitude. Estimates of Urey and Brown[3] indicate that uranium is the least common element in the earth, having an atomic abundance of 0.0002 (silicon = 10,000). However, the abundance of uranium in the earth's crust is estimated by Fleischer[4] to be 0.0002 per cent, or about the same as that of tungsten and tantalum.

According to Frondel and Fleischer,[5] about 103 minerals may contain uranium as a major component (more than 1 per cent uranium). In about one-third of these minerals the uranium is tetravalent; the remainder are hexavalent. Fifteen of these uranium minerals are simple oxides or hydrated oxides, 20 are complex titanates, niobates and tantalates, 14 are silicates, 17 are phosphates, 10 are carbonates, 6 are sulfates, 8 are vanadates, and 8 are arsenates.[5] Unidentified uranium compounds occur in some marine carbonaceous shale, lignite and coal, and as intergranular films in igneous rocks. The principal uranium minerals in the large ore deposits are the oxides pitchblende, uraninite, and coffinite; the vanadates carnotite and tyuyamunite; and the complex titanates brannerite and davidite. Uranium does not occur in nature as a native element or as a simple sulfied, arsenide, or telluride. Because uranium can exist in several oxidation states it occurs in a great variety of geologic environments.

PROCESSES THAT CONCENTRATE URANIUM

The formation of exploitable uranium concentrations in a uranium province depends on many geo-

* US Geological Survey.

logic factors. The processes involved are largely geochemical, though to a large extent they are actuated by orogenic events.

The concept of the geochemical cycle,[6,7,8] though idealized and imperfectly known, provides a means of relating the processes that concentrate uranium to the geologic, or orogenic history of an area, and it thus can be used to predict where concentrations of uranium are likely to occur and what the potential of a particular area may be. It is convenient to think of the geochemical cycle as consisting of three phases that grade into one another: one in which igneous processes prevail, one in which weathering and sedimentary processes prevail, and one in which metamorphic processes prevail. During the igneous and metamorphic phases of the cycle, magma is generated, emplaced, and consolidated, preexisting rocks are metamorphosed, and uranium deposits of igneous and metamorphic origin may be formed. During the weathering and sedimentary phases, preexisting rocks and ore deposits are weathered and eroded, uranium is transported and may be concentrated, and sediments accumulate and are lithified.

The formation of a magma, the upward movement and crystallization, and the subsequent exposure of the resulting igneous rock are a part of the orogenic cycle. The uranium content of the rocks formed from a magma increases rather constantly from the first- to the last-formed rocks and thus in a general way follows the same path as silica, the alkalis, and rare elements such as thorium, beryllium, columbium, tantalum, and the rare earths,[7] (Larsen and Gottfried[9,10,11]).

The earliest differentiates consist chiefly of olivine, pyroxene, and calcic plagioclase, minerals that tolerate only negligible quantities of uranium in their lattices. Consequently, these rocks generally contain less than 1 ppm uranium. Later differentiates contain significant amounts of biotite and accessory minerals. Some of these minerals can accommodate in their lattices from 10 ppm to a few per cent uranium, and the rocks, such as granodiorites, syenites, and granites, contain from 2 to 6 ppm uranium. The progressive increase in uranium content of rocks of the Southern California batholith from gabbro, the oldest, to granite, the youngest, is clearly demonstrated by Larsen and Phair.[12] The youngest rocks in some alkalic and silica-alkalic series, for example albite-rich riebeckite granite in Nigeria,[13] quartz bostonite in Colorado (Larsen and Phair[12]), and pegmatites from many widely scattered localities,[14] contain from 10 to 100 ppm (0.001 to 0.01 per cent) uranium; a pegmatite in western Canada contains large reserves of rock averaging 0.2 per cent uranium.[15]

Recent investigations suggest that effusive rocks are generally more uraniferous than their intrusive equivalents, possibly by a factor of 1½ or 2. Data assembled by Adams[12] indicate a range from 0.8 to 15.4 and an average of 5.6 ppm of uranium in about 50 volcanic rocks ranging from basalt to rhyolite and taken from many localities over the world. The data show that the uranium content increases as potassium increases and that the uranium content becomes progressively higher in more acidic rocks. Perhaps the best explanation of the higher average uranium content of effusive rocks is that most of the uranium is trapped in dispersed form during the crystallization of effusive magmas, where as a significant part of the uranium in plutonic magmas is concentrated in residual fluids from which pegmatites and veins may form. This interpretation agrees with the generally held belief that the most favorable settings for hydrothermal deposits of uranium are in the vicinity of plutons of acidic rock.

In some of the relatively uraniferous igneous rocks, most of the uranium is in the rather common accessory minerals, notably xenotime, zircon, monazite, and allanite,[10,16] (Larsen and Gottfried;[9] Larsen[17]). In others, most of it is in relatively uncommon uranium-rich accessory minerals such as uraninite, thorite, thorianite, brannerite, and euxenite.

Most igneous rocks also contain uranium in a form that is readily soluble in weak acids. Hurley[18] found that as much as 90 per cent of the total radioactivity of some granites could be removed by leaching the granulated rock with weak acid. He postulated that the acid-soluble radioactivity was present along fractures and on grain surfaces and may have been due to "supergene enrichment." Larsen and Phair[12] note that "commonly, close to 40 per cent of the uranium in most fresh-appearing igneous rocks is readily leachable." They suggest that this leachable radioactivity may occur "(1) in metamict phases of primary silicates (presumably such accessories as zircon, allanite, and thorite), (2) as interstitial material derived from late magmatic, deuteric, or hydro-thermal solutions, (3) in certain non-metamict partly soluble radioactive accessories, such as apatite, and (4) as adsorbed ions in disseminated weathering products such as iron oxide." Bowie[19] using autoradiographs found that ". . . in an unaltered granite the heavy minerals [accessories] account for nearly all the radioactivity," but, "in rocks slightly altered by pneumatolysis or by ground waters the radioactive elements become distributed along cracks within and as coatings to the feldspars and quartz."

Though the origin and nature of this acid-soluble material is not yet established, its presence has several important implications. First, it suggests that significant quantities of uranium can be leached from igneous rocks by ground water and perhaps later be concentrated as secondary deposits in coal or other sedimentary rocks. Secondly, the possibility that some of this acid-soluble material may be a sample of the residual fluids of a magma suggests that a close relationship may exist between the acid-soluble uranium in igneous rocks and uranium in veins and other types of epigenetic deposits.

Veins and other epigenetic uranium deposits of igneous origin are believed to have formed from the

late differentiates of a uranium-rich magma where structural conditions were favorable. Thus much of the uranium-rich residual fluid probably drained off to form veins if through-going fractures tapped the magma chamber at the proper time. If fractures did not tap the chamber at an opportune time, most of the uranium in the residual fluids was probably trapped in the last igneous rocks to crystallize, partly in specific uranium-rich minerals and partly as soluble intergranular films.

Information on the relationship of abnormally uraniferous igneous rocks and hydrothermal deposits of uranium is meager. Bain[1] noted lack of hydrothermal uranium deposits in areas containing uraniferous pegmatites, but many examples can now be cited of close association of abnormally uraniferous igneous rocks, including pegmatites, with hydrothermal uranium deposits. Some examples are:

1. In the Colorado Front Range, late Cretaceous or early Tertiary pitchblende veins are intimately associated and probably genetically related to uraniferous quartz bostonites;[20] some pitchblende veins of this same age also occur in the vicinity of uraniferous Precambrian pegmatites.

2. In the Erzgebirge and Riesengebirge of Saxony, Silesia, and Czechoslovakia uraniferous granite, uraniferous pegmatite, and pitchblende veins are closely associated.[21,22,23]

3. In the Precambrian shield of Canada, uraninite-bearing pegmatites and pitchblende veins are in close association, though they may not be of the same age, in the Goldfields region and at Stack Lake on the east arm of Great Slave Lake,[2] furthermore, the important uraniferous pegmatite at Charlebois Lake[15,25] is only about 100 miles east of the Goldfields' pitchblende veins. In the Grenville subprovince, uraniferous pegmatites are abundant and pitchblende veins occur, though none of them is at present commercially important; important uraniferous carbonates (calcite-fluorite pegmatites) also occur near Bancroft in this subprovince.[24]

Though these examples are too few to fully support a generalization, the writers are inclined to agree with Lang[26] that abnormally radioactive igneous rocks may be indicators of nearby hydrothermal uranium deposits. However, they are not necessarily so, for tectonic events during the late stage of magmatic consolidation probably determine to a large extent whether most of the uranium in the residual magmatic fluids crystallizes in late-stage igneous rocks, such as pegmatites, or in veins, or in both. If most of the uranium was drained off at a late stage to form veins, the associated igneous rocks may not be abnormally uraniferous.

Destruction by weathering and erosion of uranium-rich igneous rocks and veins and of uranium concentrations in sedimentary and metamorphic rocks, releases uranium that may be either swept out of the province or reconcentrated in suitable environments.

Whether uranium is retained or exported from a province appears to depend largely on the climate, topography, and lithology of the area. Climate is probably the most important factor. In a humid climate the water table is high, weathering is intense, and the products of weathering tend to be clay minerals. As the drainage is to the sea, the uranium, whether in solution or adsorbed on particles of clay minerals, will be permanently removed from the uranium province.

At the other extreme, in an arid climate, water tables are far below the surface or are nonexistent. Weathering tends to simply disaggregate existing rocks, and drainage is either intermittent toward the sea or centripetal. In such an environment the uranium brought near the surface by igneous activity cannot be readily exported from the area. Rain that extracts uranium from outcrops of igneous rocks or veins soon sinks deep into the soil or subsoil and may follow subterranean channels for great distances. In so doing it may traverse favorable lithologic types and be redeposited in new and perhaps much richer concentrations. Clay minerals do not form in great quantities, and little uranium is lost by adsorption in clay particles. Certainly the Western United States and the Ferghana-Kara Tau area owe many of their secondary uranium concentrations to favorable arid climatic conditions that have prevailed for many millions of years.

Soluble uranium in ground and surface waters may be extracted by organisms and incorporated in their tissues;[27] precipitated as secondary minerals such as carnotite and schroeckingerite;[28] adsorbed or absorbed by certain clays, organic and phosphatic material, and colloidal silica;[29] or extracted to form metallo-organic compounds in petroleum.[30,31] The deposits so formed include most uraniferous peat, lignite, coal, and petroleum residue, and many deposits of secondary uranium or complex metal-uranyl phosphates, carbonates, vanadates, sulfates, arsenates, etc.[32,28] In many instances, as for example deposits consisting of secondary minerals have been formed by oxidation of a primary deposit more or less in situ or by precipitation of uranium from migrating solutions in favorable geologic settings.

Whether useful concentrations of uranium are precipitated from migrating solutions is probably largely dependent on the amount of uranium in the carrier, the continuity of flow within a restricted area over a long enough period of time, and the favorable physical conditions, such as alternate wetting and drying, to remove it from solution.

Many minerals that contain small to moderate amounts of uranium, such as monazite, zircon, xenotime, brannerite, samarskite, and euxenite, are relatively resistant to chemical and mechanical attack. These resistant minerals locally become concentrated in fluviatile or marine placer deposits in the vicinity of the source rocks, but most of them become dispersed in terrestrial and near-shore marine sediments without significant concentration. Placers are typically ephemeral, but a few persist and become

lithified. Some geologists contend that the uraniferous Witwatersrand and Blind River conglomerates are fossil placer accumulations that have been subsequently modified and perhaps enriched by hydrothermal solutions;[33] others contend that the deposits cannot be placers;[34] some strongly advocate a hydrothermal origin.[35]

Soluble uranium that is not extracted from ground and surface waters is carried to the sea. Apparently most of this uranium does not long remain in solution, for Goldschmidt[36] and Russel[37] have shown by different lines of evidence that nearly all the uranium that could have been eroded from the land throughout geologic time is in the sediments rather than in the sea water.[29] Uranium may be extracted from sea water by organisms and incorporated in their tissues[38,39] or may be adsorbed or absorbed by certain clays and organic and phosphatic material.[29,40] Part of the uranium removed by these processes is very sparsely dispersed in large volumes of sediment, but some is concentrated to a rather high degree (0.005 to 0.02 per cent) in thin units of marine phosphorite and black organic shale that accumulated very slowly.

Sedimentary rocks, when deeply buried, generally during the deformation of geosynclines, are transformed to a rock or liquid that is in equilibrium with its surroundings. At various depths and under the influence of various pressures, either hydrostatic or directed, the rocks are metamorphosed to gneisses, schists, hornfels, etc., and under extreme conditions are probably liquified to magma. As a result of these processes, fractionation and concentration of uranium may take place. In the melting of rocks the first liquid to form should resemble the last liquid fraction of a magma and be rich in silica, potash, alumina, and water, and probably also in uranium and other minor elements that tend to concentrate in residual granitic fluids. If this is so, some magmas produced by ultrametamorphism should be relatively rich in uranium, and, because of their relatively high water content, might be especially likely to yield uranium-rich hydrothermal solutions. Some support for this suggestion is the fact that most of the world's important vein deposits of uranium and many uraniferous pegmatites are in ancient shields or massifs[1] where rocks have probably been subjected to at least one episode of ultrametamorphism. The fact that few or no exploitable deposits of uranium have been found in other ancient shields and massifs may be a consequence of an originally inhomogeneous crust, but it is also possible that undiscovered deposits exist in favorable settings within these ancient terranes.

It seems likely that migration and perhaps concentration of uranium also may take place under less severe conditions of metamorphism. Marine black shales commonly contain appreciable quantities of syngenetic uranium, whereas few graphitic slates have been reported to contain abnormal quantities, though several examples of epigenetic concentrations in or near such rock can be cited. In the Rum Jungle area of northern Australia, deposits of uraninite and secondary uranium minerals along with copper minerals occur in carbonaceous slates and graphitic schists; in Middle Asia, USSR, local concentrations of uraniferous turquoise, kolovratite, volborthite, and other secondary uranium-vanadium minerals occur in graphitic slate of Silurian age[41,42,43] and in chert and carbonaceous shale of Cambrian age;[44] in the Iron Ranges of the Great Lakes region, abnormal concentrations of uranium occur locally in graphitic schists and associated iron deposits of Precambrian age[45] (see also Vickers[9]). It seems quite probable that deposits of this type could be due to migration and local concentration of syngenetic uranium in black shale under conditions of moderate metamorphism rather than to introduction of uranium from an igneous source.

In summing up the concentration processes, it may be said that under the driving influence of orogenic forces, igneous processes tend to concentrate uranium in late-phase differentiates, notably in pegmatites, small alkalic plutons, and veins or other epigenetic deposits. The concentrations in igneous rocks are syngenetic and though they may be large, they are almost invariably low grade. Vein and other epigenetic deposits associated with igneous rocks are generally small, but some are high grade. Weathering and sedimentary processes may either disperse or concentrate uranium, depending primarily on the climate. Some primary uranium-bearing minerals that are resistant to chemical and mechanical attack accumulate in placers. Other uranium-bearing minerals are dissolved, and the uranium is transported by ground and surface waters, from which, if climatic conditions are suitable, it may be precipitated in favorable receptors to form epigenetic deposits of a variety of types. Most clearly epigenetic deposits, for example uraniferous lignites, are low grade, but some are very large. Some uranium in solution reaches the sea from which it may be extracted to form large low-grade syngenetic accumulations in phosphorites or black shales. Metamorphic processes may yield concentrations of uranium either by converting preexisting rocks to magma, which subsequently may yield uranium-rich differentiates, or by "sweating" uranium out of weakly uraniferous rocks and concentrating it in favorable geologic settings.

INFLUENCE OF OROGENY ON URANIUM CONCENTRATION

From the preceding discussion it is clear that uranium can be concentrated by various processes and in many geologic environments. The environments that exist and the processes that are active from time to time are largely determined by the orogenic history of a region. The world's important deposits of uranium, excluding low-grade deposits in phosphorite and black shale, are all in or adjacent to orogenic belts as might be expected, because magmas, the primary sources of uranium, are generated and em-

placed or extruded in orogenic belts. Though the histories of various orogenic belts differ in detail, all seem to evolve through four general stages: (1) the primary geosynclinal stage, (2) the primary mountain-building stage, (3) the secondary mountain-building stage, and (4) a stage of final differential uplift and local subsidence.[46,47,48]

In the primary geosynclinal stage, arcuate belts of subsidence form between major stable elements. Graywacke, argillite, chert, and submarine volcanic rocks, principally spilite, accumulate in the primary geosyncline, and shale and limestone, passing laterally in the direction of the stable block into first-cycle quartz sandstone, accumulate on the mobile shelf adjacent to the primary geosyncline. In stage 2 the primary geosyncline is strongly deformed and intruded by synorogenic batholiths of intermediate composition, and secondary geosynclines are formed. In them accumulates the debris from the primary mountains, consisting mainly of graywacke and shale and locally of arkose and second-cycle quartz sandstone. In stage 3 the geosynclinal belt is again strongly deformed, intermediate to acidic and alkalic plutons and volcanic rocks are emplaced and extruded, and continental sediments accumulate within and adjacent to the mountains. Highly differentiated small granitic and syenitic intrusives that may be rich in uranium are emplaced at or near the end of this stage, mainly in the secondary geosynclines and adjacent parts of the continental block but locally in the primary geosyncline. Stage 4 is characterized by block faulting and commonly by the extrusion of plateau basalt.

There is little likelihood that important concentrations of uranium form during the primary geosynclinal and primary mountain building stages. The sediments accumulate too rapidly for syngenetic concentrations to form and the magmas—mainly of simatic origin and ranging from ultrabasic to intermediate in composition—generally are not sufficiently differentiated to be important carriers of uranium. The lack of uranium deposits in primary geosynclinal belts and basic volcanic chains such as the Oregon-California Coast Ranges, the Philippine Islands, the Caribbean region, the Aleutian-Kamchatka arc, and much of eastern New England and the piedmont belt to the south attests to the general validity of this reasoning.

The optimum opportunity for concentration of uranium occurs during and following the secondary mountain building stage. Uraniferous marine black shales and phosphorites may accumulate in the marginal parts of secondary geosynclines and on adjacent parts of the continental block. The highly differentiated granitic and syenitic intrusives that are emplaced during this stage may be important bearers of uranium which may crystallize in the last-formed igneous rocks or, if structural conditions are favorable, in veins and other types of epigenetic deposits.

During the latter part of the stage of secondary mountain building and the succeeding stage, which is characterized mainly by block faulting and locally by extrusion of plateau basalts, the earlier formed primary concentrations of uranium are attacked by weathering and erosive agencies and, if climatic conditions are favorable, a variety of types of secondary deposits may form. Uraniferous lignites and coals—most of them apparently formed by the leaching of acidic volcanic rocks by ground water—and placer deposits are noteworthy examples.

The enigmatic sandstone-type deposits, typified by those on the Colorado Plateau,[49,50,51,52] also seem to be closely related to the latter part of stage 3 in both time and space, though their origin is a subject of heated controversy. Most deposits of this type occur in predominantly nonmarine sequences that are the erosional debris of orogenic mountains and consist of interbedded rather well-sorted sandstones and shales. It is not clear whether these deposits were formed by solution of uranium originally dispersed in the sedimentary prism, with subsequent transportation and redeposition in favorable traps, or by introduction of uranium from an igneous source, but an increasing volume of evidence seems to favor an igneous origin.[53,54] Uraniferous Precambrian conglomerates[55,56,57,58] are in some respects similar to deposits of sandstone type and may have a similar origin.

In the more ancient parts of the crust, particularly in Precambrian shields and massifs, successive periods of deformation, intrusion, and metamorphism have provided opportunities for accentuation of original differences in the uranium content of the crust. Such areas are believed to be particularly favorable sites for uraniferous igneous rocks and uranium deposits of igneous or metamorphic origin.

APPLICATIONS OF THE PROVINCE CONCEPT TO PROSPECTING

Understanding the processes that concentrate uranium and being acquainted with the uranium province in the western United States one infers that the only positive indicator of a province is the presence of a variety of types of abnormal concentrations, regardless of the amount of uranium concentrated in any particular deposit. However, the presence of a single epigenetic deposit in a geologically favorable area is sufficient to suggest that a province may exist, and if several deposits of a single type are known the chance that other deposits will be found is very good. All the concentrations in a province may be of about the same age, but because of the high degree of mobility of uranium, deposits of more than one age are typical. The boundaries of uranium provinces are controlled by the interplay of many geologic and climatic factors and consequently are likely to be rather indefinite. These criteria for the recognition of a province are perhaps obvious and undoubtedly incomplete. Almost certainly they will be sharpened as new discoveries are made and as the viewpoints of geologists change as a result of increased geologic and geochemical knowledge.

Where there is no information on the presence of

uranium minerals or abnormally radioactive rocks, complex geology and the presence of acidic and alkalic igneous rocks, including small bodies of highly differentiated types, and mineralogically complex veins of base and precious metals may point to the favorability of an area for uranium.

The province concept is valuable in roughly appraising the potential of an area in which uranium deposits are known and in pointing out settings within a province in which exploitable concentrations might profitably be sought. If an area is known or suspected to be a province, every possible setting in which uranium might be localized should be investigated. These include acidic and alkalic igneous rocks and mineralized structures in the vicinity of such rocks; placers or sites where placers might occur; sequences of continental sandstone and shale, particularly those that contain abundant carbonaceous trash, admixed tuffaceous material, and petroleum residues or that are cut by small acidic or alkalic intrusives; lignite and coal, particularly if it is or was overlain by acidic volcanic rocks or is in a basin through which ground water from a granitic, arkosic, or acidic volcanic terrane drained; metamorphosed black shales; and conglomerate-bearing sequences deposited on a crystalline basement. More specifically, if abnormally radioactive igneous rocks and a few vein deposits have been discovered in a mountainous orogenic belt, one might expect to find more vein deposits in favorable structural settings—particularly in the vicinity of igneous rocks—and placers. In the less deformed erosional debris within and marginal to this belt, especially if the climate is arid or semiarid, one should look for deposits of sandstone type, uraniferous lignite or coal, uraniferous petroleum residues, and perhaps placer deposits. If sandstone-type deposits have been found in a basin, one might profitably look for vein deposits in the adjacent mountains, provided that acidic igneous rocks and favorable structures are present.

The same principles apply to ancient shield areas where veins, uraniferous rocks, and placers are most likely to occur in the strongly deformed, metamorphosed, and intruded portions; uraniferous conglomerates may occur in peripheral less strongly deformed, metamorphosed and intruded rocks. Though uraniferous coal and petroleum residues are not to be expected, small deposits of uraniferous peat may occur locally.

As a corollary to the province concept, the writers would not expect to find more than a sporadic exploitable deposit in relatively recent eugeosynclinal belts or basic volcanic chains such as the California-Oregon coast ranges, much of the Caribbean area, Hawaii, the Philippine Islands, the Aleutian chain, and Kamchatka and the Kurile Islands. Similarly, broad areas covered by rather thick sequences of relatively recent undeformed basaltic flows are relatively unfavorable, even though they may be surrounded and underlain by favorable geologic settings. However, where eugeosynclinal rocks and especially basic igneous rocks have been involved in later orogenies and intruded by acidic igneous rocks, they may assume a relatively high degree of favorability, for many vein deposits seem to favor basic igneous host rocks.[24]

REFERENCES

1. Bain, G. W., *Geology of the Fissionable Materials,* Economic Geology 45: 273–323 (1950).
2. Davidson, C. F. and Ponsford, D. R. A., *On the Occurrence of Uranium in Coals,* Geological Survey and Museum, London, Atomic Energy Division, Report 147 (1954).
3. Urey, H. C., *The Planets, their Origin and Development,* Yale University Press, New Haven (See p. 233) (1952).
4. Fleischer, M., *Recent Estimates of the Abundances of the Elements in the Earth's Crust,* US Geological Survey Circular 285 (See Fig. 2) (1953).
5. Frondel, J. W. and Fleischer, M., *A Glossary of Uranium- and Thorium-Bearing Minerals,* US Geological Survey Bulletin 1009–F (See p. 170–173) (1955).
6. Goldschmidt, V. M., *Stammastypen der Eruptivgesteine* and *Der Stoffwechsel der Erde, Videnskapelskapets Skrifter,* Mat.-Naturv. Klasse, nos. 10 and 11 (1922).
7. Rankama, K. and Sahama, Th. G., *Geochemistry,* University of Chicago Press (See p. 189–190, 243–263, 366–368) (1950).
8. Mason, B., *Principles of Geochemistry,* John Wiley & Sons, New York (See p. 247–254) (1952).
9. Staff, US Geological Survey, *Search for and Geology of Radioactive Deposits, Semiannual Progress Report, December 1, 1952 to May 31, 1953,* US Atomic Energy Commission TEIR–330, Technical Information Service (1953).
10. Billings, M. P. and Keevil, N. B., *Petrography and Radioactivity of Four Paleozoic Magma Series in New Hampshire,* Geological Society of America Bulletin 57: 797–828 (1946).
11. Adams, J. A. S. and Saunders, D. F., *Uranium Content of the Lavas of Lassen Volcanic National Park, California* [Abstract], Geological Society of America Bulletin 64: 1389 (1953).
12. Faul, H. [Editor], *Nuclear Geology,* John Wiley & Sons, New York (See pages 80–87) (1954).
13. MacKay, R. A. and Beer, K. E., *The Albite-Riebeckite Granites of Nigeria,* Geological Survey and Museum, London, Atomic Energy Division Report 95 (1952).
14. Page, L. R., oral communication.
15. Mawdsley, J. B., *Uraninite-Bearing Deposits, Charlebois Lake area, Northeastern Saskatchewan,* Canadian Mining and Metallurgical Bulletin 45: 366–375 (1952).
16. Jahns, R. H., *Distribution of Rare Elements within Granites and Granitic Pegmatites* [Abstract], Geological Society of America Bulletin 64: 1440 (1953).
17. Staff, US Geological Survey, *Geologic Investigations of Radioactive Deposits, Semiannual Progress Report, December 1, 1953, to May 31, 1954,* US Atomic Energy Commission TEIR–440, Technical Information Service, Oak Ridge, Tennessee (1954).
18. Hurley, P. N., *Distribution of Radioactivity in Granites and Possible Relation to Helium Age Measurements,* Geological Society of America Bulletin 61: 1–8 (1950).
19. Davidson, C. F., *The Distribution of Radioactivity,* Mining Magazine 85: 329–340 (1951).
20. Phair, G., *Radioactive Tertiary Porphyries in the Central City District, Colorado, and their Bearing upon Pitchblende Deposition,* US Atomic Energy Commission TEIR–247, Technical Information Service, Oak Ridge, Tennessee; Nuclear Science Abstracts, 6: 776 (1952).

21. Kohl, E., *Grossdeutschlande Vorkommen natürlich radioaktiver Stoffe und deren Bedeutung für die Versorgung mit radioaktiven Substanzen,* Zeitsch. Berg-Hutten-u. Salinenwesen, Deutschen Reich, Berlin, 90: 153–178 (1942).
22. Hoehne, K., *Uber einige As-, Ni-, Co-, Ag-, Bi-, Und Uranerz fuhrende Kalkspatgange der Grube Bergfreiheit zu Oberschmiedeberg in Riesengebirge,* Chemie der Erde, 10: 432–474 (1936).
23. Klockmann, F., *Beitrag zur Kenntnis der granitschen Gesteine des Riesengebirge,* Deutsche geol. Gesell., Zeitsch, Berlin, 34: 373–426 (1882).
24. Lang, A. H., *Canadian Deposits of Uranium and Thorium, Interim account,* Geological Survey of Canada, Economic Geology Series 16 (See pages 20–21, 63, 71, 136–151) (1952).
25. Anonymous, *La Ronge Uranium Mines,* in provincial notes, Saskatchewan, Canadian Mining Journal, 75: 116 (1954).
26. Lang, A. H., *Notes on Prospecting for Uranium in Canada,* Geological Survey of Canada, Paper 49–4 (See page 5) (1949).
27. Cannon, Helen, *The effect of uranium-vanadium deposits on the vegetation of the Colorado Plateau,* American Journal of Science, 250: 735–770 (1952).
28. Stugard, F., Wyant, D. G. and Gude, A. J., 3d, *Secondary Uranium Deposits in the United States,* US Geological Survey Circular 220: 19–25 (1952).
29. McKelvey, V. E. and Nelson, J. M., *Characteristics of Marine Uranium-Bearing Sedimentary Rocks,* Economic Geology, 45: 35–53 (1950).
30. Gott, G. B., Wyant, D. G. and Beroni, E. P., *Uranium in Black Shales, Lignites, and Limestones in the United States,* US Geological Survey Circular 220: 31–35 (1952).
31. Erickson, R. L., Myers, A. T. and Horr, C. A., *Association of Uranium and Other Metals with Crude Oils, Asphalts, and Petroliferous Rocks,* American Association of Petroleum Geologists Bulletin 38: 2200–2218 (1954).
32. Denson, N. M. *et al., Summary of Uranium-Bearing Coal, Lignite, and Carbonaceous Shale Investigations in the Rocky Mountain Region During 1951,* US Atomic Energy Commission TEM–341, Technical Information Service, Oak Ridge, Tennessee (1952).
33. Geological Society of South Africa, *Symposium of Gold Deposits of the Rand,* 34: 1–93 (1931).
34. Davidson, C. F., *The Gold-Uranium Ores of the Witwatersrand,* Mining Magazine, 88: 73–85 (1953).
35. Graton, L. C., *Hydrothermal Origin of the Rand Gold Deposits,* Economic Geology, 25: Supplement to no. 3 (1930).
36. Goldschmidt, V. M., *The Principles of Distribution of Chemical Elements in Minerals and Rocks,* Journal of the Chemical Society: 655–673 (1937).
37. Russell, W. L., *Relation of Radioactivity, Organic Content, and Sedimentation,* American Association of Petroleum Geologists Bulletin 29: 1470–1494 (1945).
38. Burkser, E. S., Shapiro, M. Ya. and Bronstein, K. G., *Radioaktivnost Kamennykh Ugley i anthratsitov Donetskogo Bassena* (Radioactivity of Coal and Anthracite from the Donets Basin), Ukrainskii Khimichniy Zhurnal, tom 4, no. 2: Kharkov, 95–100 (1929).
39. Neuman, W. F., *The Distribution and Excretion of Uranium,* US Atomic Energy Commission, abstract of declassified documents, 1: 149 (1947).
40. Piggot, C. S., *Radium Content of Ocean-Bottom Sediments,* Carnegie Institute of Washington Publication 556: 183–193 (1944).
41. Sosedko, A. F., Osnovnye resultaty Kyzyl-Kumskoy geokhimichekoy ekspeditsii Akad. Nauk S.S.S.R., 1931 (Chief Results of the Works of Kyzyl-Kum Geochemical Expedition of the Academy of Sciences, U.S.S.R. in 1931), Akad. Nauk SSSR SOPS, Trudy, S. Karakalpakskaya no. 1, Kyzyl-Kumy, 1: 5–40 (1933).
42. Adelung, A. S., Kushnar, S. A. and Chikhachev, P. K., *Yugo-Zapadnye Kyzyl-Kumy* (The Southwestern Kyzyl-Kums), Komitet Nauk Uzbekskoy Sovetskoy Sotsialistichichoy Respubliki (Uzbek SSR), Geologiya Uzbekskoy SSR, tom II: 99–151, Leningrad-Moscow (1937).
43. Fersman, A. E., 1928, *On the Morphology and Geochemistry of Tyuya-Muyun,* Akad. Nauk, SSR, Radioaktivnykh Rud, Leningrad, III (1928).
44. Tyurin, B. A., *Karatauskoye mestorozhdeniye uranovanidiyevykh rud* (The Kara-Tau Deposit of Urano-Vanadium Ore), Akad, Nauk SSSR Moscow-Leningrad, Izvestiya, Seriya Geol. no. 2: 99–106 (1944).
45. Staff, US Geological Survey, *Geologic Investigations of Radioactive Deposits, Semiannual Progress Report, June 1 to November 31, 1954,* US Geological Survey, US Atomic Energy Commission, TEIR–490, Technical Information Service, Oak Ridge, Tennessee (1954).
46. Cady, W. M., *Classification of Geotectonic Elements,* Transactions of American Geophysics Union 31: 780–785 (1950).
47. Stille, H., *Einfuhrung in den Bau Amerikas,* Borntraeger, Berlin (1940).
48. Cady, W. M., McKelvey, V. E. and Wells, F. G., *Geotectonic relationships of mineral deposits* [Abstract], Geological Society of America Bulletin 61: 1447 (1950).
49. Fischer, R. P., *Vanadium Deposits of Colorado and Utah,* US Geological Survey Bulletin 936–P: 363–394 (1942).
50. Fischer, R. P. and Hilpert, L. S., *Geology of the Uravan Mineral Belt,* US Geological Survey Bulletin 988–A (1952).
51. Weir, D. B., *Geologic Guides to Prospecting for Carnotite Deposits on the Colorado Plateau,* US Geological Survey Bulletin 988–B (1952).
52. Finch, W. I., *Geologic Aspects of the Resource Appraisal of Uranium Deposits in Pre-Morrison Formation of the Colorado Plateau,* US Atomic Energy Commission TEIR–348, Technical Information Service, Oak Ridge, Tennessee (1953).
53. Stieff, L. R., Stern, T. W. and Milkey, R. G., *A Preliminary Determination of Age and Some Uranium Ores of the Colorado Plateaus* by the Lead-Uranium Method, US Geological Survey Circular 271 (1953).
54. Rosenzweig, A., Gruner, J. W. and Gardner, L., *Widespread Occurrence and Character of Pitchblende in the Triassic and Jurassic Sediments of the Colorado Plateau,* Economic Geology 47: 776–777 (1952).
55. Abraham, E. M., *Geology of Parts of Long and Spragge Townships, Blind River Uranium Area, District of Algoma,* Ontario Department of Mines, Progress Report 1953 (1953).
56. Traill, R. J., *A Preliminary Account of the Mineralogy of Radioactive Conglomerates in the Blind River Region, Ontario,* Canadian Mining Journal, 75: 63–68 (1954).
57. Reinecke, L., *Gold in the Witwatersrand System; Mineral Resources of South Africa,* South Africa Geological Survey: 110–163 (1940).
58. Davidson, C. F. and Bowie, S. H. H., *On Thucholite and Related Hydrocarbon-Uraninite Complexes, with a Note on the Origin of the Witwatersrand Gold Ores,* Great Britain Geological Survey Bulletin 3: 1–19 (1951).

Distribution of Uranium Occurrences in the United States

By A. P. Butler, Jr., and R. W. Schnabel,* USA

Concentrations of uranium are found in a variety of geologic environments in the United States. Nearly all the deposits mined principally for their uranium content are west of 103° W longitude. Only one small deposit in eastern United States has been mined exclusively for uranium. Most deposits are nearly tabular masses in terrestrial sedimentary rocks of Mesozoic and Cenozoic age in the intermontane plateaus and basins. Some are veins in igneous rocks of Tertiary age, and others are veins or related forms of deposits in older crystalline and sedimentary rocks. Uranium is also appreciably concentrated in black shale of Devonian and Mississippian age throughout wide areas in Central United States and in extensive phosphate deposits in several western States and in Florida. Some uranium is now recovered from the Florida phosphorite as a byproduct in the manufacture of phosphate fertilizer and chemicals.[1] Many other occurrences of diverse types are known in many parts of the country, and further exploration may show that they or other similar nearby occurrences can be mined.

More than half of all deposits and about 75 per cent of the deposits containing more than 100,000 tons of ore have been found in the last 12 years. Most of these have been found either near deposits already known or in similar geologic settings elsewhere.

Some deposits, however, such as those in coals of Tertiary age have been found in geologic settings where uranium was previously unknown, and some, such as those in marine phosphatic rocks, have been found in geologic settings where the presence of uranium, though noted, was not generally recognized.

The distribution of uranium deposits and a few of the apparently more significant occurrences in the United States is outlined in this paper by the kind of rocks or by the structural setting in which the deposits are found: (*a*) uranium in igneous rocks, (*b*) uranium in veins, (*c*) uranium in terrestrial sedimentary rocks, and (*d*) uranium in marine sedimentary rocks.

URANIUM IN IGNEOUS ROCKS

Uranium is present in all igneous rocks. It is commonly more abundant in felsic rocks, especially in small masses of soda-rich granite, syenite, and phonolite. The average uranium content in the common types of intrusive rocks ranges from a fraction of a part per million (less than 0.0001 per cent) in gabbroic rocks to about 4 ppm (0.0004 per cent) in granitic rocks (see p. 77 of reference 2). Some alkali-rich rocks contain as much as 300 to 400 ppm (0.03 to 0.04 per cent) uranium. The general pattern of distribution of extrusive rocks is much the same as in their intrusive counterparts.[3]

A considerable part of the uranium in granitic and syenitic rocks is in the major rock-forming minerals, but much of it is either concentrated along with thorium in the common accessory minerals, or adsorbed on surfaces of mineral grains. The uranium content of minor accessories can be as much as several thousand parts per million.

The uranium content of some of the more uraniferous igneous rocks found to date in the United States varies. It is 5 ppm in granite at the Adams tunnel, Grant and Larimer Counties, Colorado (page 204 of reference 4), and 11 ppm in the Conway granite in New Hampshire,[5] to 22 ppm in bostonite from Sussex County, New Jersey (p. 258 of reference 6), and 33 ppm in quartz bostonite from Gilpin County, Colorado (p. 79 of reference 2). Samples of some other rocks also contain amounts of uranium comparable to these more uraniferous rocks. No igneous rocks known in the United States, other than a few pegmatites, however, are sufficiently rich in a single uraniferous mineral to permit recovery of the uranium by means of mineral concentration.

In many parts of the United States, zoned pegmatites of granitic composition and rich in potash feldspar contain scattered grains of uranium minerals or uranium-bearing minerals.[7] Uraninite is the commonest uranium mineral. The amount of uranium in most of these pegmatites does not differ greatly from the amount in granitic rocks. The Ruggles mine, New Hampshire, and the Bob Ingersoll dike, South Dakota, among others contain notable concentrations of uranium minerals, but few pegmatites in the United States are rich enough in uranium to support mining for uranium alone.[7] Several unzoned pegmatites of Precambrian age near Idaho Springs, Colorado, however, have sufficient uraninite associated with biotite dispersed through them to be of nearly ore grade (p. 137–138 ref. 6). Uraninite occurs in mafic pegmatite and adjacent wall rock in Putnam County, New York (p. 208 of ref. 6).

VEIN AND RELATED DEPOSITS OF URANIUM

Most uranium deposits of undoubted hydrothermal origin are found in veins or stockworks whose posi-

* US Geological Survey.

tion is controlled by fractures, faults, or the interstices of breccias. The structures generally dip steeply. At some places uranium has been introduced into the wall rocks of the fractures, but this relation is an important feature of only a few deposits in the United States. Pyrometasomatic deposits are few. Replacement deposits of uranium similar to the mantotype of some sulfide ore bodies are not known in the United States.

Most vein and related deposits of uranium in the United States are distributed from the eastern side of the Rocky Mountains westward to southern California and eastern Washington (Fig. 1). A few small deposits are in the Black Hills. Occurrences of uranium in veins are known in the upper peninsula of Michigan (Fig. 2) (p. 204–206 of ref. 8). All the currently productive deposits are in about 15 areas in Utah, Arizona, Colorado, California, Montana, Nevada, South Dakota, Washington, and Wyoming.

The majority of vein deposits of uranium in Western United States are not only near intrusive rocks of Tertiary age,[9] but are probably of Tertiary age, too. Occurrences in the Coeur d'Alene district, Idaho, in veins cutting slightly metamorphosed rocks of the Belt Series of Precambrian age have been dated as Precambrian.[10] Deposits in eastern Washington, and in the Kern River area, California, at present can only be dated as Jurassic or younger. The occurrences east of the Mississippi River are in rocks of Precambrian age, and are presumably of that age.

Veins and related deposits in which uranium is associated with fluorite are the outstandingly important source of uranium mined from veins in the United States, mainly because the fairly large deposits at Marysvale, Utah, are of this type. The deposits in which uranium predominates over base metals and those in which uranium is subordinate to base and precious metals are less important.

Veins containing the complex assemblage of pitchblende, cobalt and nickel minerals, native silver, and base-metal sulfides, found in many large vein deposits elsewhere are represented only by nonproductive deposits of the White Signal district, New Mexico,[11] and in the Coeur d'Alene area, Idaho[12] where the association may be fortuitous rather than genetic.[13]

Uranium occurs in at least 20 deposits of fluorite ores or fluorite-bearing ores in Illinois,[14] Colorado, Utah, California, and adjacent states.[15] Most of the deposits are inconsequential as sources of uranium or fluorite, and are not shown on the map, but uranium minerals accompanied by fluorite in deposits near Marysvale, Utah, are presently a source of considerable uranium.

Some fairly large deposits of fluorite contain subordinate amounts of uranium. Fluorite bodies in pipes and veins in the Thomas Range, west-central Utah, contain uranium dispersed through the crystal structure of dark-purple fluorite.[16] The fluorite ores of the Jamestown district, north-central Colorado, contain small amounts of base-metal sulfides and sparse uraninite,[15] but are too lean in uranium to be mined for that element alone.

Most of the deposits near Marysvale, Utah, are in quartz monzonite of Oligocene or younger age in an area of less than a square mile. A few are in volcanic rocks older and younger than the quartz monzonite. The hypogene vein minerals consist mainly of quartz or chalcedony, pitchblende, fluorite, pyrite, and adularia, but include calcite, jordesite, hematite, magnetite, and marcasite. They form veins, stockworks, lenticular masses, and breccia cement. Locally, a little pitchblende is disseminated in wall rocks. The deposits at Marysvale are larger than all other known vein deposits in the United States combined and are comparable in size to some of the large deposits in terrestrial sandstones.

Pitchblende and fluorite are accompanied by ilsemannite in veins cutting igneous rock of Jurassic age near Kern River, south-central California; they are accompanied by pyrite, in a fault cutting brecciated, silicified, and sericitized rhyolitic rocks in the Moonlight mine, north-central Nevada; and by base-metal sulfides in another small deposit in southern Arizona.

Deposits of uranium accompanied by some iron as sulfide and by sparse, if any, base metals are known in seven western States. Ore has been produced from mines in eight areas in these states. Among these, only mines in the Dripping Spring quartzite, central Arizona, have produced an appreciable amount of ore, but a few others show promise of having a significant quantity of ore.

Although details of the structural setting differ in these deposits, nearly all the deposits are localized in fractures or fracture zones cutting the host rock or in the wall rocks of the fractures. One deposit in central Arizona, however, is within a few feet of the contact between diabase and quartzite and may be of pyrometasomatic origin.

Deposits of uranium without base-metal sulfides are present in fractures at or near the contact of granitic rocks and metamorphosed sedimentary rocks near Wellpinit, northeast Washington (p. 219 of ref. 6) and south of Austin, central Nevada; in crystalline Precambrian rocks in northern Colorado,[17] in southeastern Wyoming, and in the Black Hills, South Dakota; in granitic rocks and in Teritary volcanic rocks and detrital rocks derived from them at a few places in Kern and San Bernardino Counties, California.

Deposits in chalcedonic veins and silicified quartz monzonite in the Boulder batholith, west-central Montana,[18] in the Dripping Spring quartzite, central Arizona, and in Precambrian and Mesozoic rocks in west-central Colorado represent deposits that contain subordinate amounts of copper, lead, and molybdenum, and locally silver.

Deposits of uranium accompanied by a varied assemblage of base-metal sulfide are represented in Arizona, Idaho, Montana, Wyoming, New Mexico,

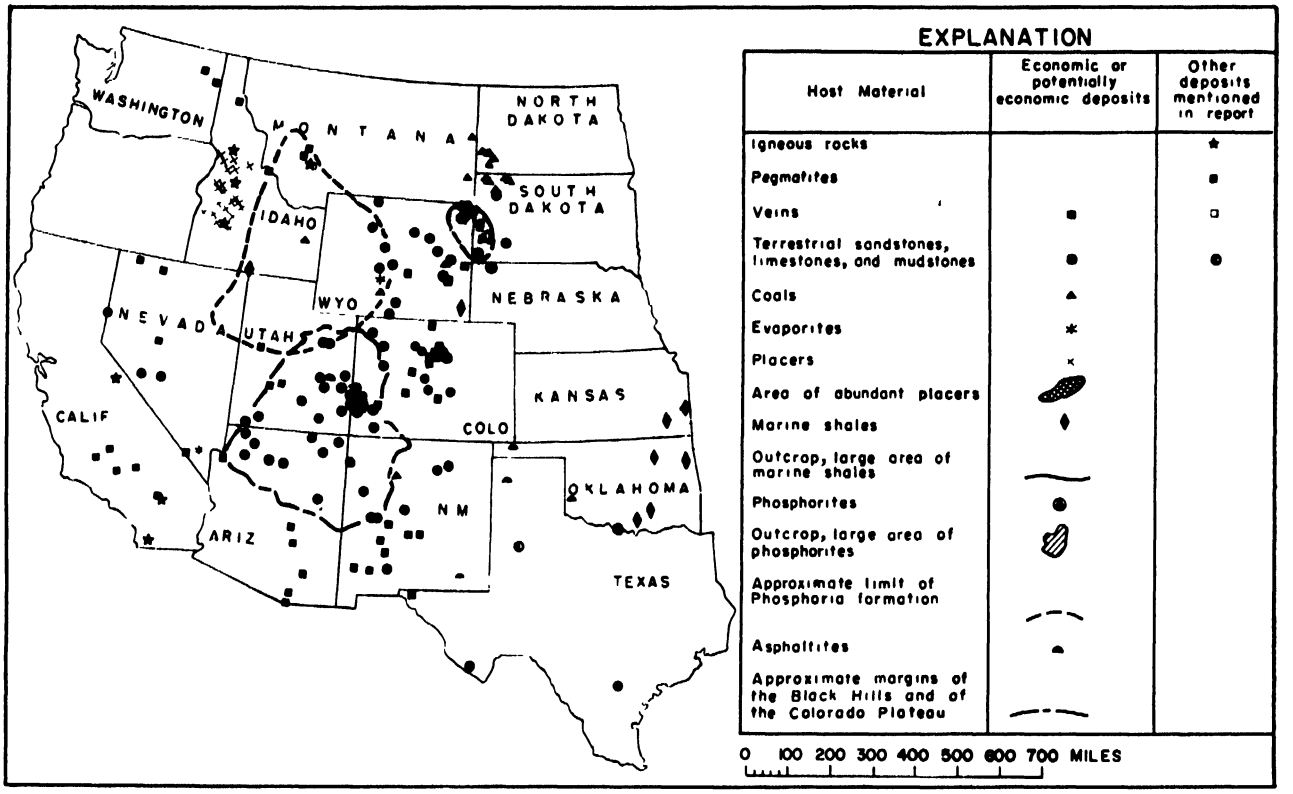

Figure 1. Index map showing deposits and principal occurrences of uranium in the Western United States

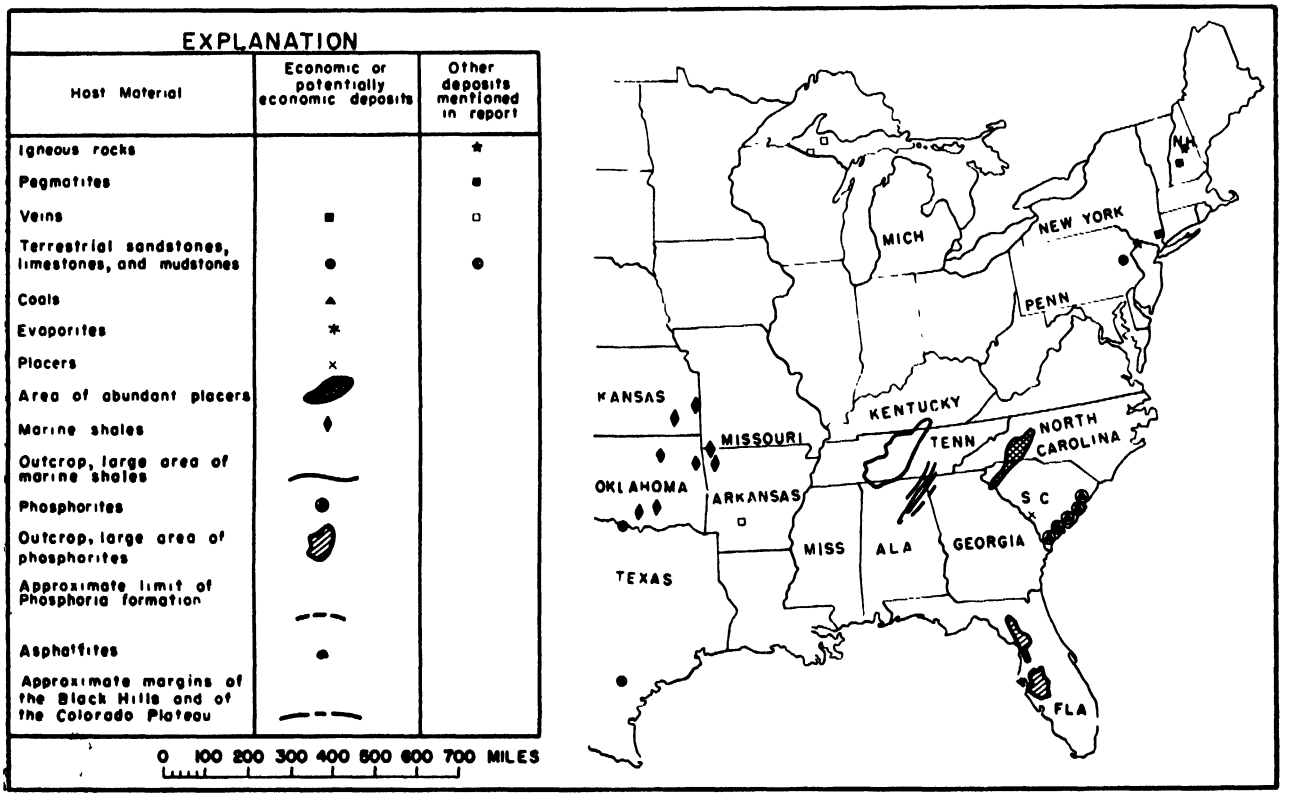

Figure 2. Index map showing deposits and principal occurrences of uranium in the Eastern United States

South Dakota, and Michigan. The pyrite gold ores of the Central City district, Colorado, may be an example of the transition between ores of this type and those ores in which uranium is a predominant ore metal. Although deposits near Central City were the source of the first uranium mined in the United States, deposits of uranium accompanying ores of base and precious metals are not an important source of uranium today.

At Central City the uranium ores occur in parts of gold- and silver-bearing pyritic quartz veins where sphalerite, galena, and chalcopyrite also are present,[19] and in parts of an adjoining zone of galena-sphalerite-carbonate quartz veins that form the outer zone of the vein system (p. 137 of ref. 6).

Other deposits and occurrences, mostly similar to some near Central City, are known in Colorado from Caribou, 13 miles north of Central City, southwestward to the San Juan Mountains. In the Boulder batholith, western Montana, other somewhat similar deposits are in shear zones of several miles in extent.[18] Veins of the uranium-predominant type are also represented in this area, and, like the Front Range of Colorado, it may be an area where there is a transition between the two types.

The uranium deposit at the Ralston Creek mine, about 12 miles east of Central City, contains more copper sulfides than are common in most of the other Front Range deposits. It consists of veins in a quartzose breccia in or adjacent to a carbonate-bearing breccia reef, which trends northwest for many miles.[20]

Other vein deposits of uranium accompanying base-metal sulfides occur in crystalline rocks in northwest Arizona[21] and in Precambrian rocks and Cambrian quartzite at Lusk, eastern Wyoming.[22]

Uranium also occurs in veins near the veins of silver-base-metal ores in the Sunshine mine, Coeur d'Alene area, northern Idaho.[12,13] Uranium is not intimately associated with the base metals, is in different structures than those ores, and may be older than them.[13] The uranium ore may be of the base-metal deficient type.

Occurrences of uranium in Precambrian rocks in Baraga County, Michigan (p. 204–206 of ref. 8) and in iron formations in the Iron River district, Michigan, are accompanied by copper, lead, and zinc sulfides.[23] They are significant mainly because they indicate the presence of uranium vein deposits in that part of the Canadian shield. Countless similar occurrences in the Western States[9,24,25] are of little consequence.

URANIUM IN TERRESTRIAL SEDIMENTARY ROCKS

Deposits of uranium minerals in terrestrial sandstone, mudstone, and limestone are the largest source of uranium in the United States today. They are most numerous and widespread from Texas and South Dakota westward to Nevada and California (Fig. 1). One small deposit and several occurrences are known in Pennsylvania and New Jersey. Although deposits in sandstone have been known in the Colorado Plateau region since 1898,[26] most of them have been found since 1947.

The uranium ore mined in the United States comes mainly from deposits in Mesozoic rocks of the Colorado Plateau, but some ore is mined from deposits in Cretaceous rocks marginal to the Black Hills in Wyoming and South Dakota, from deposits in rocks of the intermontane Tertiary basins of Wyoming and Nevada, and from a small deposit in Pennsylvanian rocks in Pennsylvania. Other occurrences are known in upper Paleozoic rocks marginal to the Permian basin in Texas, Oklahoma, and New Mexico, and in Tertiary rocks of the Texas Coastal Plain, but these have not yet produced ore.

Most uranium deposits in terrestrial rocks are in sandstone. Some large desposits in the Grants area, west-central New Mexico, are in limestone. A few are in mudstone.

Elongate lenses of impure quartzose sandstone are the host rock of many of the uranium deposits of the Colorado Plateau[26] and those in Mesozoic rocks marginal to the Black Hills. Arkosic sandstone is the host rock of many deposits in central and eastern Wyoming.[27,28] Tuffaceous sandstone and waterlaid tuff are host rocks of others in Wyoming, the Dakotas, Texas, Nevada, and California.[29] Sandy graywacke is host rock for a deposit in Pennsylvania.[30]

Deposits in some areas are near places where the rock is cemented with silica or silica and carbonate (p. 64–67 of ref. 4). Color or differences in color of sandstone are features related to deposits in some areas. The host rock is a light yellow brown in parts of the Colorado Plateau.[31] A purplish-pink iron oxide stain envelops some deposits in the southern Black Hills, South Dakota (p. 67 of ref. 4). A fairly sharp boundary between pink and buff or gray sandstone is associated with deposits in northeastern Wyoming (p. 119 of ref. 6).

The mudstone host rock of deposits is generally interbedded with uranium-bearing sandstone. Specific features of mudstone host rocks are less well known than those of sandstone host rocks because the deposits in mudstone are relatively few and most small.

The Todilto limestone in west-central New Mexico is the host rock of most of the uranium deposits in limestone of probable terrestrial origin,[25] but thin beds of algal limestone in the Browns Park formation of Tertiary age contain some occurrences in south-central Wyoming.[32] The upper ore-bearing part of the Todilto limestone is a coarse-grained recrystallized rock characterized by small folds, crenulations, and crinkly distortion of the bedding.[33]

Uraniferous asphalt-like materials occur in upper Paleozoic and Mesozoic rocks over a wide area from Oklahoma and Texas west to Utah.[34] Only in central Utah are such materials sufficiently concentrated to be a significant component of the uranium deposits in sandstone.[35]

The ages of the host rocks of deposits in terrestrial sandstone, mudstone, and limestone range from Pennsylvanian to Pliocene.[29,36] Some occurrences in

Pennsylvania are in rocks of Devonian age.[30] Deposits are most numerous in rocks of Triassic and Jurassic age in the region of the Colorado Plateau.

Some concentrations of uranium in some impure coals in Western United States, and in carbonaceous shale adjacent to or interbedded with them, are comparable in size and grade to deposits of uranium in sandstones. Less uraniferous coals are present in the some areas as the uranium-rich coals and also in several other areas. Most of the extensive anthracite and bituminous coals of Paleozoic age in Eastern and Central United States, like coals in general,[37] contain only traces of uranium.[38, 39]

The most uraniferous coals are lignites of Paleocene age in the Fort Union formation in western North and South Dakota and in eastern Montana (p. 149–155 of ref. 6) beds of Late Cretaceous age in the Mesaverde formation in north-central New Mexico,[40] and beds of Cretaceous age in southeastern Idaho.[41] Extensive, less uraniferous beds of Eocene age are present in the Wasatch formation in central Wyoming (p. 117–118 of ref. 4). Several other less extensive uraniferous coals are present elsewhere in the western States.[38]

Many of the western coals and lignites are uraniferous throughout areas of tens or hundreds of square miles. Richer parts of the beds, however, are much more local. The largest deposits are in South Dakota. Medium-sized deposits are present at La Ventana Mesa, central New Mexico, and small deposits are present in southeastern Idaho, in central Wyoming, and in east-central Colorado.

Most of the uranium in placer deposits is in relatively durable minerals, such as monazite and zircon, in which uranium is an extrinsic element. Most uranium minerals are too soft to survive transportation or too easily soluble to survive the weathering and disaggregation of their parent rocks. The principal areas of placers in the United States that contain abundant uraniferous minerals are in central Idaho and in the western part of North and South Carolina.[42] Some placers in Idaho contain appreciable amounts of euxenite, samarskite, and fergusonite, and locally uranothorite, in addition to monazite and zircon,[43] (p. 205–207 of ref. 6). Monazite and zircon are the principal uraniferous minerals in the placers in the Carolinas. These placers may be a source of uranium only to the extent that it can be recovered as a byproduct in the extraction of other metals for which the placer minerals are mined.

Most terrestrial evaporites do not contain appreciable amounts of uranium,[44] but scattered patches of tyuyamunite occur in caliche in Quaternary alluvium in southeastern Nevada,[24] and schroeckingerite forms calichelike blebs and flakes in shale and sandstone of Eocene age in south-central Wyoming.[30] Neither of these deposits is commercially significant.

URANIFEROUS MARINE SEDIMENTARY ROCKS

Uranium is appreciably concentrated in some marine carbonaceous shales and in most marine phosphate rocks. Such rocks contain 0.005 to 0.02 per cent U_3O_8.[45] On the other hand, not all marine carbonaceous shales are appreciably uraniferous, and the residual phosphate deposits, such as those in Tennessee, which are derived from the weathering of phosphatic limestone, are only weakly uraniferous.

Uranium is distributed relatively uniformly in marine black shales and phosphatic rocks throughout areas of hundreds to thousands of square miles in the United States.

Most of the appreciably uraniferous carbonaceous black shales in the United States are distributed from the western limit of the Appalachian Mountains in Virginia, Kentucky, Tennessee, and Alabama westward to the eastern front of the Rocky Mountains in Wyoming. All are of Paleozoic age.[45] These include the Chattanooga shale in Tennessee and its stratigraphic equivalents in adjacent states westward to Oklahoma, and some thinner, less persistent black shales of Pennsylvanian age in eastern Oklahoma and Kansas and in southeastern Wyoming. Other weakly uraniferous shales are known farther west but only locally do any of them contain as much uranium as the Chattanooga.[46]

In general, the uraniferous black shales contain abundant plant matter, relatively rich in iron sulfides, and are noncalcareous; and some are phosphatic. Uranium minerals are extremely rare in these shales.

The Chattanooga shale of late Devonian and early Mississippian age is the most widespread uraniferous black shale in the United States. In Tennessee, where it is most uraniferous, it consists of interbedded black shale and gray claystone. It contains abundant organic matter and some pyrite.[47] The upper 12 to 16 feet of the shale are richest in uranium in east-central Tennessee and contain between 0.006 to 0.007 per cent U_3O_8, but the shale is uraniferous throughout most of its extent.

Some beds of black shale in the Pensylvanian sequence of sedimentary rocks in eastern Kansas and adjoining parts of Missouri and Oklahoma that are 2 to 3 feet thick, such as beds in the Hushpuckney member of the Swope limestone of Moore[48] and beds in the Cherokee, contain from 0.009 to 0.013 per cent U_3O_8.[47] Some of these shales also contain scattered uraniferous phosphatic nodules. Other thin beds of black shale in the Hartville formation of Mississippian (?), Pennsylvanian and Permian (?) age, known only from samples obtained in oil test wells in eastern Wyoming, contain 0.005 to 0.02 per cent U_3O_8.[46] Most of the correlatives of the Chattanooga shale in central and eastern United States are less uraniferous than the Chattanooga shale in Tennessee. In general, numerous other shales that have been examined either contain less uranium or are thinner and less persistent than those mentioned.[46]

The largest bodies of uraniferous phosphatic rock in the United States are in the Phosphoria formation of Permian age in southeastern Idaho and nearby parts of Montana, Wyoming, and Utah (Fig. 1), and in the Bone Valley formation of middle Pliocene

age in central Florida (Fig. 2). Both formations are important sources of high-grade phosphate rocks in the United States.[49] Other smaller deposits, similar to those in the Bone Valley, are present in South Carolina; and phosphatic nodules in some of the black shales of Pennsylvanian age in eastern Kansas and Oklahoma are as uraniferous as the large bodies of phosphatic rock, but make up only a small proportion of the shales.[45,50] Uranium in major deposits of phosphatic rock is mainly in the mineral carbonate fluorapatite (p. 157–160 of ref. 4).

The Phosphoria formation and its stratigraphic equivalents underlie an area of about 135,000 square miles. It has a thin platform facies on the east and a thick geosynclinal facies on the west. The richest phosphate beds are in two phosphatic shale members of the formation in the tightly folded and faulted geosynclinal facies. In general, the beds rich in phosphate are rich in uranium;[45] they contain from 0.007 to 0.03 per cent U_3O_8.

Deposits of phosphatic rock in the Florida portion of the Gulf Coastal plain are the "hardrock" deposits of phosphatized limestone in north-central Florida, not shown on the map, and the land-pebble deposits, which are the larger and more uraniferous (Fig. 2). The land-pebble deposits underlie an area of about 1000 square miles in central Florida.[51,52] The unweathered part of the lower unit of the Bone Valley formation and some of the underlying Hawthorn residuum form the land-pebble deposits, which are mined for phosphate. About one-third of the rock mined is recovered as phosphate products, which contain from 0.005 to 0.25 per cent U_3O_8.[52] The uranium content differs from place to place depending on the composition of the rock mined and the size of the phosphatic particles in it. In places, the part of the formation nearer the surface has been weathered to produce a zone characterized by aluminum phosphate minerals.[53] The phosphate-rich parts of this zone contain about 0.012 per cent U_3O_8.[54]

REFERENCES

1. US Atomic Energy Commission, *Sixteenth Semiannual Report of the Atomic Energy Commission*, US Government Printing Office, Washington (1954).
2. Larsen, E. S., Jr. and Phair, G., *The Distribution of Uranium and Thorium in Igneous Rocks*, in *Nuclear Geology*, John Wiley & Sons, New York, 75–88 (1954).
3. Adams, J. A. S., *Uranium and Thorium Contents of Volcanic Rocks*, in *Nuclear Geology*, H. Faul, Editor; John Wiley & Sons, New York, 89–98 (1954).
4. Staff, *Geologic Investigations of Radioactive Deposits, Semiannual Progress Report, December 1, 1953 to May 31, 1954*, US Atomic Energy Commission TEI-440, Technical Information Service, Oak Ridge, Tennessee (1954).
5. Smith, W. L. and Butler, A. P., Jr., written communication.
6. Staff, *Geologic Investigations of Radioactive Deposits, Semiannual Progress Report, June 1 to November 30, 1954*, US Atomic Energy Commission TEI-490, Technical Information Service, Oak Ridge, Tennessee (1954).
7. Page, L. R., *Uranium in Pegmatites*, Economic Geology 45: 12–34, (1950).
8. Staff, *Search for and Geology of Radioactive Deposits, Semiannual Progress Report, December 1, 1952 to May 31, 1953*, US Atomic Energy Commission TEI-330, Technical Information Service, Oak Ridge, Tennessee (1953).
9. Kaiser, E. P. and Page, L. R., *Distribution of Uranium Deposits in the United States*, in *Selected Papers on Uranium Deposits in the United States*, US Geological Survey Circular 220, 1–3 (1952).
10. Kerr, P. F., *Pre-Cambrian Uraninite, Sunshine Mine, Idaho*, Science 115: 86–88 (1952).
11. Gillerman, E., *Uranium Deposits of the White Signal District, New Mexico* [abstract], Bulletin of the Geological Society of America 63: 1329 (1952).
12. Thurlow, E. E. and Wright, R. J., *Uraninite in the Coeur d'Alene District, Idaho*, Economic Geology 45: 395–404 (1950).
13. Kerr, P. F. and Robinson, R. F., *Uranium Mineralization in the Sunshine Mine, Idaho*, Mining Engineering 5: 495–511 (1953).
14. Brown, J. S., Emery, J. A. and Meyer, P. A., Jr., *Explosion Pipe in Test Well on Hicks Dome*, Hardin County, Illinois, Economic Geology 49: 891–902 (1954).
15. Wilmarth, V. R., Bauer, H. L., Jr., Staatz, M. H. and Wyant, D. G., *Uranium in Fluorite Deposits*, in *Selected Papers on Uranium Deposits in the United States*, US Geological Survey Circular 220, 13–18 (1952).
16. Staatz, M. H. and Osterwald, F. W., P/23, *Uranium in the Fluorspar Deposits of the Thomas Range, Utah*, Vol. 6, Session 6B, these Proceedings.
17. Sims, P. K. and Phair, G., *Some Features of the Pitchblende Deposits at the Copper King Mine, Larimer County, Colorado* [abstract], Bulletin of the Geological Society of America 64: 1555 (1953).
18. Becraft, G. E., *Preliminary Report on the Comet Area, Jefferson County, Montana*, US Geological Survey Circular 277 (1953).
19. Leonard, B. F., *Relation of Pitchblende Deposits in Hypogene Zoning in the Front Range Mineral Belt, Colorado* [abstract], Economic Geology 47: 773 (1952).
20. Adams, J. W., Gude, A. J., 3rd and Beroni, E. P., *Uranium Occurrences in the Golden Gate Canyon and Ralston Creek Areas, Jefferson County, Colorado*, US Geological Survey Circular 320 (1953).
21. US Atomic Energy Commission Report (unpublished).
22. Wilmarth, V. R. and Johnson, D. H., *Uranophane at Silver Cliff Mine near Lusk, Wyoming*, US Geological Survey Bulletin 1009-A (1954).
23. Barrett, L. P. and James, H. L., written communication.
24. Lovering, T. G., *Radioactive Deposits of Nevada*, US Geological Survey Bulletin 1009-C (1954).
25. McKelvey, V. E., *Search for Uranium in the United States*, US Geological Survey Bulletin 1030-A (in press).
26. Fischer, R. P., *Uranium-Bearing Sandstone Deposits of the Colorado Plateau*, Economic Geology 45: 1–11 (1950).
27. Troyer, M. L., McKay, E. J., Soister, P. E. and Wallace, S. R., *Summary of Investigations of Uranium Deposits in the Pumpkin Buttes Area, Johnson and Campbell Counties, Wyoming*, US Geological Survey Circular 338 (1954).
28. Love, J. D., *Preliminary Report on Uranium in the Gas Hills Area, Fremont and Natrona Counties, Wyoming*, US Geological Survey Circular 352, 3 (1954).
29. Finch, W. I., P/472, *Uranium in Terrestrial Sedimentary Rocks in the United States Exclusive of the Colorado Plateau*, Vol. 6, Session 6B, these Proceedings.
30. Klemic, H. and Baker, R. C., *Preliminary Summary of Uranium Occurrences in Carbon County, Pennsylvania*, US Geological Survey Circular 350 (1954).

31. Weir, D. B., *Geologic Guides to Prospecting for Carnotite Deposits on the Colorado Plateau,* US Geological Survey Bulletin 988-B (1952).

32. Love, J. D., *Preliminary Report on Uranium Deposits of the Miller Hill Area, Carbon County, Wyoming,* US Geological Survey Circular 278 (1953).

33. Ellsworth, P. C. and Mirsky, A., *Preliminary Report on Relation of Structure to Uranium Mineralization in the Todilto Limestone, Grants District, New Mexico,* US Atomic Energy Commission RME-4020, Technical Information Service, Oak Ridge, Tennessee (1952).

34. Erickson, R. L., Myers, A. T. and Horr, C. A., *Association of Uranium and other Metals with Crude Oil, Asphalt, and Petroliferous Rock,* Bulletin of the American Association of Petroleum Geologists 38: 2200–2218 (1954).

35. Gott, G. B. and Erickson, R. L., *Reconnaissance of Uranium and Copper Deposits in Parts of New Mexico, Colorado, Utah, Idaho, and Wyoming,* US Geological Survey Circular 219 (1952).

36. Wyant, D. G., Beroni, E. P. and Granger, H. C., *Some Uranium Deposits in Sandstones,* in *Selected Papers on Uranium Deposits in the United States,* US Geological Survey Circular 220, 26–30 (1952).

37. Russell, W. L., *Relation of Radioactivity, Organic Content and Sedimentation,* Bulletin of the American Association of Petroleum Geologists 29, 1480 (1945).

38. Gott, G. B., Wyant, D. G. and Beroni, E. P., *Uranium in Black Shales, Lignites and Limestones in the United States,* in *Selected Papers on Uranium Deposits in the United States,* US Geological Survey Circular 220, 31–35 (1952).

39. Patterson, E. D., *Radioactivity of Part of the Bituminous Coal Region of Pennsylvania,* US Atomic Energy Commission TEI-479, Technical Information Service, Oak Ridge, Tennessee (1955).

40. Vine, J. D., P/55, *Uranium-Bearing Coal in the United States,* Vol. 6, Session 6B, these Proceedings.

41. Vine, J. D. and Moore, G. W., *Uranium-Bearing Coal and Carbonaceous Rocks in the Fall Creek Area, Bonneville County, Idaho,* US Geological Survey Circular 212 (1952).

42. Mertie, J. B., Jr., *Monazite Deposits of the Southeastern States,* US Geological Survey Circular 237 (1953).

43. Mackin, J. H. and Schmidt, D. L., *Placer Deposits of Radioactive Minerals in Valley County, Idaho* [abstract], Geological Society American Bulletin 64: 1549 (1953).

44. Bell, K. G., P/294, *Uranium in Precipitates and Evaporites,* Vol. 6, Session 6B, these Proceedings.

45. McKelvey, V. E. and Nelson, J. M., *Characteristics of Marine Uranium-Bearing Sedimentary Rocks,* Economic Geology 45: 35–53 (1950).

46. Duncan, D. C., *Reconnaissance Investigations for Uranium in Black Shale Deposits of the Western States during 1951 and 1952,* US Atomic Energy Commission TEI-381, Technical Information Service, Oak Ridge, Tennessee, 87 (1953).

47. Swanson, V. E., P/51, *Uranium in Marine Black Shales of the United States,* Vol. 6, Session 6B, these Proceedings.

48. Moore, R. C., *A Reclassification of the Pennsylvanian System in the Northern Midcontinent Region,* Kansas Geological Society Guidebook, 6th Annual Field Conference, 97 (1932).

49. McKelvey, V. E. et al., *Domestic Phosphate Deposits,* in *Soil and Fertilizer Phosphorus in Crop Nutrition,* (Pierre, W. H., and Norman, A. G., editors), Academic Press Inc., New York, 347–376 (1953).

50. Runnels, R. T., Schleicher, J. A. and Van Nortwick, H. S., *Composition of Some Uranium-Bearing Phosphate Nodules from Kansas Shales,* Kansas Geological Survey Bulletin 102: 93–104 (1953).

51. Mansfield, G. R., *Phosphate Resources of Florida,* US Geological Survey Bulletin 934 (1942).

52. Cathcart, J. B., Blade, L. V., Davidson, D. F. and Ketner, K. B., *Geology of the Florida Land-Pebble Phosphate Deposits,* in *Origine des Gisements de Phosphates de Chaux,* Congres Geologique International, Comptes Rendus, Fascicule XI: 77–91 (1953).

53. Altschuler, Z. S., Jaffe, E. B. and Cuttitta, F., P/292, *The Aluminum Phosphate Zone of the Bone Valley formation and its Uranium Deposits,* Vol. 6, Session 6A, these Proceedings.

54. Cathcart, J. B., P/293, *Distribution and Occurrence of Uranium in the Calcium Phosphate Zone of the Land-Pebble Phosphate District of Florida,* Vol. 6, Session 6B, these Proceedings.

Uranium in Igneous Rocks of the United States of America

By G. J. Neuerburg,* USA

Uranium ore deposits are presumed to have stemmed initially from igneous rocks, either directly by magmatic processes or indirectly by way of other geologic processes. Studies of the occurrence and history of uranium in igneous rocks thus supply fundamental data pertinent to appraisals of uranium resources and to the devising of efficient and economic prospecting methods. Additional interest in this subject is impelled by the possibility that igneous rocks themselves are potentially important low-grade uranium deposits. The purpose of this report is to review briefly and critically the status of the uranium geology of igneous rocks and to explore some of the meanings and uses of this knowledge.

DISTRIBUTION OF URANIUM AMONG IGNEOUS ROCKS

The uranium contents of igneous rocks have been estimated in three ways, none of which is wholly satisfactory: (1) by direct chemical measurement; (2) by measurements of the daughter elements of uranium; and (3) by radioactivity measurements.

Considerable uncertainty is attached to chemical analyses of uranium, especially to the older analyses, because of difficulties in sample preparation and in analytical procedure involving the determination of very small quantities of uranium. Nevertheless, these data are the best at hand and may be sufficiently accurate for geologic studies.

Estimates of uranium content based on the determination of daughter products are open to serious uncertainty because the daughter products are not always in equilibrium with uranium, and accordingly may not provide a meaningful measure of the uranium content. This uncertainty is especially critical in rocks containing sulfides, because radium may be enriched many times due to leaching of uranium by acid waters formed during oxidation of the sulfides.[1]

Radioactivity estimates of uranium content may be the most misleading because not only are they subject to the uncertainties arising from possible radioactive disequilibrium, but they fail to account for variations in the ratio of uranium, thorium, and potassium, which varies widely within and among igneous bodies.

Because most of the current information on uranium in igneous rocks is based on measurements of radium and of radioactivity, a modicum of suspicion must be accorded to many present-day concepts concerning the amount of uranium in and its distribution among igneous rocks.

Most igneous rocks contain less than 10 grams per ton of uranium. Contents much in excess of this figure, except for certain rock types,[2,3] are chiefly the result of secondary addition of uranium to a rock.

Uranium contents of igneous rocks show considerable variation. In part, the variations are nonsystematic in that they appear unrelated to serial changes of other components in the rocks concerned. In larger part, the variations are systematically related to chemical, petrographic, and/or structural features of rocks. All variations that have been noted (other than those due to analytical error) are an expression of the geologic processes that affected the igneous rocks of discrete volumes of the earth's crust. The variation in one group of related rocks is not necessarily like that in another, even similar group of rocks. The following pages summarize what systematic variations have been found to date, as well as the apparently nonsystematic variations. These data, while presenting a seemingly confusing collection of concepts, are not internally inconsistent or anomalous; they are the result of an interplay of geologic events and processes that differ from rock type to rock type and from place to place in the crust.

Perhaps more commonly than not, the same rock types from different places and from single bodies have essentially the same uranium content. For example, many basalts from several localities in the western United States have a common content of about 1 gm/ton uranium.[4,5,6,7] Most granites contain about 4 gm/ton of uranium. Some samples of anorthosite from Wyoming and southern California have a common uranium content of 3 gm/ton.[4]

Many reports imply that the uranium content of any one variety of igneous rock may vary appreciably, not only among specimens from different localities, but also among specimens from within seemingly homogeneous masses and outcrops. Thus, granites of superficially similar character from different localities range in uranium content from less than 1 to 100 gm/ton or more. A fairly uniform pluton of granodiorite in the Southern California batholith ranges from 1 to 3 gm/ton uranium.[8] Two parts of a single apparently uniform specimen of anorthosite from southern California showed uranium contents of 4 and 11 gm/ton.[4]

Several explanations have been offered for variations in the uranium content of superficially similar

* US Geological Survey.

rocks. Most commonly, the differences have been correlated with the abundance of uraniferous minor accessory minerals, especially zircon.[9,10,11] Other petrographic features, such as grain size[9,12,13] and secondary mineralization,[4] have also been offered in explanation. These explanations imply petrographic and chemical dissimilarity among the rocks being compared and give reason to conclude that the rocks being compared, while superficially similar, are not identical.

Differences in the uranium content of apparently similar rocks have been correlated with the geologic positions of the rocks. Radioactivity in some Canadian batholiths[10] and in the alkaline Nigerian granites[14] is concentrated in the peripheries of the intrusions. Concentrations of radioactivity in Canadian intrusives that are related to structures in their wallrocks have been noted.[15] Here again, there is reason to think that the rocks being compared are not identical in every way.

The possibility of otherwise identical rocks containing different amounts of uranium is an intriguing and important problem. The possibility is fairly documented for radium in two cases. Petrographically identical dacites from one flow on Mount Lassen, California, have different radium contents.[16] Radium is most abundant in the upper parts of a Caucasian granodiorite laccolith[17] and its distribution appears to be independent of rock type.

Uranium contents of igneous rocks may also vary according to their position in the earth's crust. The possibility is pointed out[18] that volcanic rocks and hypabyssal rocks may contain more uranium than plutonic rocks of similar composition. However, the radium contents of many igneous rocks[19] show no appreciable difference between plutonic and volcanic rocks belonging to the same clans, and the uranium in granites and rhyolites shows no significant differences.[20] The possibility of systematic differences in the uranium in correlative plutonic and volcanic rocks requires further exploration.

In many igneous rock provinces, the uranium of the several differentiates commonly shows serial variations analogous to those shown by other components of the rocks. Serial variations in uranium content differ considerably from province to province, and locally within provinces. Perhaps most commonly, the uranium content of the rocks varies directly with the silica content[10,12,13,18,19,21,22,23] especially among the calcalkalic plutonic rocks. A similar variation with potassium has been noted[5,12,16] and recognized[22] as a parallel enrichment of the two elements during differentiation; this variation may be most pronounced in calcalkalic volcanic rocks. Uranium is commonly enriched in hydrothermal and pegmatitic stages of crystallization.[24] For example, the uranium of post-Cretaceous volcanic rocks in the western United States varies directly with niobium, beryllium, lead, and tin, but not with boron and zirconium.[25] The uranium of igneous rocks has been found to vary directly with the order of extrusion or intrusion in volcanic and hypabyssal rocks in California,[26] in Colorado,[2] and in plutonic rocks in California.[18]

In places uranium contents vary inversely with these same factors. The more mafic border rocks of the Boulder Creek batholith, Colorado, contain 14 gm/ton of uranium in contrast to a content of 1 gm/ton of uranium in the felsic interior, 12 miles away.[3] Specimens of diabase pegmatite from Arizona contain only 3 gm/ton uranium in contrast to 12 gm/ton in the enclosing diabase proper.[27] The high uranium content of some lamprophyres[4,18] also implies this inverse relationship to silica content.

In a few places, the uranium content shows no change among a group of related igneous rocks of different chemical compositions. This feature is best shown by Piggot's radium analyses of basalts in Hawaii,[28] which do not differ significantly either with respect to sequence of extrusion or to composition, which ranges from picrite to trachyte. A few of the granites of the Southern California batholith[18] contain low uranium—less than one or two gabbros—a fact which may mean that more than one type of uranium variation may take place in a single petrographic province. Finally, the uranium content of related groups of igneous rocks may show no readily discernible relation to other compositional variations among the enclosing rocks, a possibility exemplified by the lavas of the San Juan Mountains.[18]

Different petrographic associations have different levels of uranium content,[20] and, in general, the more uraniferous petrographic associations tend to be of rocks with uncommon compositions[18] and to occur in small bodies. The alkalic associations are generally richer in uranium than the calcalkalic associations.[2,18] The White Mountain plutonic volcanic series of alkalic affinities is twice as uraniferous as the calcalkalic rocks of the Southern California batholith.[18] The uranium contents of associations of similar rocks, such as the Southern California, Sierra Nevada, and Idaho batholiths, are similar.[29]

Attempts to define uranium-rich and uranium-poor igneous provinces have been made by a number of authors;[5,11,12,14,21,30,31,32] Davis and Hess[21] also suggested uranium epochs. Only two of these authors[12,25] considered the possibility that the contrasting geographic provinces are instead contrasting petrographic provinces. Though the possible existence of uranium provinces and epochs is suggested by variable contents of uranium in similar rocks from different localities, the arguments offered for this concept are based on comparisons of unlike rocks or mixtures of unlike rocks[18] and for this reason they are not conclusive.

Explanations for the variations among rocks, described in the preceding paragraph, are to be sought in information on the detailed fabric distribution of uranium, on the history of changes that affect rocks, and in theoretical considerations of the history of rock crystallization. These subjects are discussed in the following sections of this paper.

DISTRIBUTION OF URANIUM WITHIN IGNEOUS ROCKS

Studies of the fabric distribution of uranium in igneous rocks are based upon radioactivity measurements, upon chemical determinations of daughter elements of uranium and thorium, and, only recently, upon chemical determination of uranium. Both chemical and radiometric techniques must be used in these studies for they supplement one another in many important ways. Thus the uranium in minerals is best determined chemically, and the point distribution of uranium is determinable only by means of autoradiographic techniques.

Considerable information is available on the fabric distribution of the radioelements as a group and of certain daughter elements of uranium and thorium. Little information is yet available on the fabric distribution of uranium itself; it is assumed here that information concerning groups of radioelements can be extended, at least qualitatively, to uranium.

Uranium is thought to have six modes of occurrence in the fabric of igneous rocks:[33] (1) uranium minerals; (2*a*) uranium substituting in minor amounts for cations in the structures of rock minerals; (2*b*) uranium located in minor amounts in structural defects of rock minerals; (3) uranium held in cation exchange position; (4) uranium adsorbed on crystal surfaces, on surfaces of crystallographic discontinuities, and on surfaces of irregular cracks within crystals; (5) uranium dissolved in fluid inclusions contained within rock minerals; and (6) uranium dissolved in intergranular fluids.

Uranium Minerals

Primary or quadrivalent uranium minerals are uncommon in igneous rocks; they occur as minor accessories, usually disseminated throughout the fabric. The so-called secondary or sexivalent uranium minerals are more common, and are generally localized along cracks and in aggregates of altered rock minerals. Minerals such as uraninite and betafite are perhaps most commonly primary products of magmatic crystallization, but they may be of deuteric or hydrothermal origin in some rocks. The sexivalent uranium minerals probably most commonly originate in secondary hydrothermal or ground water processes, but in some cases they may be deuteric.[34]

Uranium in Mineral Structures

Small amounts of uranium are contained in many, if not in all, common rock-forming minerals and their alteration products. Most authors imply that such uranium proxies for one or more cations in the structure of the host mineral. This implication is not wholly justified because the analytically determined uranium may occur in the crystals in several ways that are not related to the structure of crystals. The substitution of uranium for a cation in a mineral structure can be documented only rarely and with difficulty. The concept seems valid for minerals in which the concentrations of uranium are zonally arranged, such as zircon,[35] and in those minerals thought or known to have an analogous uranium compound; e.g., thorite. In other minerals, such as plagioclase and quartz, most, if not all, of the uranium is in inclusions of uraniferous minor accessories and along cracks and crystallographic discontinuities.[36]

Uranium may be disposed in structural defects in rock minerals, defects such as mosaic boundaries, twin boundaries, zonal boundaries,[37] and lineage structure.[9] Most of the uranium contained within common rock minerals may have this mode of occurrence, judging from the work of DeVore,[37] even though he makes no specific mention of uranium.

The uranium content of any one mineral species within a given rock may vary enormously within and among crystals of that mineral. Zonal variations in uranium and rare-earths content have been noted by Larsen and others[35] and by Brotzen.[38] The trace-element content of some pegmatite minerals changes along the direction of growth of the crystals,[39] a type of variation that uranium may also show in some crystals. Nonsystematic variations with respect to uranium and thorium were described by Von Buttlar and Houtermans.[40] Variations of uranium among different zircon crystals from single rocks are indicated by Larsen and Phair.[18] Uranium in minor accessories may differ according to whether it is included in hornblende, biotite, plagioclase, other rock minerals, or occurs between the crystals of these minerals.[33] Ample theoretical justification for appreciable variation in the uranium content of rock minerals from crystal to crystal and within crystals is found in several papers on the distribution of minor elements during crystallization.[37,41,42,43,44]

Considerable research has been done on the quantitative distribution of uranium and other radioelements among the different minerals of several rocks.[8,11,16,21,36,45,46,47,48,49] Analyses of separate fraction of the major minerals are probably misleading owing to the virtually certain inclusion of the uraniferous minor accessories and to the occurrence of radioelements along cracks and crystallographic discontinuities.[8,36,48] Analyses of the minor accessories may refer only to the particular grain size fraction used for analysis.[33] Though the results of studies of this sort probably have no strictly quantitative significance, they define roughly the semiquantitative distribution of uranium among the minerals of any given rock. The highest uranium contents, excluding uranium minerals, are found in the minor accessory minerals and to a considerably lesser degree in the iron oxides. Zircon is generally the most uraniferous of the minor accessories, but in places it is less uraniferous than associated minor accessories, such as monazite[50] or allanite.[4] The amount of uranium in the mafic silicate minerals is small but exceeds that in the feldspars and in quartz.

The relative distribution of uranium among the rock minerals differs from rock to rock. The uranium content of any one mineral commonly increases with the silica of the rock.[20,29] Uranium contents of minerals are apparently usually least contrasted among

the minerals of mafic rocks.[36,51] With few exceptions, the minor accessories and some deuteric minerals[21] commonly contain most of the total amount of uranium located in the structures of the minerals of a rock.

Uranium in Cation-exchange Position

The occurrence of uranium in cation-exchange position has not been proved although it is a probable mode of occurrence. Montmorillonite in bentonites from the central United States may contain uranium in this position.[52] Zeolites from southern California contain as much as 28 gm/ton of uranium.[4] Because it is predicted that uranium should not be accommodated in the zeolite structure,[53] these uranium analyses may mean that zeolites contain uranium in cation-exchange positions.

Adsorbed Uranium

Adsorption of uranium on crystal surfaces and on a variety of discontinuities within crystals has been predicted from theory,[37,43,54] inferred from chemical studies,[49,55,56,57] and indicated by autoradiographic observations.[15,36] Experimental demonstration of the occurrence of adsorbed uranium will be exceptionally difficult. Current autoradiographic studies have not distinguished between uranium, thorium, and their daughter elements, although the distinction is theoretically possible. Thus, these studies have not fully documented the occurrence of adsorbed uranium. Hurley's work[57] may be interpreted to mean that much of the radioactivity on grain surfaces and along cracks may well be due almost entirely to daughter elements. Furthermore, Picciotto[36] believes that some interstitial radioactivity found in autoradiographs is contained in thin films of such secondary minerals as epidote.

The leaching of radioactivity and uranium from rocks by mineral acids has been cited as evidence for the occurrence of adsorbed uranium. Where leaching has been done in conjunction with determinations of the distribution of radioactive particles in rock powders,[57] the thesis is convincing. Some leaching studies of mineral fractions[58,59] present evidence that uranium is strongly concentrated in the outer parts of crystals and crystal fragments. Most leaching studies, however, have been inconclusive with respect to the occurrence of adsorbed uranium, simply because much if not all of the leached uranium or radioactivity is derived from the solution of uranium-bearing minerals.[4,56]

Current usage implies that adsorbed uranium, leachable uranium, and interstitial uranium are identical. Leachable uranium includes all uranium that is readily soluble under the experimental conditions, whatever its mode of occurrence in the rock. Interstitial uranium, most carefully defined by Picciotto,[36] includes uranium contained in films and stringers of secondary minerals along cracks and grain boundaries, as well as adsorbed uranium.

The opinion is commonly expressed that interstitial uranium, in the sense of adsorbed uranium as used here, is a product of the last stages of crystallization of the rock.[15,18] This conclusion seems untenable because adsorbed material probably changes in amount after crystallization[57] and because the material adsorbed on the faces of some crystals is the same material that was adsorbed on the crystal nucleus and remained bound to the surface as the crystal grew.[37]

Dissolved Uranium

Uranium may be dissolved in the fluid inclusions of rock minerals;[36] the suggestion remains to be documented. Uranium in this situation may be unrelated to the crystallization of the rock, for fluid inclusions commonly belong to a number of generations, including many that postdate crystallization. Some fluid inclusions may have formed even during weathering.[60]

No direct experimental evidence yet demonstrates that the intergranular fluids of igneous rocks contain dissolved uranium. However, any soluble uranium contained in the rock will be partly dissolved in these fluids. The ubiquitous uranium in streams and ground waters draining terranes of igneous rock, which contribute to and interchange with intergranular fluids, is sufficient evidence that intergranular fluids contain some uranium in solution.

Discussion

There is reason to believe that the amount of uranium in each of its modes of occurrence differs appreciably from rock to rock, in places within small outcrops. Uranium dissolved in fluid inclusions and in intergranular fluids may not constitute any appreciable fraction of the total uranium content of the rock because these fluids are limited in volume. The quantity of uranium in intergranular fluids probably varies by small amounts with crustal position, with rock structure, with climate, and with season. Uranium minerals may constitute a small to large portion of the total uranium in an igneous rock. Because most igneous rocks contain very small amounts of uranium, concentration into discrete uranium minerals is unlikely. The relative distribution of uranium between structural defects and diadochic substitution might prove to vary systematically with silica content of the rock. Mafic rocks may contain more uranium in structural defects than felsic rocks, because the mafic rocks contain fewer minerals with structures receptive to accommodation of uranium. The relative proportion of adsorbed uranium probably differs from rock to rock. In part such a variation may be systematic; Picciotto[36] suggests that interstitial radioactivity constitutes a smaller fraction of the total radioactivity of mafic igneous rocks than of felsic igneous rocks. Experiments on anorthosites, which show a variation in leachable uranium from 1 to 93 per cent,[4] may mean that Picciotto's suggestion is premature. Also, adsorbed uranium probably varies in amount and strength of bonding from mineral to mineral.

The uranium in each of the fabric situations out-

lined above undoubtedly differs in its accessibility to and reactivity with the various geologic agents affecting the chemistry of a rock. Easily soluble uranium minerals generally occur along passageways for the various solutions that may have passed through the rock. Regardless of the manner in which uranium may be contained within the structure of any one mineral, it is tightly held and protected from reaction with fluids that do not react with the host mineral. Uranium in cation-exchange position should be readily extracted or enriched by various natural solutions. Adsorbed uranium would be especially liable to reaction and to change in amount with solutions passing through a rock. To the extent that fluid inclusions are accessible to and formed by exotic solutions, the amount of uranium they contain may have been appreciably changed during the rock's history. The amount of uranium dissolved in intergranular fluids is exceptionally subject to change in amount from time to time.

In view of the varying accessibility and reactivity of uranium in each of its fabric occurrences to natural solutions, the conclusion is unavoidable that the uranium in each occurrence may have changed in amount and physical state to a different degree and in a different way from that in the other occurrences during the history of a rock.

URANIUM IN THE MAGMATIC PERIOD OF ROCK HISTORY

Theories concerning the distribution of trace elements during crystallization of magmas permit some qualitative generalities concerning the role of uranium. Presumably a magma begins with a certain unknown quantity of uranium. This amount may be increased or decreased by addition of foreign substances to the magma and may be decreased by the loss of uranium-bearing fluids before or during crystallization. During crystallization uranium is distributed among its several occurrences in proportions and amounts dependent on the prevailing—and changing—geologic and physical chemical conditions.

The geologic controls on the fixation of uranium during crystallization may be illustrated by means of a few hypothetical examples. If a magma crystallizes entirely as a closed system, the final rock probably contains all of the magmatic uranium. For example, a miarolitic granite should contain more uranium than a massive granite containing swarms of pegmatites and aplites, providing the two granites crystallized from magmas of the same uranium content.

If the geologic conditions during crystallization are such that fluids are lost only sporadically, most of the magmatic uranium may or may not be lost to the final rock. If, before fluids are lost, much of the uranium is fixed in minerals that can structurally accommodate uranium, i.e., its prime receptors such as zircon, much of the uranium would be retained in the rock. On the other hand, should uranium-bearing fluids leave the magma before crystallization of prime uranium receptors, the resulting rock would contain only a small fraction of the magmatic uranium.

Physical-chemical factors also determine in what amounts and what manner uranium will be fixed in the final rocks. If the uranium concentration is high, uranium minerals may form. If the concentration is sufficiently low, most of the uranium may remain dissolved in fluids that leave the rock after crystallization. Should uranium be fixed in some early crystallized mineral and thereby removed from the fluid phase during most of the remaining period of crystallization and then subsequently be released to the rest fluids on recrystallization of that mineral, it may again be lost to the rock.

A stock of the Boulder Creek batholith, where the more mafix border rocks contain the greatest concentration of uranium,[3,29] may be an illustration of these considerations. The initial concentration of uranium in the magma was perhaps sufficiently high to force its fixation in the minerals first crystallizing in the outer parts of the stock. As a result only a small fraction of the magmatic uranium may have been left to be fixed in the more felsic center. Alternatively, much of the uranium may have migrated out of the stock after crystallization of the border and before crystallization of the interior.

Another possible way in which the crystallization history affects the fraction of magmatic uranium fixed in the final rock is Mawdsley's explanation[61] of the high uranium content of some pegmatites in Saskatchewan, Canada. The pegmatites rich in uranium are fine-grained and show evidence of assimilation of limy sediments, whereas associated pegmatites unrelated to limy sediments are coarse-grained and relatively poor in uranium. These observations are interpreted by Mawdsley to mean that assimilation of lime from the sediments promoted rapid cooling and forced crystallization of uraninite, whereas those pegmatites not assimilating lime crystallized more slowly and uranium escaped with late-stage fluids.

The uranium content of different magmas is assumed to have differed widely, but the uranium content of the final product of each magma is thought to provide little if any quantitative clue to the original uranium content of the magma. The relatively low uranium content of basalts and the uniformly higher content of granites implies a similar contrast in the uranium content of their respective magmas. However, this contrast is conceivably, perhaps certainly, aggravated or lessened by differences in the fixative power of the contrasting magma compositions toward uranium, by differences in the geologic environment of crystallization, or even for that matter, by assimilation of wallrocks. Sullivan[62] suggests that the uranium of granites was obtained from its sedimentary country rocks and implies that the resulting content of uranium in the igneous rock is a function of the composition of the magma. His suggestion serves well to underline the uncertain status of the understanding and interpretations of observations in this realm of uranium geology.

URANIUM IN THE POST-MAGMATIC HISTORY OF IGNEOUS ROCKS

The uranium content of an igneous rock may be changed in many ways after crystallization. Internal readjustments consequent on the cooling of the solidified rock may effect changes in the distribution of uranium within rocks. Recrystallization, such as the sub-solidus unmixing of perthite, or deuteric reactions such as chloritization of bitoite may change the uranium contents of such minerals. Recrystallization probably generally results in expulsion of uranium from the altering mineral—uranium is then deposited elsewhere in the rock fabric or lost from the rock.

Data on the effects of metamorphism, hydrothermal alteration, ground-water processes, and weathering on the uranium contents of igneous rocks are surprisingly few. The few analyses of altered igneous rocks, principally weathered rocks, are compelling evidence that the uranium contents of igneous rocks are generally appreciably changed as a result of alteration. Most commonly, the uranium content is decreased. Increases in uranium content are usually confined to the vicinity of uranium ore deposits.

Though the changes of uranium content during alteration of igneous rocks are not well understood, some of the controlling factors may be inferred. The proportional distribution of uranium among its several fabric occurrences will determine the quantity of uranium that may be changed during alteration. The physical chemistry of the altering system, the degree to which the rock is an open system, and the composition of any invading solutions will determine the changes that take place. Permeability and the structural position of the rocks, which control the passage of solutions, are of major importance because they may induce varying compositional changes from place to place in a single uniform rock mass. Both climate and the stage of geomorphic development of a region may dictate what changes will take place in weathering.

CONCLUSIONS

The principal conclusion of this review is that the uranium content of each igneous rock reflects a complicated history. Ample opportunity existed and exists for repeated change not only of the total uranium content, but also of the proportional distribution of uranium among each of its occurrences in the rock fabric. The *total uranium content* of an igneous rock thus represents the interaction of a complex series of events taking place during and since its crystallization. The *total uranium contents* of igneous rocks are *dynamic* quantities that cannot be referred to any single event and that are probably changing from day to day by some infinitesimal amount. Corollary to this proposition is the conclusion that the total uranium content of an igneous rock is a highly uncertain or indecipherable measure of the uranium content of its magma.

Little basis is available for estimating the quantitative effects of an involved history on the uranium content of a rock. It may be that the uranium contents of very fresh, unaltered, impermeable rocks are but little changed from the uranium contents existing at the end of crystallization. This possibility seems indicated by the fairly consistent uniformity of uranium content among similar rock types and by a fairly systematic internal variation with gross composition among differentiated rocks such as the Southern California batholith.

The natural history of uranium in igneous rocks will not be elucidated solely from quantitative correlations of uranium content with the composition of the containing rock. Much better understanding will be gained from studies of uranium content in terms of the geologic history of each rock. Appraisals of compositional changes in groups of igneous rocks are frequently cast into terms of their crystallization history in a qualitative manner, and such appraisals are among the most meaningful of petrologic interpretations. Two examples of this sort of approach consist of Mawdsley's work,[61] already cited, and of Wager's and Mitchell's study[63] of trace element variation in the Skaergaard intrusive. Wager and Mitchell plotted minor element content against per cent of magma solidified. The resul provides an excellent example of chemical variation as it has been guided and controlled by pertinent geologic processes.

Extensions of such appraisals to take into account post-crystallization history add much to an understanding of the quantitative data yielded by analyses. Again, the Boulder Creek stock[3] may serve as a possible example. It is conceivable to me that much of the uranium in this stock may be of supergenetic origin, its proportional distribution being controlled by structural and mineralogic features of the contrasting rocks in the stock. If the added uranium is in the form of adsorbed uranium, it is possible that platy minerals, like biotite and platy rock structures, perhaps characteristic of the mafic border rocks of this stock, would more readily and in larger quantities adsorb uranium from supergene solutions than the more massive felsic rocks of the interior of the stock.

By this analysis of the uranium geology of igneous rocks, I hope to emphasize the mandatory need for geologic interpretation of uranium analyses and to indicate the misdirection fostered by divorcing analytical data from geology.

Because uranium in each of its fabric occurrences shows variable accessibility and reactivity to solutions which may affect the rock, it may be possible to isolate or determine separately the amount of uranium in each fabric occurrence. Some of this quantitative information may be referred to specific events in a rock's history. The information will not only be of theoretical interest but may well prove to be economically important to prospecting and to extractive metallurgy. Currently available techniques will permit only crude and semiquantitative determinations of the amounts of uranium in each of its fabric occurrences, or groups of fabric occurrences.

Autoradiographic studies, though exceptionally tedious and time consuming, offer the greatest promise for quantitative determinations of the amounts of uranium in its several occurrences in igneous rock fabrics. It is doubtful if the quantitative results would warrant the time and expense involved in this method, but the method has been and will continue to be the prime tool for documenting the fabric distribution of uranium and indicating its semi-quantitative distribution, providing uranium is sorted from thorium and the daughter elements of uranium and thorium.

The quantities of uranium adsorbed on crystal boundaries and internal discontinuities and that held in cation-exchange positions may be determined by means of techniques used to study base exchange in clays, soils, and zeolites. This information will be of special interest in studies of the amounts of uranium held in the structure of rock minerals compared with that contained in the structural defects and adsorbed onto the crystal. Furthermore, this sort of study may be useful in prospecting. Large amounts of uranium in cation-exchange position, in zeolites for instance, may serve to indicate passage of uraniferous solutions and to locate the volumes of rock through which such solutions passed.

Except in such relatively soluble minerals as apatite, metamict minor accessories, and some secondary rock minerals, the uranium contained in the structures of rock minerals and in structural defects of their crystals is probably not appreciably dissolved by weak acids in the laboratory or by the mild solutions near the surface of the earth's crust. The material that is readily soluble in dilute acids includes most oxidized (U^{6+}) uranium minerals, uranium adsorbed on crystal surfaces, uranium held in cation-exchange positions, and uranium already dissolved in fluid inclusions and in intergranular fluids. Uranium in these fabric situations—or environments—is also expected to have changed most during the history of any igneous rock. The quantity of uranium that is dissolved from these environments and left undisturbed in the relatively insoluble environment of structural capture depends, both in the laboratory and in nature, on a number of factors, principally: (1) the state of disaggregation—or permeability—of the rock; (2) the mineral species making up the rock and the distribution of uranium among them; (3) the relative bonding strength of adsorbed uranium; and (4) the physical chemistry of the solvent system. The numerous variables involved in studies of the proportions of readily soluble—or labile—uranium make absolutely comparable figures between unlike rocks difficult to obtain, but by the judicious use of petrographic and geologic controls, meaningful information should be obtained.

Studies of labile uranium may aid in deciphering the significance of variations in uranium content among rocks. Uranium that is not dissolved may represent substantially the uranium that was fixed in the structures and structural defects of rock mineral crystals at the time of their completed crystallization, or at the time of their last recrystallization. For example, Phair[2] found that labile uranium, represented largely by sexivalent uranium minerals, in two bostonites contributed a substantial part of their anomalously high uranium contents.

The quantity and proportion of labile uranium may be taken as a parameter of the extent to which the uranium content of a rock changed during ore deposition. For this reason, the aureoles of added uranium surrounding ore deposits in igneous rocks may be measured by the quantity and proportion of labile uranium rather than by the total quantity of uranium in the rock. As a corollary to this suggestion, it may be supposed that exceptionally small quantities and low proportions of labile uranium may identify some rocks that were a source of uranium, possibly deposited elsewhere in economic amounts. These suggestions gain a measure of practical interest in view of the ease with which labile uranium may be measured in the field by chemical techniques being developed by the US Geological Survey.[64]

The labile uranium content of an igneous rock is also of commercial importance because this is the quantity which may be most easily and economically extracted from an igneous rock by hydrometallurgical techniques. Most of the labile uranium can be removed from crushed igneous rocks with very dilute acids.

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REFERENCES

1. Phair, G. and Levine, H., *Notes on the Differential Leaching of Uranium, Radium, and Lead from Pitchblende in H_2SO_4 Solutions,* Economic Geology 48: 358–369 (1953).
2. Phair, G., *Radioactive Tertiary Porphyries in the Central City District, Colorado, and their Bearing upon Pitchblende Deposition,* US Geological Survey TEI 247, US Atomic Energy Commission Technical Information Service (1952).
3. Larsen, E. S., Jr., *Distribution of Uranium in Igneous Complexes,* in *Geological Investigations of Radioactive Deposits, Semiannual Progress Report, June 1, 1954, to November 30, 1954,* US Geological Survey TEI 490, US Atomic Energy Commission Technical Information Service, 255–261 (1954).
4. Neuerburg, G. J., unpublished data.
5. Adams, J. A. S., *Uranium and Thorium Contents of Volcanic Rocks* in *Nuclear Geology,* edited by H. Faul, John Wiley and Sons, Inc., New York, 89–98 (1954).
6. Cannon, R. S., Jr., verbal communication.
7. Larsen, E. S., Jr., verbal communication.
8. Larsen, E. S., Jr., *Distribution of Uranium in Igneous Complexes* in *Geological Investigations of Radioactive Deposits, Semiannual Progress Report, December 1,*

1953 to May 31, 1954, US Geological Survey TEI 440, US Atomic Energy Commission Technical Information Service, 202–205 (1954).

9. Amstutz, G. C., *Radioaktivitätsmessungen an den Glarner Laven,* Verhandlungen der Schweizerischen Naturforschen Gesellschaft, 131 Jahresversammlung, 138–139 (1951).
10. Ingham, W. N. and Keevil, N. B., *Radioactivity of the Bourlamaque, Elzevir, and Cheddar batholiths, Canada,* Bulletin of the Geological Society of America 62: 131–148 (1951).
11. Keevil, N. B., Keevil, A. R., Ingham, W. N. and Crombie, G. P., *Causes of Variation in Radioactivity Data,* American Journal of Science 241: 345–365 (1943).
12. Asayama, T., *On the Radioactivity of Rocks in Japan and Vicinity, I. Radium of Volcanic Rocks,* Kyoto University, Science and Technology, Memoir 2–B, 53–67 (1953).
13. Daniels, F., *New Methods for Uranium Exploration and Recovery from Low Grade Ores,* US Atomic Energy Commission Contract Number AT(11–1)–178, Progress Report, January 1, 1952 to January 1, 1953 (1954).
14. Davidson, C. F., *The Distribution of Radioactivity,* The Mining Magazine 85: 329–340 (1951).
15. Gross, W. H., *Radioactivity as a Guide to Ore,* Economic Geology 47: 722–742 (1952).
16. Evans, R. D. and Williams, H., *The Radium Content of Lavas from Lassen Volcanic National Park, California,* American Journal of Science 229: 441–452 (1935).
17. Soloviev, S. P., *The Granodiorite Laccolith of the Malka River (North Caucasus) and its Content of Radium,* American Journal of Science 232: 380–391 (1936).
18. Larsen, E. S., Jr. and Phair, G., *The Distribution of Uranium and Thorium in Igneous Rocks* in *Nuclear Geology,* edited by H. Faul, John Wiley and Sons, Inc., New York, 75–89 (1954).
19. Evans, R. D. and Goodman, C., *Radioactivity of Rocks,* Bulletin of the Geological Society of America 52: 459–490 (1941).
20. Ingerson, E., *Geochemical Work of the Geochemistry and Petrology Branch, U. S. Geological Survey,* Geochimica et Cosmochimica Acta 5: 20–39 (1954).
21. Davis, G. L. and Hess, H. H., *Radium Content of Ultramafic Igneous Rocks: II. Geological and Chemical Implications,* American Journal of Science 247: 858–883 (1949).
22. Larsen, E. S. and Keevil, N. B., *Radioactivity of the Rocks of the Batholith of Southern California,* Bulletin of the Geological Society of America 58: 483–493 (1947).
23. Westerveld, J., *Radioactivity and Chemistry of Some Indonesian Eruptive Rocks,* Verhandelingen der Koninklijke Nederlandse Akademie van Wetenschappen, Afd. Natuurkunde, Eerste Reeks, Deel XX, no. 4 (1954).
24. Rankama, K. and Sahama, Th. G., *Geochemistry,* The University of Chicago Press, Chicago, Illinois (1950).
25. Coats, R. R., *Relationship of Uranium and Other Trace Elements to Post-Cretaceous Vulcanism in Geological Investigations of Radioactive Deposits, Semiannual Progress Report, December 1, 1953 to May 31, 1954,* U. S. Geological Survey TEI 440, US Atomic Energy Commission Technical Information Service, 99 (1954).
26. Adams, J. A. S. and Saunders, D. F., *Uranium Content of the Lavas of Lassen Volcanic National Park, California* (Abstract), Bulletin of the Geological Society of America 64: 1389 (1953).
27. Cannon, R. S., Jr. and Neuerburg, G. J., unpublished data.
28. Piggot, C. S., *Radium in Rocks: III. The Radium Content of Hawaiian Lavas,* American Journal of Science 222: 1–8 (1931).
29. Larsen, E. S., Jr., *Distribution of Uranium in Igneous Complexes* in *Geological Investigations of Radioactive Deposits, Semiannual Progress Report, June 1, 1953 to November 30, 1953,* US Geological Survey, TEI 390, US Atomic Energy Commission Technical Information Service, 240–244 (1953).
30. Aswathanarayana, U., *Distribution of Radioactivity in the Rocks of South India: I. Charnockites and Associated Rocks,* Journal of Science and Industrial Research (India), 13B: 87–92 (1954).
31. Coats, R. R., *Relation of Uranium to Post-Cretaceous Vulcanism* in *Geological Investigations of Radioactive Deposits, Semiannual Progress Report, December 1, 1952 to May 31, 1953,* US Geological Survey TEI 330, US Atomic Energy Commission Technical Information Service, 87–88 (1953).
32. Senftle, F. E. and Keevil, N. B., *Thorium-Uranium Ratios in the Theory of Genesis of Lead Ores,* Transactions of the American Geophysical Union 28: 732–738 (1947).
33. Neuerburg, G. J., *The Significance of Uranium Analyses of Igneous Rocks and Minerals in Terms of the Geologic Nature of the Sample,* manuscript (1955).
34. Page, L. R., *Uranium in Pegmatites,* Economic Geology 45: 12–34 (1950).
35. Larsen, E. S., Jr., Waring, C. L. and Berman, J., *Zoned Zircon from Oklahoma,* American Mineralogist 38: 1118–1125 (1953).
36. Picciotto, E. E., *Distribution de la Radioactivité dans les Roches Eruptives,* Bulletin de la Société belge de Géologie, de Paleontologie, et d'Hydrologie 59: 170–198 (1950).
37. DeVore, G. W., *The Role of Adsorption in the Fractionation and Distribution of Elements,* The Journal of Geology 63: 159–190 (1955).
38. Brotzen, O., *Die zonaren Zirkone des Ramberggranites,* Geologiska Föreningens i Stockholm, Forhandlingar, Stockholm, 74: 173–184 (1952).
39. Jahns, R. H., verbal communication.
40. Buttlar, H. von and Houtermans, F. G., *Photographische Messung des U- und Th-Gehaltes nach der Auflagemethode,* Geochimica et Cosmochimica Acta 2: 43–61 (1951).
41. Holland, H. D. and Kulp, J. L., *The Distribution of Accessory Elements in Pegmatites. I. Theory,* American Mineralogist 34: 35–60 (1949).
42. Neumann, H., *Hydrothermal Differentiation,* Economic Geology 43: 77–83 (1948).
43. Neumann, H., Mead, J. and Vitaliano, C. J., *Trace Element Variation during Fractional Crystallization as Calculated from the Distribution Law,* Geochimica et Cosmochimica Acta 6: 90–99 (1954).
44. Shaw, D. M., *The Camouflage Principle and Trace-Element Distribution in Magmatic Minerals,* The Journal of Geology 61: 142–151 (1953).
45. Davis, G. L., *Radium Content of Ultramafic Igneous Rocks: I. Laboratory Investigations,* American Journal of Science 245: 677–693 (1947).
46. Hee, Mme. A., Derville, R. P. and Jarovoy, M., *Determination of the Radioactivity of the Quincy Granite by the Photographic Method,* American Journal of Science 252: 736–744 (1954).
47. Keevil, N. B., Larsen, E. S., Jr. and Wank, F. J., *The Distribution of Helium and Radioactivity in Rocks. VI. The Ayer Granite-Migmatite at Chelmsford, Mass.,* American Journal of Science 242: 345–353 (1944).
48. Larsen, E. S., Jr. and Keevil, N. B., *The Distribution of Helium and Radioactivity in Rocks. III. Radioactivity and Petrology of Some California Intrusives,* American Journal of Science 240: 204–215 (1942).

49. Piggot, C. S., *Radium in Rocks: I,* American Journal of Science 217: 13–34 (1929).

50. Hutton, C. O., *The Nuclei of Pleochroic Haloes,* American Journal of Science 245: 154–157 (1947).

51. Cannon, R. S., Jr., verbal communication.

52. Osmond, J. K., *Radioactivity of Bentonites,* US Atomic Energy Commission Contract Number AT(11-1)-178, Final Report (1954).

53. Goldschmidt, V. M., *Principles of Distribution of Chemical Elements in Minerals and Rocks,* Journal of the Chemical Society of London, Part 1: 655–673 (1937).

54. Jahns, R. H., *Distribution of Rare Elements Within Granites and Granitic Pegmatites* (Abstract), Bulletin of the Geological Society of America 64: 1440 (1953).

55. Brown, H., Blake, W. J., Chodos, A. A., Kowalkowski, R., McKinney, C. R., Neuerburg, G. J., Silver, L. T. and Uchiyama, A., *Geochemical Aspects of Interstitial Material in Igneous Rocks* (Abstract), Bulletin of the Geological Society of America 64: 1400 (1953).

56. Brown, H., Blake, W. J., Chodos, A. A., Kowalkowski, R., McKinney, C. R., Neuerburg, G. J., Silver, L. T. and Uchiyama, A., *Leaching Studies of Interstitial Material in Igneous Rocks* (Abstract), Bulletin of the Geological Society of America 64: 1400–1401 (1953).

57. Hurley, P. M., *Distribution of Radioactivity in Granites and Possible Relation to Helium Age Measurement,* Bulletin of the Geological Society of America 61: 1–8 (1950).

58. Tilton, G. R., Patterson, C., Brown, H., Inghram, M., Hayden, R., Hess, D. and Larsen, E. S., Jr., *The Isotopic Composition and Distribution of Lead, Uranium, and Thorium in a Pre-Cambrian Granite,* Manuscript submitted to the Geological Society of America (1954).

59. Larsen, E. S., Jr., verbal communication.

60. Folk, R. L., *Note on the Significance of "Turbid" Feldspars,* American Mineralogist 40: 356–357 (1955).

61. Mawdsley, J. B., *Uraninite-Bearing Fine-Grained Pegmatite of the Charlebois Lake Area, Northeastern Saskatchewan* (Abstract), Bulletin of the Geological Society of America 64: 1550 (1953).

62. Sullivan, C. J., *Metallic Melting Point and Ore Deposition,* Economic Geology 49: 555–574 (1954).

63. Wager, L. R. and Mitchell, R. L., *The Distribution of Trace Elements during Strong Fractionation of Basic Magma—A Further Study of the Skaergaard Intrusion, East Greenland,* Geochimica et Cosmochimica Acta 1: 129–207 (1951).

64. Lakin, H., verbal communication.

Uranium in Magmatic Differentiation

By E. S. Larsen, Jr.,* G. Phair,* D. Gottfried* and W. S. Smith,* USA

Research in progress for the past four years at the US Geological Survey on the distribution of uranium in magmatic complexes has as an ultimate aim the delineation of the role of uranium in petrogenesis in detail not presently practicable for any other trace element. The ease and accuracy with which uranium can be determined analytically make it almost unique among trace elements. At the same time, before maximum use can be made of this high analytical accuracy, problems in field and laboratory sampling must first be overcome; work along such lines is now underway.

This report is largely factual. It presents new data—some of them preliminary in nature. The detailed interpretation of the data will be given in a series of future papers on individual magma series. For a brief discussion of the present status of the general problem of the distribution of uranium in igneous rocks the reader is referred to a recent paper.[1]

URANIUM IN THE MESOZOIC BATHOLITHS OF WESTERN UNITED STATES

Partly for reasons of ionic radius and charge, uranium becomes increasingly concentrated in the residual liquid throughout crystallization differentiation. As a result a substantial part of the uranium in any one rock, regardless of bulk composition, appears to be "late," and in nearly all plutonic series so far investigated the youngest members contain the most uranium.

In the calc-alkalic rocks typical of the large Mesozoic batholiths of western United States the rocks richest in uranium are granites high in SiO_2 and K_2O. The intermediate rocks are more variable in uranium contents than the granites but have, on the average, about half as much uranium; the gabbros contain, on the average, less than 10 per cent as much uranium as the granites.

Uranium Analyses

In any group of genetically related rocks the amount of uranium does not follow as simple a relation as do the major constituents. Broad belts rather than narrow bands are the rule when the uranium contents of the related rocks are plotted on a variation diagram. Table I and the variation diagram (Fig. 1) show how uranium content varies with differentiation in the rocks of the Southern California batholith.[2]

The intrusive rocks of the Mojave Desert area have been excluded from the variation diagram (Fig. 1). These include, in order of decreasing abundance, quartz, monzonites, granites, and granodiorites, all of which are low in mafic minerals and relatively very low in uranium. These rocks make up only a small part of the batholith. They occur as small bodies separated by large masses of pre-batholithic rocks.

The average uranium content of the Southern California batholith is estimated to be 1.7 ppm. The batholith underlies about 6000 square miles in the United States alone. Its extension into Lower California underlies an area in the northern part of the peninsula about twice as large as its area in the United States. Its extension in southern Lower California is of unknown dimensions.

The batholiths of the Sierra Nevada occupy an area of about 17,000 square miles if the intrusives of the Klamath Mountains are included. The rocks are similar to those of the Southern California batholith but have more granodiorite and less quartz diorite. The average uranium content is higher than that of the Southern California batholith and is about 2.3 ppm. The data were obtained on a suite of samples submitted by Paul Bateman of the US Geological Survey.

The Idaho batholith occupies an area of about 13,000 square miles. It is made up chiefly of quartz monzonite and granodiorite of somewhat variable uranium content. Its average uranium content is about 2.1 ppm.

Table II gives data on the uranium content for these three batholiths. The average uranium content for all three batholiths is estimated at 2.1 ppm. Abundance estimates for the separate rocks are based on relative areas.

Leachable Uranium

Hurley[3] showed that the alpha activity of certain granites could be drastically reduced by leaching the granulated rock in dilute hydrochloric acid. Several workers, including those at the US Geological Survey, subsequently found that uranium is the chief radioactive constituent leached. The group at the California Institute of Technology found that in addition to uranium much of the rare-earth content of certain rocks is readily leachable.[4,5]

The exact locus of this leachable uranium is in many respects an enigma, and several hypotheses,

* US Geological Survey.

Table I. The Average Uranium Content of the Rocks of the Southern California Batholith

Rock	No. of samples	Range (ppm)	Average (ppm)	Part of batholith
Gabbro	10	0.2 to 0.3	0.3	Main mass
Tonalite	18	0.3 to 3.0	1.4	Main mass
Granodiorite	37	0.7 to 4.8	2.0	Main mass
Quartz monzonite and granite	9	2.7 to 6.0	4.2	Main mass
Tonalite	3	0.8 to 1.9	1.5	Desert area
Granodiorite	10	0.2 to 1.7	0.9	Desert area
Quartz monzonite and granite	12	0.4 to 2.6	1.4	Desert area

Table II. Comparison of Three Batholiths

	Southern California		Sierra Nevada		Idaho	
Rock	Abundance (per cent)	U content (ppm)	Abundance (per cent)	U content (ppm)	Abundance (per cent)	U content (ppm)
Gabbro	7	0.31	some	0.60	rare	
Quartz diorite	62	1.42	rare	1.2	12	1.8
Granodiorite	27	2.03	chief rock	2.4	31	2.3
Quartz monzonite	2	4.2	abundant	3.4	25	3.1
Granite muscovite	2	2.3		3.0	9	1.6
Fine granodiorite					21	1.0
Average	1.6			2.3		2.1

none of which is wholly acceptable, have been proposed to account for it. The problem is explored in detail in recent papers.[4,5]

The fact that leaching sufficient to reduce the uranium content by more that 25 per cent commonly dissolves only a small percentage of the rock suggests that the leachable uranium is coated on the surfaces of mineral grains—hence "late." At the same time the fact that not only the amounts of total uranium but also the amounts of leachable uranium increase in a roughly systematic way with the amounts of SiO_2 and of alkalies in the rocks suggest that the distribution of uranium is not haphazard but is intimately tied to processes of magmatic differentiation. As yet it is not known whether leachable uranium is present in deeply buried rocks. The uranium(IV) of a primary rock mineral is readily oxidized to uranium(VI), in which state it forms soluble compounds, so it seems reasonable to expect some internal redistribution to have taken place in surface rocks. The question remains, "how much?"

Table III gives the per cent uranium removed from separate splits of a sample of coarse granite from Rubidoux Mountain[2] from the Southern California batholith by leaching in different acids of different concentrations. The samples were crushed to pass 20-mesh screens; 5-gram splits were simmered in 50 milliliters of acid for two hours.

The individual minerals separated from the same rock were leached in 25 milliliters of 1*N* hydrochloric acid by boiling 1-gram samples for 30 minutes in a reflux condenser. The weight of residue and uranium content of the residue and of the solution were then determined, with the results given in Table IV.

These data are approximate in that they neglect the effect of minute impurities, but they show that most of the uranium associated with the common rock-forming minerals is leachable and that such uranium is released by removal of relatively small amounts of the mineral. Thus the leaching patterns shown by the bulk rock are accentuated in the leaching of the major minerals.

Uranium in the Minerals of the California Batholith

It is unfortunate that even the most carefully separated mineral fraction contains numerous microscopic inclusions. These minute impurities limit the significance that can be attached to uranium determinations upon the mineral separates. However, the relative volume of such inclusions is very small, and in most instances the amount of uranium they contribute to the total for the rock is probably neg-

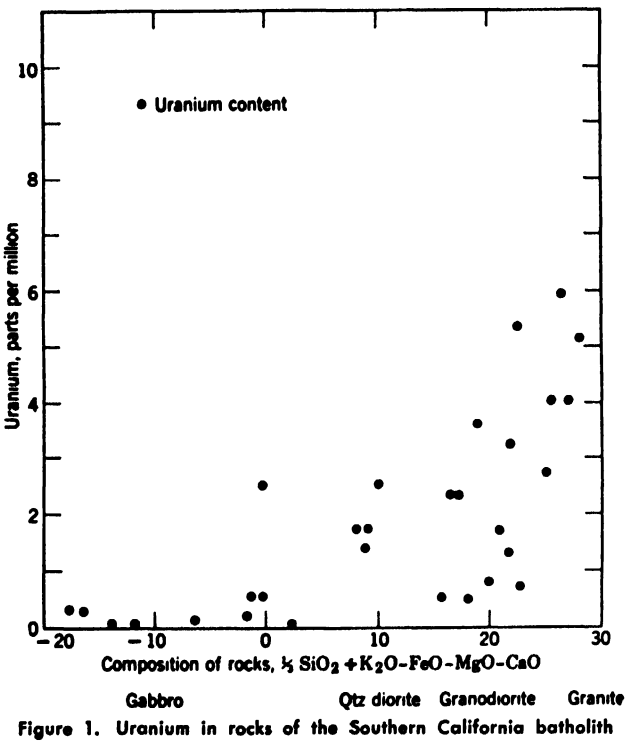


Figure 1. Uranium in rocks of the Southern California batholith

Table III. Results of Leaching Studies on a Sample of Granite from Rubidoux Mountain

Normality	Acid	Uranium leached (per cent)	Normality	Acid	Uranium leached (per cent)
0.1	HCl	25	2.5 (Cont.)	HNO_3	59
	HNO_3	59		Ascetic	50
1.0	HCl	50	5.0	HCl	59
	HNO_3	59		HNO_3	59
2.5	HCl	59			

ligible. Only in unusual instances should the measured uranium values fail to indicate the proper order of magnitude (Table V).

It seems clear from these data that most of the uranium in the rocks is associated with the major rock-forming minerals. The common accessory minerals, zircon, sphene, and apatite, have relatively high uranium contents, but collectively these accessory minerals are not sufficiently abundant to account for more than an estimated 20 per cent of the total uranium in the rocks. In general the major minerals do not depart widely in uranium content from the bulk rock: quartz and feldspar contain about half as much uranium as the bulk rock, and biotite, hornblende, and pyroxene contain about the same percentage as the bulk rock. The uranium content of the common rock-forming minerals tends to increase along with the total uranium in the bulk rock as SiO_2 increases in the rocks.

Accessory minerals are generally not uniformly distributed. The radioactivity of at least some accessory minerals, such as zircon, increases with the total radioactivity of the bulk rock, from gabbro to granite. Alpha-activity data on zircon separated from the different rocks of the Southern California batholith are given in Table VI.

Monazite and xenotime are common in quartz monzonite and granite, especially in muscovite-bearing varieties. Monazite appears to crystallize first, followed by xenotime. Colorless, isotropic, metamict thorite is found in about 1 in 10 granitic rocks. Sphene and apatite have moderate uranium contents.

URANIUM IN VOLCANIC ROCKS

Data have been obtained on lavas in the San Juan tuff of western Colorado[7] and the Modoc lava series of Powers[8] in northern California. The rocks of the San Juan tuff resemble in chemical composition the plutonic rocks of the Southern California batholith, but run consistently higher in K_2O. The lavas may be divided into three major groups separated by large erosional unconformities: (1) pre-Potosi rocks (the most highly altered) of early Miocene (?) age; (2) lavas of the Potosi volcanic series and their equivalents of Miocene age; and (3) post-Potosi rocks of the Hinsdale formation, probably Pliocene in age.

Rocks of the Hinsdale are mildly alkalic; rhyolites of this group contain more uranium (9 ppm) than does any other rock of the San Juan tuff. Within most groups and subgroups the average uranium content tends to increase with silica, but individual analyses for different rock types scatter widely and in general overlap (Table VII).

Uranium analyses were obtained on a suite of samples representing most of the major units in the Modoc lava series of Powers,[8] collected and described by Powers.[8] The oldest rocks in the series are Miocene in age; the youngest rhyolite is probably less than 300 years old, according to Powers.[8]

Uranium in these rocks is more uniformly distributed than in rocks in the San Juan Mountains. The uranium contents of the various rock types are about the same as for their plutonic equivalents. The data are given in Table VIII.

URANIUM IN ALKALIC LATE-STAGE DIFFERENTIATES

Not uncommonly, particularly in nonorogenic regions, quartz separates late in the differentiation history; the normal calc-alkalic lines of descent are shifted toward monzonite and syenite and yield, as an end product, alkalic granite having exceptionally low CaO content. The albite-riebeckite granites of Nigeria,[9] the Conway granite of New Hampshire,[10] and the late rhyolites and trachytes of the Front Range intrusive sequence of Tertiary age[11] are all extreme differentiates of this type. All are enriched in uranium over normal calc-alkalic granite —biotite granite in the Conway about twice, and the other two many fold.

Some 400 samples of the Laramide "porphyries" of the Colorado Front Range have been analyzed

Table IV. Leachable Uranium Content of Rock-forming Minerals Separated from Granite (coarse phase from Rubidoux Mountain)

Minerals	Original uranium content (ppm)	Uranium content of residue from acid leach (ppm)	Per cent of uranium leached	Per cent of sample leached
Perthite	1.1	0.3	70	3.1
Quartz	1.1	1.4?	none?	2.2
Plagioclase	5.1	0.2	98	2.0
Biotite	5.1	1.8	64	30.0
Hornblende	10.0	2.3	77	11.5
Hypersthene	5.2	1.70	68	10.8

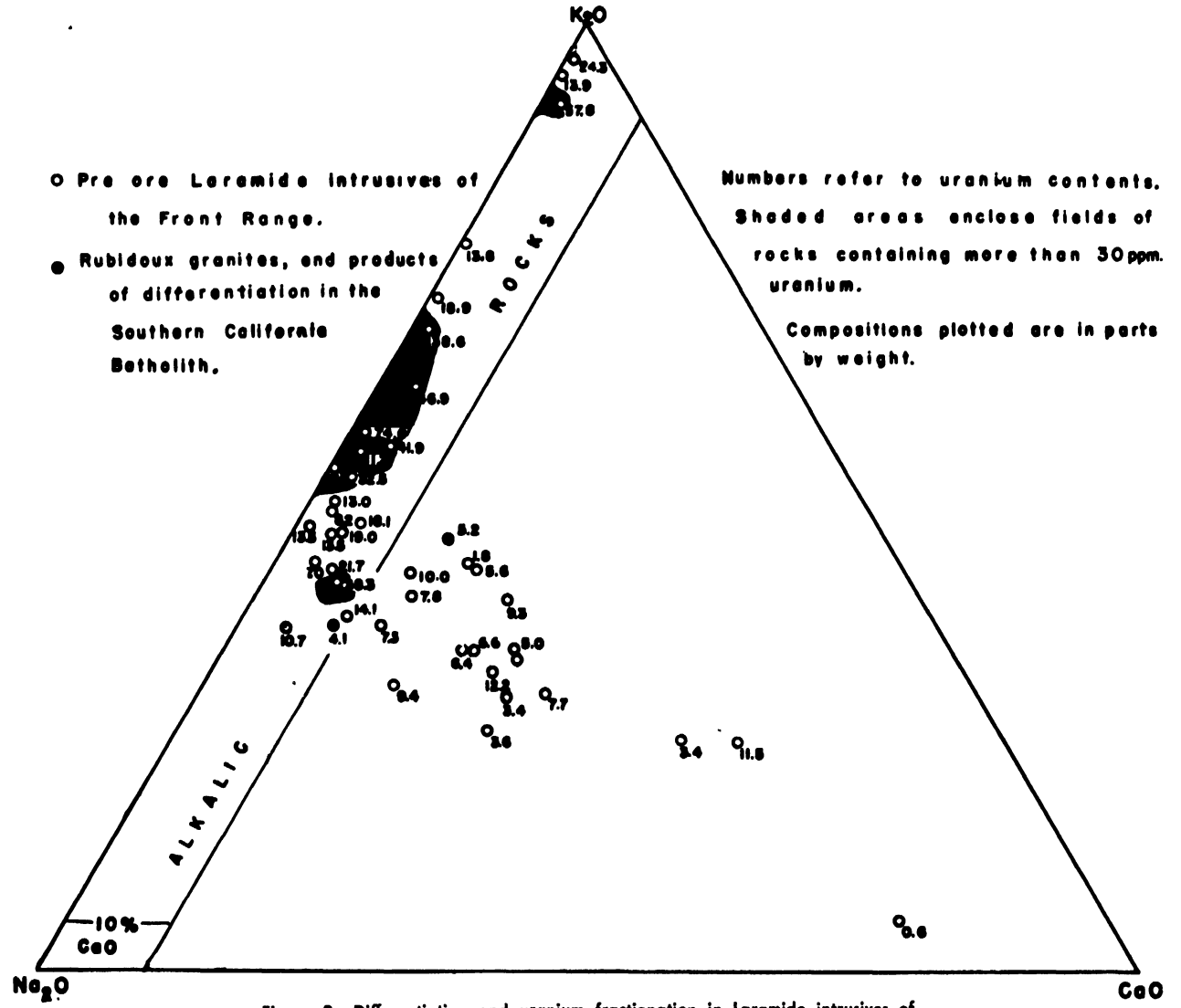


Figure 2. Differentiation and uranium fractionation in Laramide intrusives of the middle and northern parts of the Front Range Porphyry Belt, Colorado

for uranium by one method or another as part of a detailed sampling program investigating the relationship between uraniferous intrusives and pitchblende deposits.[11] Forty-five of the same samples were analyzed for uranium by precise methods; the same sample splits were analyzed for major chemical constituents by standard rapid methods. The data, plotted on a triangular CaO-Na_2O-K_2O diagram (Fig. 2), show a sensitive inverse relationship between uranium and CaO.

For the purposes of this paper all rocks having a CaO/Na_2O+K_2O+CaO ratio of less than 0.10 are considered to be CaO-poor. A ratio of 0.10 represents the approximate limit of differentiation in the Southern California batholith (Fig. 2, solid dots). Twenty-three of the 45 rocks plotted fall in the CaO-poor field. These include most "bostonites" and many "monzonites" and "quartz monzonites" of previous investigators.

Almost all of the rocks analyzed are enriched in uranium by more than 50 per cent over the comparable rock type in the normal calc-alkalic series. The maximum uranium contents (69–138 ppm) are found in the rocks having the least CaO. Those rocks highest in uranium also have K_2O in excess of Na_2O, but the present data show no consistent differences between CaO-poor types containing a moderate excess of K_2O and those having a very large excess of K_2O. The CaO-poor rocks containing Na_2O in excess over K_2O have slightly higher CaO contents than the potassic rocks; most of them show signs of albitization. These rocks have uranium contents that are generally intermediate between the potassic CaO-poor rocks and the earlier more calcic members of the same sequence.

The build-up of uranium in the magmatic residuum apparently culminated in the local deposition of pitchblende at an early stage of metallization in the veins adjacent to the major uraniferous centers of intrusion.

Part of the uranium in the CaO-poor rhyolite and trachyte is in zircon, and some is in allanite, xeno-

Table V. Uranium Content of Separate Mineral Fractions from the Southern California Batholith

	Rattlesnake granite of Hudson[6]			*Green Valley tonalite*			*Gabbro*		
	Mineral wt %	*U (ppm)*	*Wt % × U / 100*	*Mineral wt %*	*U (ppm)*	*Wt % × U / 100*	*Mineral wt %*	*U (ppm)*	*Wt % × U / 100*
Quartz	40	2.4	0.96	24	1.3	0.31			
Orthoclase	36	1.3	0.47						
Plagioclase	16	2.3	0.37	48	0.56	0.28	67	0.32	0.21
Biotite	0.1	5.2	0.01	12	0.8	0.10			
Hornblende				11	3.5	0.39	10	0.26	0.03
Hypersthene							2	0.01	–
Augite				3	2.5	0.09			
Olivine							18	0.01	–
Garnet	0.2	5.8	0.01						
Apatite	0.001	47	–	tr	290	0.01±			
Sphene	tr		–	tr	360	0.04±			
Zircon	0.002	4600	0.10	tr	305	0.03±			
Monazite	0.004	2500	0.10						
Muscovite	7	8.0	0.56						
Xenotime	0.003	360	0.01						
Magnetite	tr	3.0	–	1	3.5	0.04	1	0.6	0.01
U in rock (by sum of minerals)			2.59			1.29			0.25
U in rock (measured)			2.7			1.70			0.16

time, and thorite. A maximum of about half of the uranium can be leached in 1:4 HCl.[11]

The uranium contents of the granitic rock types in the White Mountain plutonic series[10] are listed in Table IX. A fairly regular increase in uranium content with silica content is indicated for the limited range of differentiation so far studied. The uranium contents of the minerals in two phases of the youngest member of the series, the Conway granite, are given in Table X.

The flows and small stocks of the Cripple Creek volcanic area, Colorado, furnish an exception to the rule that high uranium goes with high silica in any one magma series. Preliminary data indicate that the more silica-rich flows, the latite and phonolite, are poorer in uranium than the younger phonolites, which are richer in nepheline. Here again the maximum uranium contents are found in the youngest rocks.

URANIUM IN POTASSIC MAGMA SERIES

In contrast to the rocks already described, K_2O separated at an early stage in the differentiation of the Highwood Mountain[12] and Bearpaw Mountain[12] series, giving rise to unusual rock types—both intrusive and extrusive. Each magma series includes several subseries, but the predominant rock types are rich in mafic minerals and are characterized by high K_2O, high CaO, low Na_2O, and very low SiO_2. In general these K_2O-rich rocks average 50 to 100 per cent higher in uranium than do their mafic counterparts among normal calc-alkalic rocks.

In the igneous rocks of Highwood Mountains, shonkinite is the predominant intrusive and mafic phonolite the predominant extrusive. The rocks analyzed belong to two subseries: (1) the older quartz latite flows, and (2) the younger mafic phonolite-shonkinites and their syenitic derivatives.

Table VI. Distribution and Alpha Activity of Zircon from Rocks of the Southern California Batholith

	Zircon content		*Alpha activity of zircon*	
Rock	*Range (ppm)*	*Average (ppm)*	*Range (α/mg/hr)*	*Average (α/mg/hr)*
Gabbro	0–50	10	30–100	
Tonalite	20–300	60	143–646	307
Granodiorite	10–200	80	433–1235	830
Quartz monzonite and granite	5–100	50	190–4660	1545

Table VIII. Uranium Contents of the Modoc Lava Flows of Powers[8] (Samples from the US National Museum)

			Uranium content	
Rock	*No. of samples*	*No. of determinations*	*Range (ppm)*	*Average (ppm)*
Recent				
Obsidian	4	8	5.2–7.4	6.0
Rhyolite	3	6	1.2–5.0	3.6
Dacite	2	5	3.6–4.2	4.1
Basalt	2	5	0.25–0.8	0.5
Late Pleistocene				
Dacite	1	2	3.8–4.0	3.9
Pliocene and early Pleistocene				
Vesicular basalt	1	2	3.4–3.7	3.6
Pliocene				
Obsidian	2	6	4.5–5.6	5.1
Rhyolite	1	2	3.7–3.8	3.8
Andesite	3	6	1.3–6.0	3.0
Basalt	4	8	0.18–0.85	0.44

The latter group includes layered laccoliths, stocks, and dikes (Table XI).

The igneous rocks of Bearpaw Mountains include some rocks richer in K_2O than any from the igneous rocks in the Highwood Mountains. Uranium analyses have been obtained on a suite of samples collected by W. T. Pecora of the US Geological Survey (Table XII).

Table VII. Uranium Content of Lavas in the San Juan Mountains

Age	*Rock*	*No. of samples*	*No. of determinations*	*Range U (ppm)*	*Average U (ppm)*
Pliocene(?)	Hinsdale formation				
	Basalt	1	1		1.0
	Trachydolerite	2	6	1.1–1.6	1.4
	Andesite-basalt	2	6	1.5–3.4	1.9
	Intrusive andesite	1	2		3.2
	Latite	1	4	2.5–3.1	2.9
	Rhyolite	2	2	8.6–9.8	9.2
Miocene	Fisher quartz latite				
	Quartz latite	4	8	2.8–4.7	3.7
	Glass	1	2		4.0
Miocene	Potosi volcanic series				
	Piedra rhyolite				
	Quartz latite	5	7	2.8–5.4	3.7
	Rhyolite	10	13	2.5–5.6	4.5
	Rhyolite tuff	2	3	1.5–3.4	2.5
	Huerto quartz latite				
	Dark quartz latite	1	4	1.5–2.4	1.9
	Light quartz latite	2	5	1.9–4.7	3.2
	Alboroto rhyolite				
	Quartz latite	8	8	2.6–4.6	3.6
	Rhyolite	7	13	3.0–9.0	5.1
	Rhyolite tuff	2	3	5.2–7.7	6.6
	Sheep Mountain quartz latite				
	Dark quartz latite	3	9	1.2–3.3	2.5
	Quartz latite	2	5	1.9–4.7	3.2
	Treasure Mountain rhyolite				
	Dark quartz latite	1	2		1.9
	Biotite quartz latite	5	7	2.0–2.9	2.5
	Quartz latite	1	4	3.6–4.3	3.8
	Rhyolite	4	8	2.1–5.4	3.5
	Welded tuff	1	4	2.1–2.8	2.0
	Conejos quartz latite				
	Dark quartz latite	8	11	1.3–7.7	2.9
	Rhyolite	3	12	1.0–2.0	1.6
	Dark intrusive	1	5	1.2–2.1	1.8
Miocene	pre-Potosi rocks				
	Silverton volcanic series				
	Pyroxene quartz latite	3	4	3.2–4.7	4.2
	Burns quartz latite	2	4	4.0–5.5	4.8
	Eureka rhyolite	1	2	6.6–6.8	6.7
	Picayune quartz latite	4	8	3.0–11.5	6.5
	San Juan tuff	6	16	1.5–7.7	4.3
	Lake Fork quartz latite				
	Quartz latite	3	5	4.0–6.4	5.1
	Rhyolite	1	2	7.2–7.7	7.5
	Dark dike	1	1		1.7
	Igneous rocks in the San Luis Hills (eastern San Juan Mountains)				
	Trachydolerite	1	2		0.8
	Quartz latite, Beidel	4	8	1.2–2.6	1.8
	Quartz latite	3	6	3.6–9.2	5.6
	Diorite (intrusive)	1	2		4.3

URANIUM IN THE PRECAMBRIAN BOULDER CREEK BATHOLITH, COLORADO

Preliminary data, based on the uranium analyses of 13 samples (Table XIII), suggest that the one Precambrian batholith under study—the Boulder Creek batholith of Colorado—shows a distinct reversal in the path of uranium enrichment. The uranium is high (8–14 ppm) in the border quartz diorites, intermediate in the less mafic rocks of the middle zone, and lowest in the quartz monzonites and granites, which underlie most of the interior of the batholith. Compared to the younger intrusives already described this batholith has had a complex history, having been crushed, foliated, and partly recrystallized along its western margin. The mafic border rocks grade eastward into more massive siliceous rocks in the interior in which primary flow structure, both planar and linear, is commonly preserved. Minor

Table IX. Uranium in the Intrusive Rocks of the White Mountain Plutonic-Volcanic Series

Rock	Square miles	Per cent of magma series	No. of samples	No. of determinations	Uranium content: Range (ppm)	Uranium content: Average (ppm)
(Youngest)						
Biotite granite	315.5	68.9	17	42	4.3–19.5	11.7
Amphibole granite			23	46	2.3–23.0	8.8
Granite porphyry	43.3	9.41	2	5	6.4–9.4	8.1
Quartz, syenite	47.4	10.25	3	7	4.5–7.2	5.9
Syenite	43.1	9.41	8	15	1.2–20.0	5.7
Quartz monzonite	6	1	2	4	1.8–7.6	4.7
Diorite	1.7	0.4	2			
(Oldest)						

Table X. Uranium Contents (in ppm) of the Minerals in the Conway Granite, So-called Redstone Types, New Hampshire

Mineral	Biotite granite: Range	Biotite granite: Average	Amphibole granite: Range	Amphibole granite: Average
Feldspar	2.0–5.3	3.1	1.3–2.2	1.8
Quartz		2.3		5.0
Magnetite	0.8–32.0	15.8	1.0–25.7	9.6
Amphibole	16–43	29	1.0–48.8	20.4
Fluorite		14.0		63.0
Biotite	37–9.39	38		19.7
Ilmenite	47–50	48.5		9.8
Zircon	252–1750	1202	755–2350	1249
Allanite	540–656	617		785
Astrophyllite				15
Rock	39.0–18.2	11.8	7.2–11.6	8.7

Table XI. Uranium in the Igneous Rocks of the Highwood Mountains

Rock	No. of samples	No. of determinations	Uranium: Range (ppm)	Uranium: Average (ppm)
Extrusives[13]				
Mafic phonolite	8	18	1.6–3.2	2.7
Quartz latite	2	5	2.8–4.9	3.6
Stocks[14]				
Shonkinite	3	7	1.5–4.6	2.9
Leucite ijolite	1	2	0.3–0.3	0.3
Leucite malignite	1	2		0.3
Fergusite	1	2	2.0–1.8	1.9
Missourite	2	5	1.4–2.4	2.4
Syenite	1	2	2.1–2.3	2.2
Laccoliths[15]				
Shonkin Sag				
Chilled shonkinite	1	2	6.9–7.4	7.2
Lower shonkinite	1	2	3.0–3.1	3.0
Transition rock	3	7	4.0–7.3	5.2
Upper shonkinite	1	2	3.0–3.3	3.1
Square Butte				
Shonkinite	1	2	2.3–2.4	2.4
Transition	1	2		1.9
Syenite	1	2	5.4–5.9	5.6
Dikes[16]				
Mafic phonolite	6	12	1.5–2.8	2.3

Table XII. Uranium Analyses of Igneous Rocks of the Bearpaw Mountains

Rock	No. of samples	No. of determinations	Uranium: Range (ppm)	Uranium: Average (ppm)
Biotite-apatite pyroxenite	1	3	1.1–1.2	1.13
Nepheline shonkinite	1	2	5.1–5.5	5.3
Mafic monzonite	2	4	1.4–2.3	1.8
Monzonite	1	3	4.2–4.8	4.4
Mafic shonkinite syenite	1	3	4.3–4.8	4.6
Mafic nepheline syenite	1	2		5.0
Porphyritic syenite	1	3	1.7–2.1	2.0

Table XIII. Distribution of Uranium in the Boulder Creek Batholith, Colorado (Samples are listed in order from west to east along a 12-mile section across the western half of the batholith)

	Uranium content: Range (ppm)	Uranium content: Average (ppm)
Rocks of the border zone		
Biotite-quartz diorite gneiss	14.5–14.5	14.5
Biotite-quartz diorite gneiss	8.1–7.3	7.7
Hornblende-bearing biotite-quartz diorite	5.5–5.9	5.7
Rocks of the intermediate zone		
Hornblende-bearing porphyritic biotite granodiorite	5.5–5.1	5.3
Hornblende-bearing biotite-quartz monzonite	3.8–3.4	3.6
Hornblende-biotite-quartz monzonite (altered)	7.3–6.4	7.8
Hornblende-bearing biotite-quartz diorite	5.5–5.5	5.5
Hornblende-biotite-quartz diorite	5.9–6.4	6.1
Rocks of the interior zone		
Hornblende-biotite granodiorite	3.0–3.4	3.2
Hornblende-biotite-quartz monzonite	4.0	4.0
Hornblende-biotite-quartz diorite gneiss	1.4	1.4
Biotite-quartz monzonite gneiss	1.7	1.7
Porphyritic quartz monzonite	1.7	1.7

repetitions of more mafic rocks are common throughout the exposed section; in the interior of the batholith these are not enriched in uranium.

The differences in composition of the wall rock in different areas along the original contacts are believed to be reflected, in a broad way, in the composition of the adjacent batholithic rocks and may be reflected in their uranium contents as well. Quartz diorites were developed adjacent to areas of mafic schist, granodiorite adjacent to areas of mixed

siliceous schist, gneiss, and mafic schist, and quartz monzonite and granite adjacent to areas of older granite gneiss and quartzite. Deep-seated processes of assimilation of metasomatism or both were probably involved in the differentiation along with the fractional crystallization. It is hoped that further work will permit an evaluation of the separate effects.

At present it is considered probable that the high uranium contents of the border quartz diorites resulted from the assimilation of, or reaction with, older uraniferous rocks, but the possibility that uranium was introduced during metamorphism of outer parts of the complex cannot be discounted.

SUMMARY

The results reported here indicate that the change in uranium content of the successive members of any one magma series is less systematic than is the change in major oxides. How much of this variability is real—growing out of the diverse paths open to trace elements during magmatic differentiation—and how much is apparent—inherent in the traditional methods of sampling igneous rocks—remains to be determined. The most variable rocks are those of intermediate composition; there is little or no overlap between the uranium contents of the gabbroic and granitic extremes in any one magma series. Even in the least favorable instances it is generally possible to define a trend by assembling uranium data on a relatively large number of samples. In all those series studied in which fractional crystallization may be assumed to have been the major factor in differentiation the trends are similar: uranium is enriched in the youngest rocks, these being generally high in SiO_2 and K_2O and low in CaO and MgO. The maximum enrichment ($>$ 20 ppm) is found in extreme differentiates very poor in CaO. More data are needed on those series in which processes other than fractional crystallization are believed to have played important roles. In such rocks the uranium content developed may depend upon local geological conditions.

REFERENCES

1. Larsen, E. S., Jr. and Phair, G., *The Distribution of Uranium and Thorium in Igneous Rocks,* in Faul, H., *Nuclear Geology,* John Wiley and Sons, New York: 75–89 (1954).
2. Larsen, E. S., Jr., *The Batholith of Southern California,* Geological Society of America Memoir 29 (1948).
3. Hurley, P. M., *Distribution of Radioactivity in Granites and Possible Relation to Helium Age Measurements,* Geological Society of America Bulletin 61: 1–7 (1950).
4. Brown, H., *et al., Geochemical Aspects of Interstitial Material in Igneous Rocks* (abstract), Geological Society of America Bulletin 64: 1400 (1953).
5. Brown, H., *et al., Leaching Studies of Interstitial Material in Igneous Rocks* (abstract), Geological Society of America Bulletin 64: 1400 (1953).
6. Hudson, F. S., *Geology of the Cuyamaca Region of California, with Special Reference to the Origin of the Nickeliferous Pyrrhotite,* California University, Department of Geological Science, Bulletin 13: No. 6, 175–252 (1922).
7. Larsen, E. S., Jr. and Cross, W., *Geology and Petrology of the San Juan Mountains, southwestern Colorado,* US Geological Survey Professional Paper 258 (in press).
8. Powers, H. A., *The Lavas of the Modoc Lava-Bed Quadrangle, California,* American Mineralogist 17: 253–294 (1932).
9. Greenwood, R., *Younger Intrusive Rocks of the Plateau Province, Nigeria, compared with the Alkalic Rocks of New England,* Geological Society of America Bulletin 62: 1151–1178 (1951).
10. Chapman, R. W. and Williams, C. R., *Evolution of the White Mountain Magma Series,* American Mineralogist 20: 502–530 (1935).
11. Phair, G., *Radioactive Tertiary Porphyries in the Central City District, Colorado, and Their Bearing upon Pitchblende Deposition,* US Atomic Energy Commission TEI–247 (1952).
12. Larsen, E. S., Jr., *Petrographic Province of Central Montana,* Geological Society of America Bulletin 51: 857–948 (1940).
13. Larsen, E. S., Jr., *Igneous Rocks of the Highwood Mountains, Montana, Part II. The Extrusive Rocks,* Geological Society of America Bulletin 52: 1733–1752 (1941).
14. Burgess, C. H., *Igneous Rocks of the Highwood Mountains, Montana, Part IV. The Stocks,* Geological Society of America Bulletin 52: 1809–1828 (1941).
15. Hurlbut, C. S., Jr., *Igneous Rocks of the Highwood Mountains, Montana, Part I. The Laccoliths,* Geological Society of America Bulletin 50: 1043–1112 (1939).
16. Buie, B. F., *Igneous Rocks of the Highwood Mountains, Montana, Part III. Dikes and Related Intrusives,* Geological Society of America Bulletin 52: 1753–1808 (1941).

Distribution of Uranium and Certain Other Trace Elements in Felsic Volcanic Rocks of Cenozoic Age of the Western United States

By R. R. Coats,* USA

This investigation was begun as a result of the observed close geographic relationship between known structurally controlled uranium deposits in the Cordilleran region, and the distribution of post-Cretaceous volcanic rocks.[1] It is also apparent that, although few uranium deposits are remote from areas of volcanic and shallow intrusive rocks, broad areas of volcanic rocks, the Columbia Plateau, the Sierra Nevada, and the Cascade Mountains, etc., are completely lacking in known uranium deposits. The problem posed by this observation was: does this distribution reflect a real scarcity of uranium deposits in these areas, or merely insufficient prospecting, lack of exposures, or both? If, as is believed by many, there is a genetic relation, direct or indirect, between the uranium deposits and post-Cretaceous vulcanism, then an investigation of the content of uranium in igneous rocks appeared to offer an indirect means of getting an answer to the question posed above. The investigation is predicated on the existence of uraniferous metallogenetic provinces, and on the concept that there is a relationship between (*a*) the metal content of the igneous rocks of a given comagmatic province and (*b*) the type of ore deposits found in the province.

In order to obtain results that would permit the comparison of rocks from one district, or differentiation series, with those of another, sampling was restricted to the felsic and members, chiefly rhyolites and dacites, which were known to be highest in uranium.[2] Glassy and partly glassy rocks were emphasized in the sampling to obtain samples as representative as possible of unaltered and undepleted magma; such rocks might be expected to show obvious traces of any hydrothermal alteration or weathering to which they had been subjected; weathered and altered rocks were avoided. In the field work reported herein, 116 samples were collected from the states of Washington, Oregon, Idaho, Montana, Wyoming, Colorado, Utah, Nevada, California, and Arizona. All these samples were analyzed fluorimetrically for uranium, chemically for fluorine, and spectrographically for B, Be, La, Li, Nb, F, Sn, Pb, and Zr. In about 50 samples, Mn was sought and found; Ta, Th, and W, were also sought but not found. Zinc and Ge were sought in some of the same 50 samples but found in none. The results are summarized in Table I above.

Table I. Minor Element Content (ppm) of Some Rhyolitic and Dacitic Volcanics of Post-Cretaceous Age from Western United States

Element	*Arithmetic mean (ppm)*	*Range (ppm)*
U	5	0–30
B	32	0–100
Sn	5	0–40
Be	5	2–20
Nb	22	0–200
La	40	0–200
Pb	24	0–90
Zr	139	30–2700
F	655	0–4300
Li	46	0–300

The geographic distribution of high and low content of the several elements is not a random one; locally well-defined boundaries can be drawn between provinces of high content of some elements and those of average content or less than average. Figure 1 shows distribution of values thus obtained. Similar plots were made for each of the other elements listed in the table above. For Sn, Be, Nb, Pb, and F, the pattern of distribution resembles that for uranium. For Zr and Li the resemblance is less marked. The distribution of La is apparently nearly a random one and that of B shows well-marked patterns which differ from those of any other element and in which the highest values are distributed in the Coast Ranges of California and along the east front of the Sierra Nevada. The provincial boundaries shown in Fig. 2 were tentatively drawn to obtain the best fit to the distributions of that group of elements showing the closest coherence, viz., U, Be, Sn, Nb, Pb, and F.

STATISTICAL RELATIONS AMONG ELEMENTS

Correlations coefficients were calculated by the usual methods and are shown in Table II to determine the degree to which the distribution of the several elements resembled that of uranium.

The coefficients for niobium, tin, beryllium, lithium, fluorine, and lanthanum reach or exceed the 0.1 per

* US Geological Survey. Including work by R. R. Coats, P. R. Barnett, N. M. Conklin, W. Mountjoy, J. Meadows, S. P. Furman and E. F. Rader.

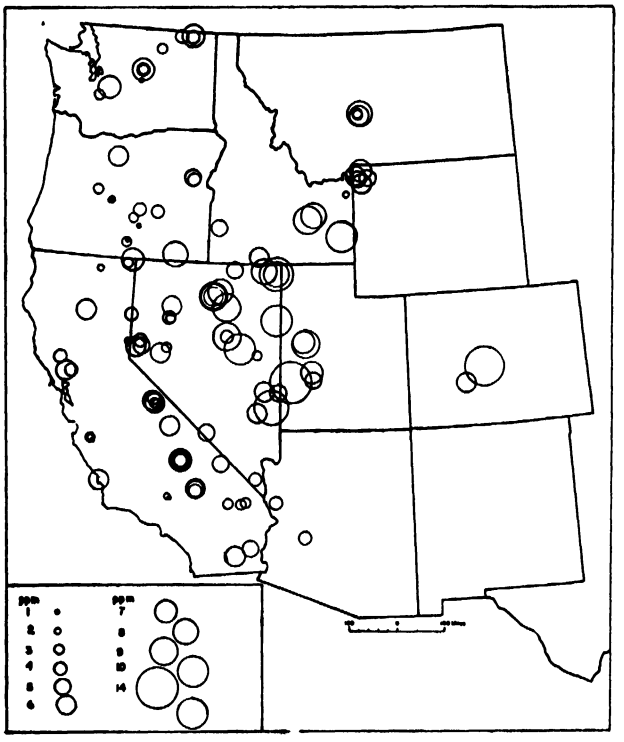


Figure 1. Uranium content of Cenozoic rhyolitic and dacitic rocks

Figure 2. Comagmatic provinces in the Cordilleran region

cent level of significance; that is, there is less than one chance in a thousand that a correlation this high could be the result of random distribution. The coefficient for boron is about that of the 5 per cent level of significance. Coefficients for lead and zirconium are not significant. The probable significance of these relationships is that those elements that correlate well with uranium are those typically concentrated in residual magmas, such as in pegmatites. The association with fluorine is a different sort, and is possibly to be attributed to the formation of an uranium fluoride compound or complex ion in the magma.

Table II. Correlation Between Content of Uranium and Other Minor Elements, in 116 Analyses of Cenozoic Rhyolitic and Dacitic Rocks.

Element	*Coefficient*	*Element*	*Coefficient*
F	0.55	Pb	0.159
Nb	0.447	Zr	0.01
Be	0.445	B	−0.178
Sn	0.364	La	−0.412
Li	0.317		

STATISTICAL ANALYSIS OF PROVINCIAL DISTRIBUTION

As indicated in Table III, the highest mean uranium content is found in the rocks of the Shoshone province, with lower values in rocks from the Ute and Coastal Provinces. In the table, the column headed "content" lists the values reported in the rocks analyzed, which range from zero, or a trace, to 30 ppm. The columns headed by provincial (or subprovincial) names show, for each of the values, the number of analyses corresponding to that value, for the rocks sampled from that province. The column headed "Sum" shows the total number of analyses for each of the analytical values. The entries in the row at the bottom of the table list the total number of rocks analyzed from each province. In the row below these totals is listed the total number above the mean value of 5 ppm. The next row lists the number to be expected above this value, assuming that the distributions of analyses, by value, are the same for all provinces. The row headed "Deviation" gives the deviations, positive or negative, of the actual numbers of values found, compared with the numbers expected. (The number expected will, in general, not be a whole number). The row following gives the calculated contribution to chi-squared, arrived at by the formula χ^2 = (Deviation)^2/Expectation. The last row shows the probabilities, in percentages, that the number of analyses giving values above the mean within each of the several provinces might be obtained by a chance drawing of the total number of analyses appropriate to the province from the total number (112) of analyses. A high probability means that the observed distribution might readily be obtained by chance; a probability of 5 per cent means that there is one chance in 20 that the observed distribution could be a matter of chance alone. The values calculated show that the positive deviation shown by the values for the Shoshone Province is highly significant, and the negative deviation shown by the values for the Cascade Province is possibly significant. The statistical study of the distribution suggests strongly that the Shoshone Province is a uraniferous province, or part of a larger uraniferous province, at the levels of concentration measured by the analyses used herewith, for the type of rocks analyzed. The boundaries as indicated on Fig. 2 are, of course, tentative, and the Shoshone Province may

Table III. Distribution of Uranium, with Respect to Province and Content in 112 Rhyolitic and Dacitic Rocks

	Province							
	Ute			*Cascade*	*Coastal*	*Shahaptin*	*Shoshone*	*Sum*
Content (ppm)	*Mohave*	*Yuma*	*Mountain Border*					
0				1		1		2
1			1	3	1	2		7
2			1	4	1		1	7
3	3		2	5	1	2	6	19
4	2	1	2	4	2	3	4	18
5	3	1	2			2	5	13
6	1	1	5		2	1	10	20
7			1	3			4	8
8							7	7
9							5	5
10							2	2
11	1						1	2
14							1	1
30							1	1
Sum	10	3	14	20	7	11	47	112
Number above 5 ppm	2	1	6	3	2	1	31	46
Expectation	4.1	1.23	5.75	8.2	2.87	4.51	19.25	
Deviation	−2.1	−.23	.25	−5.2	−0.87	−3.51	11.75	
Contribution to χ-squared	1.07	0.04	0.01	3.29	.26	2.74	7.67	
Probability				7.5%		10%	0.6%	

prove to be, when other aspects of the distribution of uranium are taken into account, part of the larger uraniferous province that includes the Colorado Plateau. On the negative side, a rational explanation for relative scarcity of uranium deposits in some provinces may be the relative poverty in uranium of magmas from which some uranium deposits are derived.

TYPES OF REGIONAL VARIATION

The evidence presented indicates that the regional variations in uranium content in rhyolitic and dacitic rocks are nonrandom in nature. Similar types of variation may be shown for Sn, Be, Nb, Pb, and F. Two types of nonrandom variation of regional extent may be discerned in the distribution mapped. One of these may be described as consisting of apparently random fluctuations of minor-element content about a given level, with broad areas that are relatively sharply delimited from neighboring areas, which are in turn characterized by rocks showing apparently random fluctuations about a different level of concentration. The other type of nonrandom variation consists of progressive gradational changes in minor element content within a broad area. This latter is apparently what Pirsson called a "regional progression of types".[8] Both types of variation may be present in the Cordilleran region. It should be noted that both types of variation may imply compositional gradients, the differences lying merely in the steepness of the gradient.

ORIGINS OF REGIONAL VARIATIONS

If we neglect the possibility of initial nonuniformity in the granitic crust, subsequent lateral variation in the concentration of minor elements at accessible levels of the the crust may arise in two ways: by lateral variation in the effectiveness of vertical transport, or by horizontal transport. Horizontal transport may be either endogene, operating within the crust, or exogene, operating surficially.

Processes involved in exogene horizontal transport are relatively familiar to us, because they are those of weathering, erosion, and sedimentation. Recently, Cady, McKelvey, and Wells[4] have pointed out the close relationship between mineral deposits, particularly syngenetic deposits in sedimentary rocks, and the sedimentary facies and geotectonic environment in which the rock was deposited. Any particular example of regional variation can reasonably be attributed to exogene segregation and redistribution where the element in question is known to be concentrated in the minor cycle or in sedimentary rocks characteristic of a particular facies, and where the area in which a particular element is concentrated coincides fairly closely with the distribution of the favorable sedimentary facies. In this study, however, the set of elements that seems most closely associated is characteristically a pegmatitic one, that is, a set of elements characteristic of granitic rest magmas, rather than one characteristic of any particular sedimentary facies. Furthermore, the provincial boundaries that seem to express best the minor-element relationships are quite discordant with those of the major geosynclinal troughs of the Cordilleran region through most of known geologic history. To some extent, of course, this discordance may be a reflection of the somewhat restricted distribution of Cenozoic rhyolitic and dacitic rocks, but the province with the most distinctive chemical characteristics and the best-defined boundary, the Shoshone Prov-

ince, is the one that shows the most pronounced discordance with past geosynclinal trends.

Endogene horizontal transport of material within the crust, if we exempt the short-distance effects of overthrusts, must be by ionic diffusion, gas transport, or liquid transport. Owing to the directions of the prevailing thermal and pressure gradients, such transport is more difficult than transport in a vertical sense. (Again, we may except the migration of petroleum and of ground water.) Stress conditions in the crust apparently make any extensive lateral displacement of magma impossible. Recently, however, Gilluly[5] has suggested subcrustal transport of sialic material. If such transport takes places, it is probable that it may be, to some extent, differential, because the remelting is also likely to be differential. This mechanism seems to offer promise as an explanation of progressive gradational changes in the composition of igneous rocks.

LATERAL VARIATION IN THE EFFECTIVENESS OF VERTICAL TRANSPORT

Rankama[6] has shown that certain elements, viz., Li, Be, Rb, Cs, Ba, rare earths, Ta, and Pb, tend to be more highly concentrated in younger granites, within the area he studied. Rankama attributes the change to the repeated sweating out and upward migration of palingenetic magmas, successively more and more enriched in the elements that enter least readily into the earlier formed minerals. These are largely the elements for which regional differences in concentration are found in this study.

It is suggested that, in those areas where, because of favorable tectonic conditions, Rankama's process has been most effective over a long period of time, the concentration of the residual pegmatitic elements will be highest at a given level in the crust; and that rhyolitic magmas, generated at such levels in such areas, will have more of the residual elements than rhyolitic magmas generated elsewhere at corresponding levels. By this hypothesis, tectonic trends and magmatogenic episodes of the Precambrian are responsible for some provincial differences found in younger igneous rocks.

REFERENCES

1. Kaiser, E. P. and Page, L. R., *Distribution of uranium deposits in the United States,* US Geological Survey, Circular 220: 11 (1952).
2. Adams, J. A. S., *Some aspects of the geochemistry of uranium,* (Abstract) Geological Society of American Bulletin 63: 1229 (1952).
3. Iddings, J. P., *Igneous rocks,* John Wiley & Sons, New York (1913).
4. Cady, W. M., McKelvey, V. and Wells, F. G., *Geotectonic relations of mineral deposits,* Geological Society of America Bulletin 61: 1447 (1950).
5. Gilluly, J., *Connection between orogeny and epeirogeny as deduced from the history of the Colorado Plateau and Great Basin,* (Abstract) Geological Society of America Bulletin 63: 1529–1530 (1952).
6. Rankama, K., *On the geochemical differentiation in the earth's crust,* Comm. Geol. Finland, Bulletin 137: 16 (1946).

Uranium Deposits in Volcanic Rocks of the Basin and Range Province

By Byron J. Sharp,* USA

GENERAL GEOLOGY

The Basin and Range province[1] was the site of several basins of deposition throughout most of the Paleozoic and Mesozoic eras. In late Jurassic time, the western edge of the province was disturbed by the Nevadan orogeny with the formation of the Sierra Nevada Mountains. During late Cretaceous and early Tertiary time, folded and thrusting of the Laramide orogeny occurred along a north-south trending belt which included most of the Basin and Range province and extended north and south into Canada and Mexico.

The major intrusive rocks in the area range in age from Jurassic (?) to Miocene (?). The younger intrusives are in the eastern portion of the province, and the older in the west, apparently related to the Sierra Nevada batholith. Most of the volcanic rocks in the province are Tertiary in age. They are present throughout the area, but are particularly abundant in southwestern Utah, northwestern and south-central Nevada, and eastern California.

After the Nevadan and Laramide orogenies, an episode of high angle faulting, superimposed on older structures, created the Basin and Range physiographic province of sharply defined mountain ranges and alluvial valleys. Most of the high angle faults are late Tertiary in age and some are still active.

INDIVIDUAL DEPOSITS

Marysvale Area, Utah

Geography

The Marysvale mining district is in south-central Utah, about 200 miles south of Salt Lake City (Fig. 1). The Antelope Range to the east rises to an elevation of 7600 feet, which is 2000 feet above the Sevier River, near the western edge of the area.

General Geology

The Bullion Canyon formation, which consists of a great thickness of latite flows, volcanic breccias, and tuffs, represents the earliest igneous activity in the area.[2] These volcanics were intruded by quartz monzonite and granite which were exposed by erosion. Extrusion of the Mt. Belknap rhyolite series followed the erosion interval.

Faulting took place both before the erosion interval and at the time of the extrusion of the Mt. Belknap rhyolite series. Vein deposits in the Marysvale district are best developed in the quartz monzonite. A red rhyolite agglomerate at the base of the Mt. Belknap series contains uranium minerals along weak fractures which appear to offset the quartz monsonite-rhyolite agglomerate contact. Uranium is also present along small fractures in glassy rhyolite dikes which are presumably feeder dikes of the Mt. Belknap extrusives.

Ore Deposits

Uraninite has been identified both in rhyolite glassy dikes and rhyolite agglomerate. Finely divided uraninite is closely associated with fluorite, but fluorite also occurs without uraninite. Part of the fluorite may have formed contemporaneously with uraninite but some is later.[2] Secondary uranium minerals in the rhyolites are autunite, meta-autunite, torbernite, and uranophane.

Fluorite and uranium minerals occur in lenticular pods and bands along flow planes of the rhyolite agglomerate.[3] The mineralized zones follow the flow planes in some places, but elsewhere they cut sharply across them (Fig. 2). The ore is commonly associated with lenses of clay, and fluorite has apparently replaced part of this clay in both ore and barren zones.

Glassy dikes, flow planes, clay lenses and local structures in the rhyolite agglomerate are all closely related to uranium mineralization. The close association of fluorite and uranium may be a key to the mode of emplacement of the uranium. There are indications that they may have been introduced as a late phase of the volcanic activity.

Kings River Area, Nevada

Geography

Uranium is found in the foothills east of Kings River Valley in Humboldt County, Nevada, about 74 miles north of Winnemucca (Fig. 1). The mountains immediately east of the occurrence rise about 2000 feet above the broad floor of the valley.

General Geology

The rock units in the Kings River area consist of granodiorite, diabase, agglomerate, rhyolite, vitrophyre, and lake sediments (Fig. 3). Granodiorite of Jurassic(?) age[4] crops out to the north of the mine shaft, and is also exposed in the lower workings. Diabase dikes intrude the granodiorite and larger

* US Atomic Energy Commission.

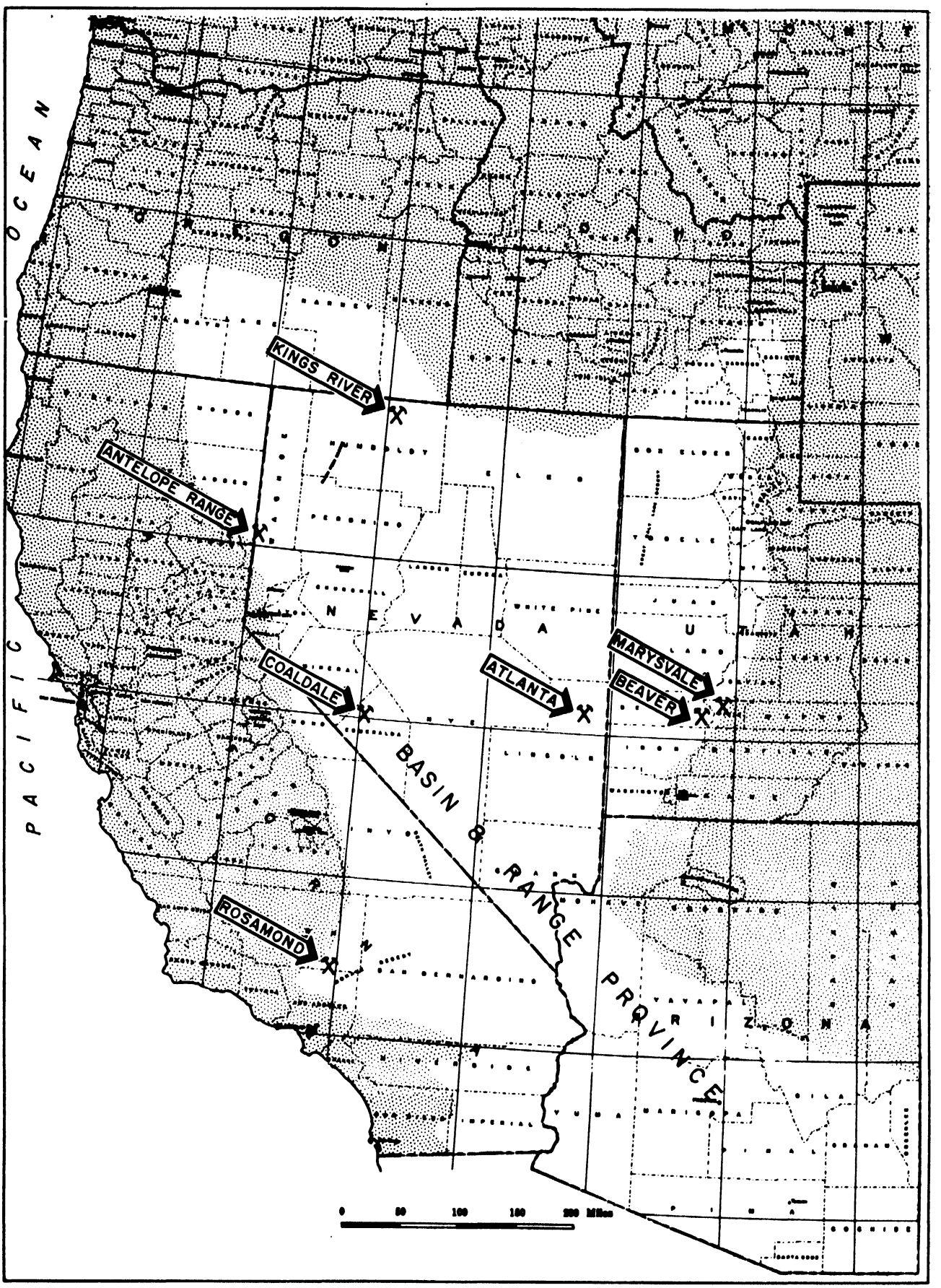


Figure 1. Index map showing uranium deposits in volcanic rocks of the Basin and Range province

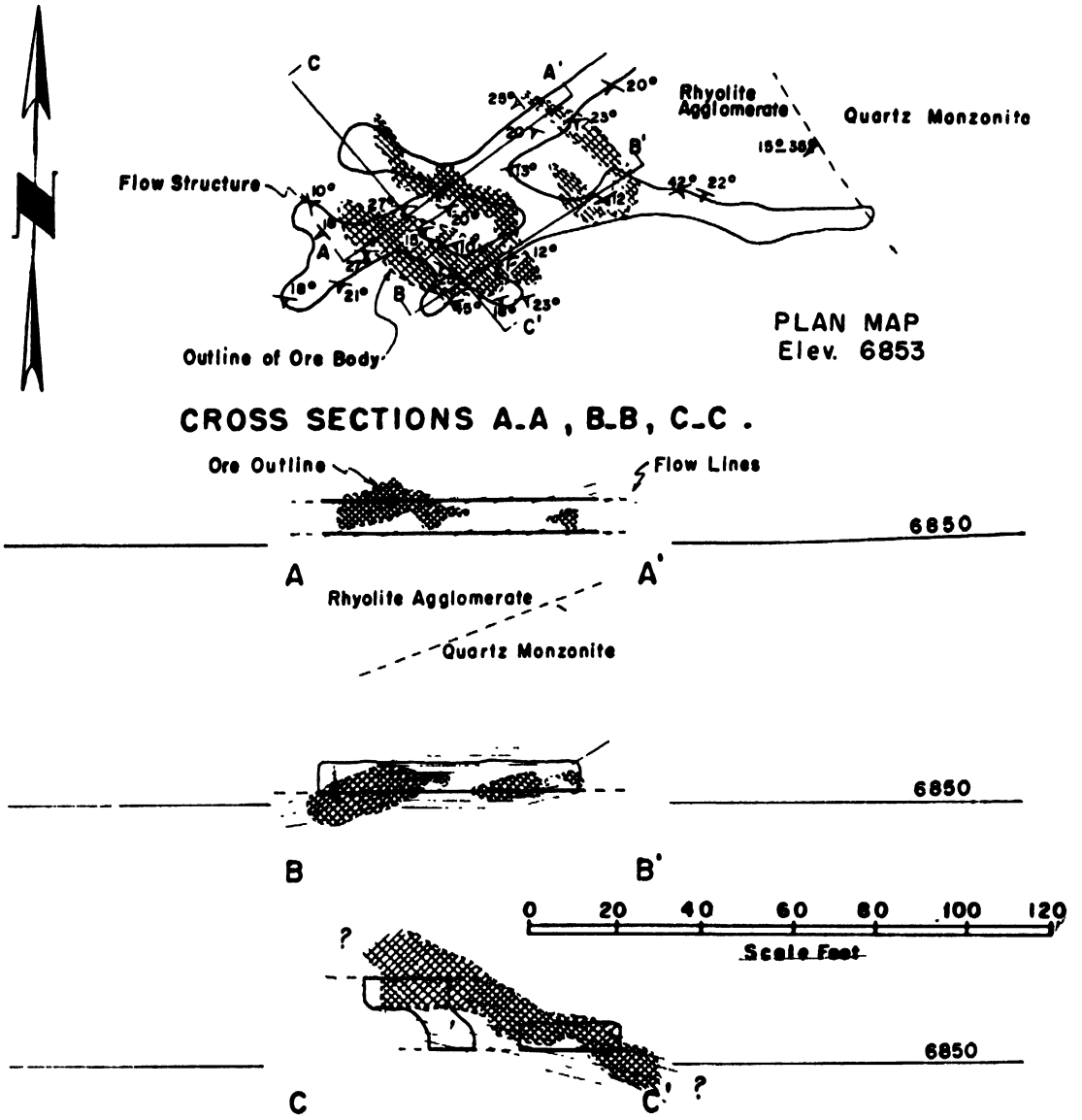


Figure 2. Underground workings in the rhyolite agglomerate in the Marysvale area, Utah

outcrops of similar material may be extrusive equivalents of the diabase dikes. A Miocene volcanic sequence of agglomerate, rhyolites and vitrophyre appears to have been extruded over an erosion surface on the granodiorite and diabase. Later Miocene(?) like sediments were deposited in the lower areas near the thick sequence of volcanics.

A series of north-south trending faults displaces the rocks of the area. These faults parallel the mountain front and are both normal and reverse. Uranium minerals have been exposed in mine workings on one of the faults, and anomalous radioactivity has been detected along the surface extension of this structure to the north.

Ore Deposits

The fluorescence of autunite was originally detected along the surface exposure of the north-south trending fault structure. Torbernite, gummite(?), and uraninite(?) occur at depth. Gangue minerals include iron oxides, pyrite, smoky quartz, fluorite, and clays. The structure is mineralized throughout its exposed depth of 270 feet and several parallel faults, but no appreciably radioactive material has been found along the other faults.

Uranium occurs in irregular zones along a north trending fault in volcanic rocks of the Kings River area. The mineralizing solutions are probably genetically related to the volcanic activity.

Other Deposits

Other uranium occurrences in volcanic rocks of the Basin and Range province include those in the Antelope Range of Nevada and California; the Atlanta and Coaldale areas of Nevada; Beaver, Utah; and Rosamond, California.

Antelope Range Area, Nevada and California

A uranium deposit is situated on the western slopes of the Antelope Range about 30 miles north of Reno, Nevada (Fig. 1) at an elevation about 6000 feet above sea level, on the California-Nevada state

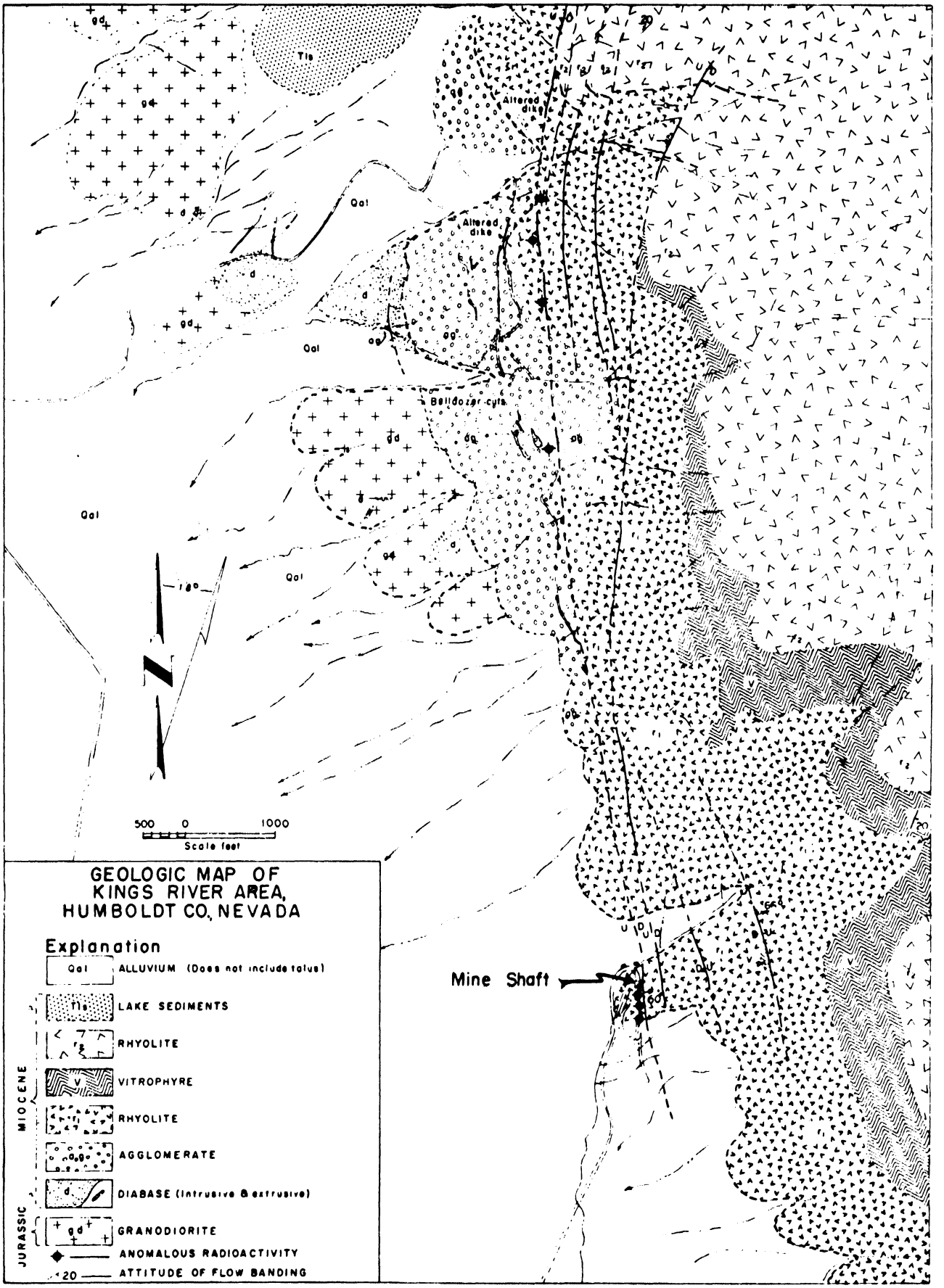


Figure 3. Geologic map of Kings River area, Humboldt Co., Nevada

boundary. Rocks exposed in the Antelope Range consist primarily of Jurassic granite overlain by Tertiary volcanics. Gummite and uranophane occur along narrow silicified northeast-trending fractures in rhyolite and rhyolitic tuff. Other nearby uranium occurrences in the volcanic rocks suggest that the rhyolite and rhyolitic tuff are favorable units for uranium deposition.

Atlanta District

Uranium in extrusive rocks occurs in the Atlanta mining district about 50 miles north of Pioche, Nevada. Uranium minerals are scattered through coarse, silicified, rhyolite agglomerate, which is exposed for about 500 feet along a low ridge. The agglomerate at the outcrop strikes north 75 degrees east and dips 15 degrees to 25 degrees to the north. The principal ore minerals in this district have been tentatively identified as uraninite, uranophane, and autunite. Numerous steep fractures which trend north 35 degrees west may have localized the mineralization.

Coaldale Area, Nevada

Uranium-bearing rhyolitic tuff is exposed at the southern end of the Silver Peak Mountains, about four miles south of Coaldale. The deposit consists of weakly mineralized tuff containing veinlets and small irregular pods of higher grade uranium-bearing rock.[5] Autunite and phosphuranylite coat fractures and partly fill feldspar crystal cavities in the tuff. Uranium in an unidentified form is also present in small veinlets of siliceous material and in limonite-stained fracture coatings.

Beaver Area, Utah

Several small uranium deposits are situated on the western slopes of the Tushar Mountains near Beaver, Utah. The Mt. Belknap and Bullion Canyon volcanic series previously described for the Marysvale area form the host rock of the deposits near Beaver. Uranium occurs in the Bullion Canyon series along dikes which are probably feeder dikes to the Mt. Belknap series. Autunite, torbernite and uranophane are also found in small fractures, faults, and shear zones in both volcanic sequences. Gangue minerals include fluorite, pyrite, quartz, chlorite, sericite, and iron oxides.

Rosamond Area, California

Near Rosamond, California, uranium is associated with the volcanic rocks of the Miocene Rosamond series. Autunite and gummite (?) have been found in dacite dikes, flows, and tuffs. Small faults and fractures probably controlled the uranium-bearing solutions and localized the deposits.

REFERENCES

1. Davis, D. L. and Hetland, D. L., *Uranium in clastic rocks of the Basin and Range Province,* Volume 6, Session 6B, P/44, These Proceedings.
2. Kerr, P. F., Brophy, G., Dahl, H. M., Green, Jack and Wollard, L. E., *A Geologic Guide to the Marysville Area,* US Atomic Energy Commission, RMO-924 (1952).
3. Gilbert, R. W., private communication..
4. Yates, R. G., *Quicksilver Deposits of the Opalite District, Malheur County, Oregon and Humboldt County, Nevada,* US Geol. Survey Bull, 931-N (1952).
5. Duncan, D. C., *A Uranium-Bearing Rhyolitic Tuff Deposit near Coaldale, Esmeralda County, Nevada,* US Geol. Survey Circ. 291 (1953).

Uranium-Bearing Vein Deposits in the United States

By Donald L. Everhart,* USA

Uranium-bearing vein-type deposits are among the foremost uranium ore-producers in the world. Such types of deposits appear to be relatively common in the United States, as they are elsewhere on North America and on other continents, although to date they have not proven to be as important commercially in the United States as have disseminated uranium deposits in sedimentary rocks. In the United States, there are known at least 100 vein deposits containing significant amounts of uranium minerals.

The vein deposits discussed herein are essentially mineral-filled fractures in which uranium minerals are an important constituent. The metallic ions in the vein minerals are believed to have come originally from sources at depth in the earth's crust, although secondary redistribution is characteristic in many deposits of this type. Replacement of host rock by the metallic minerals along fractures or shears occurs in some instances, but this mechanism is considered subordinate to open-space filling.

DISTRIBUTION OF URANIFEROUS VEIN DEPOSITS IN THE UNITED STATES

In the western United States, vein deposits containing significant amounts of uranium minerals are distributed generally throughout the Rocky Mountain ranges and the Basin-Range province. In the Eastern United States, in Michigan, a few uraniferous veins are located along the southern edge of the Canadian Shield.

In the Western United States an interesting spatial relationship is apparent between known uraniferous veins and the Colorado Plateau and Wyoming basins (Fig. 1). In the northeastern part of this area minor veins are known in the core of the Black Hills of South Dakota. To the southwest, a "belt" of vein deposits includes the Lusk, Wyoming district, the deposits of the Colorado Front Range, extending from the area west of Fort Collins southward through the Front Range Mineral Belt to the New Mexico border, and into the Southern Rocky Mountains and the Basin-Range province of eastern New Mexico. Uraniferous vein deposits are distributed throughout the Basin-Range province of Western New Mexico, Arizona and Nevada, surrounding the Colorado Plateau to the south, southwest, and west. Northwest and west of the Colorado Plateau and the Wyoming Basins, uranium-bearing vein deposits are distributed throughout the Northern Rocky Mountains and in the Central Rockies to the south. The major U.S. vein deposit district, near Marysvale, Utah, lies in the High Plateaus that constitute the western border zone of the Colorado Plateau. West of the Basin Range province, a few significant vein deposits are known in the Sierra Nevada of California—particularly in the southern part.

CLASSIFICATION OF URANIUM VEIN DEPOSIT TYPES IN THE UNITED STATES

The uranium-bearing vein deposits of the United States may be classified into several major types, based on significant geologic features. Such classification serves as a basis for understanding the environments under which they may form and the geochemistry of the ore bearing solutions. It is assumed herein that the two most pertinent characteristics to be used as a basis for classification are (1) favorable host rock and (2) typical mineral assemblages. The six types of host rocks found to be most favorable for vein deposits in the United States are: (1) felsic intrusives, (2) rhyolitic extrusives, (3) schist and gneiss of sedimentary origin, (4) quartzite, (5) metavolcanic rocks, and (6) arenaceous sedimentary rocks. The major mineral assemblage types number five, respectively characterized by: (1) uranium, iron and silica oxides, and fluorite; (2) uranium and silica oxides, copper, lead and molybdenum sulfides, silica and fluorite; (3) uranium oxides, copper, cobalt, nickel, lead, zinc, and silver sulfides, and carbonates; (4) uranium oxides and gold-bearing pyrite, and (5) uraniferous hydrocarbon.

In Table I, the mineral assemblage types are plotted against the favorable host rock types, indicating the nature and incidence of selected type examples of vein deposits in the United States. In Table II, the principal and/or geologically significant vein deposits of the country are tabulated, summarizing their major geologic characteristics, in the order of the classification scheme shown in Table I.

GEOLOGICAL CHARACTER OF THE DEPOSITS

Favorable Host Rocks

It has been noted by Everhart and Wright[1] that the major uranium-bearing vein deposits of the world generally occupy fractures, either in granitic intrusive rocks or in metasediments. In the United States, several significant vein deposits have also been noted in rhyolitic extrusive rocks (chemically related to

* US Atomic Energy Commission.

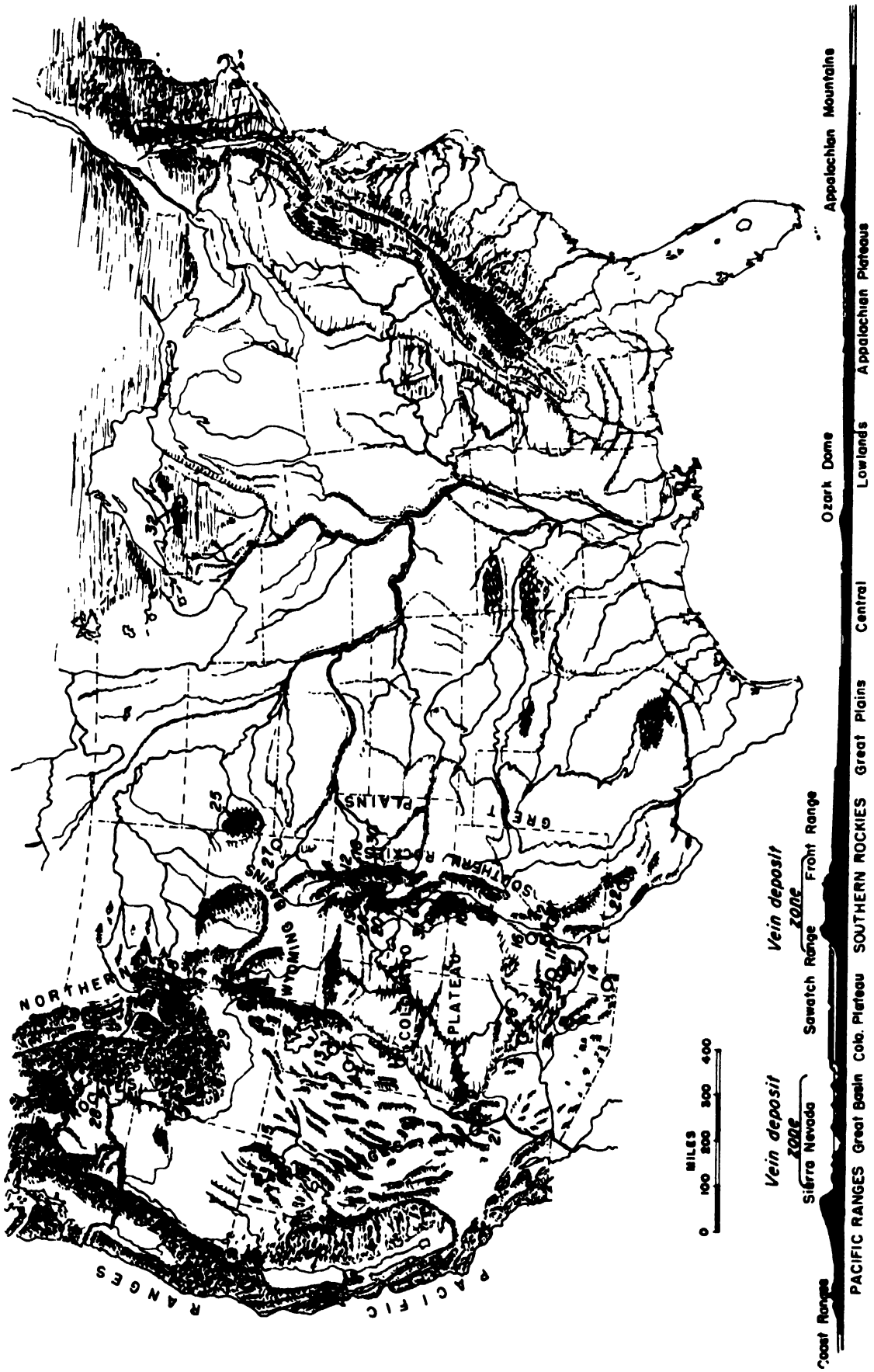


Figure 1. Distribution of significant uranium bearing vein deposits of the United States

granitic rocks), in metavolcanic rocks associated with metasediments, and unmetamorphosed arenaceous sediments.

A large proportion of the significant vein deposits is in granitic host rocks ranging in age from pre-Cambrian to late Tertiary (Nos. 1 through 13, Table II). The petrographic designation of these rocks varies from true granite to rocks as mafic as diorite, but the majority are in the granite-granodiorite-quartz diorite range. For the most part, the rocks are medium to coarse-grained, and are susceptible to extensive fracturing. In pre-Cambrian terrane they are commonly metamorphosed to granite gneiss.

In parts of New Mexico and Nevada, uraniferous vein deposits are in rhyolite. In Socorro County, New Mexico, the volcanic rocks are intermediate in composition (Nos. 3 and 14 through 16, Table II). These volcanics are Tertiary in age and are generally fresh, although subject to argillization and silicification adjacent to the veins.

The majority of the remaining significant vein deposits are in metasediments (Nos. 17 through 29, Table II). Quartzite (Nos. 26 through 29) and micaceous schist appear to be the most favorable hosts among the metasediments, although in places dolomite is predominant. Ages of these rocks range from Archean to Mississippian, but most of them are pre-Cambrian. Amphibolite and hornblende gneiss, interbedded with metasedimentary rocks, are predominant as favorable phases in Jefferson County, Colorado.[2]

Unmetamorphosed arenaceous sedimentary rocks are the host for uraniferous hydrocarbon vein in San Miguel County, Colorado, on the eastern margin of the Colorado Plateau (No. 31, Table II), and for a uraninite vein in nearby Saguache County (No. 6).

Mineralogic Types

Any attempt to categorize ore deposits by mineralogic types is complicated by unique local features and variations, and by exceptions to apparent natural groupings. However, at least five distinct mineral assemblages occur in the uraniferous vein deposits of the United States (Table I, A through E).

In a few deposits, where only the oxidized zone of the deposits has been explored, the major uranium minerals are secondary and no important metallic associates are present except iron, usually in the form of hydrated oxides. Silica minerals and fluorite may be present as gangue, but generally only in minor amounts. Typical examples of this mineralogic assemblage are the carnotite and autunite-bearing veins cutting the Sierra Nevada batholith, in Kern Canyon, east of Bakersfield, California (No. 1, Table II). Notable variations in this type are the uraniferous fluorite deposits of the Thomas Range, Juab County, Utah (No. 17, Table II).

One of the major mineral assemblages in uraniferous vein deposits in the world is the "siliceous-pyrite-galena" type.[1] This type is widely represented in the United States (see Table II) and has been the source of most vein-deposit ore produced in the country. These veins characteristically are highly siliceous and contain primary uraninite (most commonly in the variety pitchblende), iron and copper sulfides, galena, and commonly sphalerite. Many of them have an appreciable content of molybdenum minerals as well, and are characterized by abundant fluorite gangue (along with the quartz) and by heavy hematite staining. In the oxidized zones, the secondary uranium minerals most commonly are "sooty pitchblende", autunite, torbernite, and uranophane, and the other metallic oxides and hydrous oxides are typical oxidation products of base metal deposits. Perhaps the most prominent examples of this type are the deposits of the Marysvale district, Piute County, Utah, although they lack the rather common copper minerals present in other deposits in this mineralogic types.

Table I. Mineral Character*

Host Rock	*Type A*	*Type B*	*Type C*	*Type D*	*Type E*
1. Granitic Rocks	Kern Canyon, California	Marysvale, Utah†	Caribou Mine, Colorado		
2. Rhyolitic Extrusive Rocks	Moonlight Mine, Nevada		San Acacia Mine, New Mexico		
3. Metasediments (Schist and Gneiss)	Thomas Range District, Utah	Schwartzwalder Mine, Colorado†	Black Hawk Mine, New Mexico	Central City District, Colorado	
4. Quartzite	Red Bluff Mine, Arizona†		Sunshine Mine, Idaho		
5. Metavolcanics		Golden Gate Canyon District, Colorado			
6. Arenaceous Sedimentary Rocks	Iron Ore District, Michigan	Los Ochos Mine, Colorado†			Placerville District, Colorado

* Typical uranium vein deposits of the United States are: Type A: Uranium, silica and iron oxide minerals, with some fluorite but generally no appreciable gangue or other metallic associates. Secondary uranium minerals—mostly hydroxides. Type B: Silica-rich veins, containing uraninite, iron and copper sulfides, galena sphalerite and molybdenite; commonly characterized by abundant fluorite gangue. Type C: Uraninite associated with Co, Ni, Cu, and other base metal sulfides and silver; characterized by carbonic gangue, as well as lesser silica and barite. Type D: Uraninite associated with gold-bearing pyrite in siliceous veins. Type E: Uraniferous hydrocarbons.

† Consistent ore producer.

Table II. Geologic Character of Vein Deposits in the United States

Map number, name of deposit, and location by state and county	*Host rock (formation name and age; lithologic type)*	*Uranium minerals*	*Associated metallic minerals*	*Gangue*	*Structural features*	*Hydrothermal alteration*	*Geologic age of deposit*
1. Kern Canyon District, Kern Co., Calif.	Sierra Nevada batholith; late Cretaceous; granodiorite	Carnotite, autunite, sooty pitchblende	Pyrite, limonite, roscoelite, ilsemannite	No appreciable gangue (minor fluorite)	North-trending near vertical shear zones	Argillization	Post-Cretaceous
2. Pitchblende Strike Prospect, Sierra Co., New Mexico	Andesite, with included body of brecciated chart of El Paso Group (Ordivician)	Uraninite, uranophane	No appreciable metallic associates	Seconadry chert and fluorite	NW-trending chert inclusion in Tertiary andesite	No appreciable	Tertiary
3. Marysvale District, Piute Co., Utah	Quartz monzonite, granite, and Mt. Belknap volcanic rocks; Tertiary	Pitchblende, autunite, torbernite uranophane, other secondary minerals	Pyrite, magnetite, hematite, jordisite, ilsemannite, umohoite Mn oxides	Silica minerals, adularia, fluorite, minor calcite	N 65 E and NW trending steep fractures	Argillization; silicification	Late Tertiary
4. Copper King Mine, Larimer Co., Colorado	Pre-Cambrian granite with schist inclusions	Pitchblende	Pyrite, galena, sphalerite, Cu sulfides, Fe oxides, molybdenite	Quartz, minor siderite	Normal fault N 75° W, dip steeply SW	Sericitization, chloritization	Tertiary
5. W. Wilson Claims, Jefferson Co., Montana	Boulder batholith granitic rocks; Cretaceous	Uraninite, minor secondary minerals	Pyrite, sphalerite, galena, chalcopyrite, traces of Ag minerals	Silica minerals exclusively	"Siliceous reefs" trending N 60° E, dipping steeply southeast	Silicification, argillization and sericitization	Tertiary
6. Los Ochos Mine, Saguache Co., Colorado	Pre-Cambrian granite and included schist and gneiss, overlain by sandstone of the Morrison formation (Jurassic)	Pitchblende, autunite, uranophane	Marcasite, chalcopyrite, bornite, and ilsemannite	White and black crystalline quartz	Major E-W fault zone with NE trending cross faults	Silicification and argillization	Post-Jurassic
7. Merry Widow Mine, Grant Co., New Mexico	Granite and mafic dikes (pre-Cambrian) and intermediate to felsic dikes (Tertiary), binary granite	Meta-autunite, metatorbernite	Pyrite, chalcopyrite, specularite	Quartz	Complex faulting and fracturing	Sericitization, silicification	Tertiary
8. Comet-Gray Eagle District, Jefferson Co., Montana	Boulder batholith granitic rocks; Cretaceous	Uraninite	Pyrite, sphalerite, galena, chalcopyrite, argentite	Crystalline quartz	Generally NE to E trending "base-metal" veins	Argillization and sericitization	Tertiary
9. Wallapai Mining District, Mohave Co., Arizona	Pre-Cambrian granite, gneiss, and schist and Ithaca Peak granite (Mesozoic)	Uraninite, traces of autunite	Fe, Zn, Pb, Cu and Ag sulfides and sulfarsenides; Mn oxides	Quartz, calcite, siderite, rhodochrosite	Swarm of veins N 30° to 60° W, with steep dips	Very slight	Post-Mesozoic

Table II. Geologic Character of Vein Deposits in the United States (Continued)

Map number, name of deposit, and location by state and county	Host rock (formation name and age; lithologic type)	Uranium minerals	Associated metallic minerals	Gangue	Structural features	Hydrothermal alteration	Geologic age of deposit
10. Tusas Mtn. Prospect, Rio Arriba Co., New Mexico	Tusas granite and Hopewell series (Proterozoic); biotite granite and quartz-mica-schist	Uraninite, sabugalite, metatorbernite	Pyrite	Quartz-fluorite	N-trending bodies of included schist in granite	Chloritization	Tertiary
11. Plainview Prospect, Sierra Co., New Mexico	Granite (late-Archeozoic or early Proterozoic) biotite granite	Uraninite, uranophane	Galena, specularite	Chlorite, fluorite	NE-trending fracture zone	Chloritization	Tertiary
12. Caribou Mine, Boulder Co., Colorado	Caribou quartz monzonite stock (late Cretaceous)	Uraninite, mostly pitchblende	Pyrite, chalcopyrite, sphalerite, galena gersdorffite, argentite, proustite, native Ag	Quartz chalcedony calcite, siderite	Two sets of fractures: trend E and NE; dip 70°–90° N	Silicification, sericitization, argillization, chloritization	Tertiary
13. Erickson District, (Sheeprock Mts.), Juab Co., Utah	Tertiary granite	Pitchblende	Pyrite, oxidized Co, Cu, and Mn minerals	Fluorite	Narrow fissure veins	No appreciable	Tertiary
14. Antelope Wells Prospect, Hidalgo Co., New Mexico	Rhyolite (Tertiary)	Uraniferous opal	None	Quartz	Highly fractured zone	Silicification	Tertiary
15. Moonlight claims, Humboldt Co.,	Rhyolite (Tertiary)	Autunite, minor uraninite	Iron oxides	Fluorite	N-trending breccia zone, dipping 60° E	Argillization	Tertiary
16. San Acacia Mine, Socorro Co., New Mexico	Tertiary volcanic flows; amygdaloidal, intermediate volcanics	Secondary autunite, torbernite, tyuyamunite	Copper sulphides, native Cu	Copper carbonates	N-trending fault zone		Tertiary
17. Thomas Range District, Juab Co., Utah	Laketown and Fish Haven dolomites (Silurian and Ordovician)	Finely powdered uraninite disseminated in fluorite	Pyrite (minor)	Fluorite (major mineral)		None	
18. Schwartzwalder Mine, Jefferson Co., Colorado	Hornblende gneiss and mica schist of the Idaho Springs formation (pre-Cambrian)	Pitchblende, torbernite, autunite	Pyrite, galena, sphalerite, Cu sulfides and minor Mo and Mn minerals	Quartz, ankerite, adularia	NE-trending "silica reef" cut by NW-trending fractures	Silicification, sericitization, minor chloritization	Tertiary
19. Carroll Mine, Gilpin Co., Colorado	Idaho Springs schist (pre-Cambrian)	Pitchblende, torbernite	Pyrite, galena, Cu and Ag sulfides	Quartz	E-W fractures	Silicification, argillization	Tertiary
20. Cherokee Mine, Gilpin Co., Colorado	Quartz-biotite schist of the Idaho Springs formation (pre-Cambrian)	Pitchblende, minor gilpinite	Galena, pyrite, sphalerite, Cu sulfides, minor Ag minerals	Quartz, calcite, minor fluorite, siderite, rhodochrosite	Vein system striking E-W, dipping very steeply N; vertical in places	Silicification and minor sericitization	Tertiary
21. Green Mountain Mine, Clark Co., Nevada	Mississippian dolomite	Kasolite, dumontite	Malachite, cuprite, cerussite, limonite	Calamine	Steeply dipping breccia zone	None	?

(Continued on next page)

Table II. Geologic Character of Vein Deposits in the United States (Continued)

Map number, name of deposit, and location by state and county	Host rock (formation name and age; lithologic type)	Uranium minerals	Associated metallic minerals	Gangue	Structural features	Hydrothermal alteration	Geologic age of deposit
22. Van Horn District, Culberson Co., Texas	Pre-Cambrian schist and dolomite	Carnotite	Cu sulfides, pyrite	Silica minerals	North-trending shears, dipping easterly	No appreciable	Early Tertiary
23. Black Hawk Mine, Grant Co., New Mexico	Gneiss (pre-Cambrian) porphyritic, biotite, gneiss	Pitchblende	Pyrite, galena, chalcopyrite, niccolite, rammelsbergite, amaltite, native Ag	Carbonates, quartz	Fissure veins	Silicification	Late-Cretaceous or early-Tertiary (?)
24. Wood-Calhoun Mine, Gilpin Co., Colorado	Pre-Cambrian granite gneiss	Pitchblende	Gold-bearing pyrite, minor Cu and Zn sulfides	Quartz	E-W fissure veins	Silicification and minor sericitization	Tertiary
25. Bald Mt. Mining District, Lawrence Co., South Dakota	Pre-Cambrian schist and gneiss (metasediments)	Pitchblende, autunite	Gold-bearing pyrite, and chalcopyrite	Quartz	NE-trending fissure zone	Silicification	Tertiary
26. Red Bluff Mine, Gila Co., Arizona	Pre-Cambrian Dripping Springs quartzite	Finely disseminated pitchblende, metatorbernite and others	Pyrite, minor Cu and Pb sulfides	Minor fine-grained quartz	Dominant vertical fractures trending N 75° W and minor set trending N 20° E	Hematitization and minor silicification	Tertiary (?)
27. Silver Cliff Mine, Niobrara Co., Wyoming	Cambrian quartzite	Uranophane, minor uraninite	Pyrite, Ag and Cu sulfides	Calcite	High angle reverse fault, trending N 20° E	None	?
28. Sunshine Mine, Shoshone Co., Idaho	St .Regis quartzite member of the Belt Series (pre-Cambrian)	Pitchblende	Pyrite, arsenopyrite, chalcopyrite stibnite, tetrahedrite galena, erythrite	Quartz, siderite	Tensional fracture, trending E and dipping 60°–80° S	Hematitization	Generally considered Tertiary; pre-Cambrian according to Kerr and Kulp[5]
29. Surprise claims near Gibbonsville, Lemhi Co., Idaho	Quartzite of the Belt Series, (pre-Cambrian)	Autunite, metatorbernite	Limonite	Quartz	Fissure striking N 60° W, dipping steeply NE	Hematitization	?
30. Golden Gate Canyon District, Jefferson Co., Colorado	Amphibolite	Pitchblende, uranospinite, torbernite	Chalcopyrite, pyrrhotite, chalcocite, bornite	Feldspar, quartz	N to NW-trending tensional faults	No appreciable	Tertiary
31. Placerville District, San Miguel Co., Colorado	Dolores formation (Chinle) sandstone, conglomerate, and mudstone (Triassic)	Thucholite	Pyrite, sulfides of Cu, Pb, Zn, Mo, and Sb, erythrite	Calcite and barite	Fault striking N 45°–50° W, dipping 60° NE	Argillization	?
32. Michigan Iron District occurrences, North Peninsula	Upper Huronian, Iron formation, slates and quartzite	Uraninite	Iron minerals	No appreciable	Tensional fractures	No appreciable	Late pre-Cambrian

A third mineralogic type (Type C on Table I), also important among world uranium producers, has been described as the "nickel-cobalt-native silver ore type".[3] This type is represented in the United States but contributes only a minor part of total production. The veins are characterized by uraninite (usually in the variety pitchblende) associated with cobalt, nickel, copper, and other base metal sulfides, and silver. Carbonate minerals are the predominant gangue, along with lesser silica minerals and occasional barite. Secondary alteration of this ore type largely forms "sooty pitchblend", but torbernite, autunite and other secondary minerals may be present. As in Type B, heavy hematite staining is characteristic. The Black Hawk Mine, Grant County, New Mexico, is perhaps the most typical example of this assemblage in the United States.

A fourth mineralogic type consists of pitchblende associated with gold-bearing pyrite in highly siliceous veins. Several small deposits in the Quartz Hill district, Gilpin County, Colorado, typify this category.

A distinctive mineralogic vein type, in which the uranium mineral is the hydrocarbon thucholite, occurs in the Placerville district, San Miguel County, Colorado. This deposit, which is similar to the Nicholson Mine, Lake Athabaska district, Saskatchewan, also contains a complex assemblage of iron, copper, lead, zinc, molybdenum and antimony sulfides, and erythrite.

Structural Characteristics

As in the majority of the uraniferous vein deposits of the world, those in the United States deposits are characterized by "open" structural features. Almost without exception, the vein deposits lie in districts where the rocks have been subjected to tensional forces at the time of mineral deposition. In detail, the ores show typical evidence of open-space filling in nearly all cases. The intensity and distance from fractures to which replacement by uranium minerals of host rock has taken place depends on the nature of the host itself. In quartzite (as in the Red Bluff Mine of Arizona) or in dolomite (as in the Thomas Range of Utah) replacement by uranite and associated minerals extends several feet outward from the controlling fractures.

Hydrothermal Alteration

Hydrothermal alteration effects, of varying degree, are evident adjacent to nearly every uraniferous vein deposit in the United States (see Table II). The chemical and mineralogic nature of these effects varies markedly from one environment to another, and, of course, is determined largely by the complex physiochemical interrelationship of the host rock and the invading solutions. Silicification is prominent, where the invading solutions are rich in silica, and particularly in granitic host rocks. Argillization is most common in igneous host rocks of all types. The nature of such clay alteration has been thoroughly studied by Kerr and associates[4] at Marysvale, Utah. Sericitization is prevalent where abundant potassium is available, as in chloritization, where iron and silica are both abundant. Hematitization is one of the most prominant features of uranium-bearing hydrothermal veins and adjacent rocks, throughout the world. In the United States, this effect is particularly evident in metasedimentary host rocks.

Geologic Age of Deposits

As shown in Table II, there is a remarkable consistency in evidence that all the uraniferous vein deposits of the western United States were formed in various Tertiary periods, closely related in time to the igneous activity of that era. The one piece of conflicting evidence is in age determination by Kerr and Kulp[5] indicating that the ores of the Sunshine Mine, Idaho, are pre-Cambrian. In Michigan, the deposits appear to be late pre-Cambrian, as are all others that have been determined in the Canadian Shield further to the north.

Origin of the Deposits

In the United States, as in other parts of the world, the following postulations for the employment of uranium minerals in vein deposits appear valid:

1. Because the more felsic magmas, and intrusive and extrusive rocks derived from them, are the most uraniferous known, the residual fluids forming hydrothermal solutions at the end of a granitic or syenitic magmatic cycle constitute a rich source for uranium.
2. These uraniferous solutions, under high pressure and temperature, follow well-developed tensional, open-space fractures.
3. Uranium, in the uranyl ion, begins to encounter conditions favorable for precipitation in the higher-temperature mesothermal to hypothermal zones. The host is most commonly the parent granitic rock. If the solutions contain a complex assemblage of base metal ions, the gold-uranium, or Co-Ni-Ag type of ore may be deposited in the mesothermal zone. Metasedimentary and metavolcanic rocks appear to be the most favorable hosts for the precipitation of this type of assemblage. Fine-grained dissemination of hematite in and around the veins also typifies these deposits.
4. The simpler ore types (Type A and B, Table I) appear to be deposited throughout a larger range of temperatures and pressures, approaching the epithermal zone at the lower end, and preferentially in felsic instrusives. These types appear to be particularly susceptible to subsequent, nearsurface oxidation effects, giving rise to the "sooty pitchblende" variety of uranium oxide and variable combinations of secondary phosphates, sulfates, arsenates, vanadates, hydrous silicates and hydrous oxides. Such host rocks are also commonly affected by the alteration effects of the hydrothermal solutions, as expressed by the zoning of clay, silica, chlorite, and other "alteration" minerals. Hence, caps of secondary minerals and alteration commonly characterize the deposits down to as much as 200 feet from the surface, and extensive physical exploration is necessary to ascertain the true primary nature of the deposit.

In the western United States, the emplacement of uraniferous vein deposits as described above, has taken place in a broad, horseshoe-shaped zone surrounding the Colorado Plateau, Wyoming Basin, and Black Hills districts of disseminated ores in sedimentary rocks. These deposits occur in rocks in which the migration of ore solutions and precipitation of minerals from them must have been accomplished more easily through one-spaced fractures rather than through pore spaces. There is a strong suggestion that the "uranium province" of the entire western United States is the result of a complex series of inter-related metallogenic processes, of which the emplacement of the vein deposits was an integral part.

REFERENCES

1. Everhart, D. L. and Wright, R. J., *The Geologic Character of Typical Pitchblende Veins,* Eco. Geol. 48: 77–95 (1953).
2. Adams, J. W., Gude, A. J., III and Berone, E. P., *Uranium Occurrences in the Golden Gate Canyon and Ralston Creek Area, Jefferson Co., Colorado,* US Geol. Survey TEMR–154 (1951).
3. Bastin, Edson S., *The Nickel-Cobalt-Native Silver Ore Type,* Eco. Geol. 34: 1–40 (1939).
4. Kerr, P. F., et al. *Alteration and Uranium Mineralization at Marysvale, Utah,* Geol. Soc. Amer. Memoir (in press) (1955).
5. Kerr, P. F. and Kulp, J. L., *Pre-Cambrian Uraninite, Sunshine Mine, Idaho,* Science, 115: 86–88 (1952).

Pitchblende Deposits in the Central City District and Adjoining Areas, Gilpin and Clear Creek Counties, Colorado

By P. K. Sims and E. W. Tooker,* USA

Pitchblende was first discovered in the United States in 1871 on the dump of the Wood mine on Quartz Hill, a mile southwest of Central City. Since that time, the Central City district has been the source of small amount of high-grade uranium ore and more than 100,000 pounds of U_3O_8 have been shipped from the region. Most of the ore was mined prior to 1917 and was used as a source of radium. Until recently, when pitchblende production from the Marysvale district, Utah, surpassed the total yield of the Central City district, the Central City region was this country's principal source of pitchblende ore. The uranium is in sulfide-bearing quartz veins of early Tertiary age.

The Central City district (lat. 39° 48′ N, long. 105° 30′ W) is in southern Gilpin County, Colorado, about 30 miles west of Denver, on the east slope of the Front Range. The adjoining mining districts —Idaho Springs, Lawson-Dumont-Fall River, Freeland-Lamartine, and Chicago Creek—are south and southwest of Central City. The area is mountainous and ranges in altitude from 7500 feet to about 11,000 feet. The region is in the mineral belt of the Front Range, an area of coextensive Laramide intrusives and mineral-producing districts.

The geology of the Central City region has been described by Bastin and Hill,[1] and the geology of the area to the south and southwest, in North Clear Creek County, has been described by Spurr, Garrey, and Ball.[2] Recently Lovering and Goddard[3] presented an excellent summary of the geology of all the mining districts in the Front Range. The uranium deposits have been studied by several geologists and mining engineers; the most important publications resulting from these investigations are by Pearce,[4] Moore and Kithil,[5] Rickard,[6] Alsdorf[7] and Bastin.[8,9]

GEOLOGIC SETTING

The Central City district and adjoining areas are in the core of the Front Range, a region consisting dominantly of complex metasedimentary, metasomatic, and intrusive igneous rocks of Precambrian age. These rocks are cut by faults of Laramide age, and by many small dikes and plugs of intrusive porphyries of early Tertiary age.

In the Central City region the Precambrian rocks consist of about 50 per cent metasedimentary rocks and 50 per cent granitic rocks. Interlayered biotite gneisses—biotite-quartz-plagioclase gneiss and sillimanitic biotite quartz gneiss—are the most abundant metasedimentary rocks, but lime-silicate rocks and amphibolites are locally present. The granitic rocks are principally quartz monzonite gneiss, granite gneiss and pegmatite, granodiorite, biotite-muscovite granite, and a variety of pegmatites. These rocks are folded along northeast-trending axes. The folds are mostly open and have moderate-dipping limbs, but locally they are closed. The Tertiary intrusives range in composition from granodiorite to granite; monzonites and bostonites are the most abundant and widespread types. The fault pattern is similar throughout the Central City region, but it differs somewhat in detail from area to area. In the Central City district and the nearby Fall River area, the earliest faults persistently trend northwest and dip steeply north. Later faults are generally less persistent and strike from east to north-northeast; they generally dip steeply to moderately and have small displacements. The faults in order of age sequence trend northwest, east, east-northeast, northeast, and north-northeast.

The veins in the Central City district, and adjoining areas, contain gold-, silver-, copper-, lead-, zinc- and uranium-bearing ores and formed as hydrothermal fissure-fillings in the faults. Most of the ore is valued principally for its gold and silver content.

The structure and mineralogy of the veins are similar to those described by Lindgren,[10] as typical for mesothermal deposits. The veins range from single, well-defined fissure-fillings to complex branching lodes. Although some veins or vein systems are a mile or more long, most are not more than a few hundred feet long. The veins have been mined to depths as great as 2200 feet. Vein widths vary from a fraction of a foot to several feet but they average a foot or less. The fissures are moderately persistent in strike and dip, and changes in trend and dip commonly are the loci of ore shoots. The walls commonly are smooth and regular.

The wall rocks adjacent to the veins are altered to varying degrees, characteristically with an envelope of silicified and sericitized wall rock not exceeding a root in thickness, surrounded by a wider zone of argillized rock.

* US Geological Survey. Including work by A. A. Drake, J. E. Harrison, C. C. Hawley, F. B. Moore, J. D. Wells, A. E. Dearth and R. H. Moench.

The principal ore minerals are sulfides and sulfosalts of iron, copper, lead, and zinc; pitchblende, silver-bearing sulfo-salts, and free gold are locally important. Quartz is the dominant gangue mineral, but calcite, ankerite, rhodochrosite, and siderite are present in some veins.

The veins in the region can be classified according to mineralogy into two main types, one charactized by dominant pyrite and the other by galena and sphalerite. Composite type veins are present at places, and consist of minerals characteristic of both the pyritic type and galena-sphalerite type veins. Veins of the pyritic type consist predominantly of pyrite and quartz with subordinate chalcopyrite, tennantite, and at places other metallic minerals. Most of the dollar value of these ores is in gold. Veins of the galena-sphalerite type contain dominant sphalerite and galena; pyrite is present in minor amounts and tennantite and chalcopyrite are local components. At places veins of this type, particularly in the Lawson-Dumont-Fall River district, contain rich silver-bearing ores. The composite type ores are the result of two periods of mineralization. Most commonly veins of the pyritic type have been reopened and minerals characteristic of the galena-sphalerite type veins have been introduced. The veins of the composite type have been the principal sources of gold-bearing ore in the Central City district.

A zonal arrangement of the ores is shown by the distribution of veins of different mineralogic types. At Central City a core area about 2 miles in diameter containing veins of the pyritic type is surrounded by a peripheral area containing veins of the galena-sphalerite type; an intermediate zone contains veins of the composite type. Veins show similar but less well-developed hypogene zonal arrangement in the adjoining Lawson-Dumont-Fall River district. In the Freeland-Lamartine district, the individual veins show zoning, with central segments of pyritic type ore passing laterally into galena-sphalerite type ore.[11]

URANIUM DEPOSITS

Uranium is a local constituent of the veins in the Central City region, where it is associated with veins of all mineralogic types but is most abundant in composite and galena-sphalerite type veins. The pitchblende was deposited early in the sequence of vein formation, essentially contemporaneous with quartz, and before most of the other ore minerals were formed. At Central City and the adjacent Fall River area, southwest of Central City, the significant pitchblende deposits occur only along veins that trend northwest, west-northwest, east, and east-northeast. The pitchblende is in shoots, small pods, or lenses along the veins; the shoots are small, seldom exceeding a few tens of feet in maximum dimensions along the vein and a few inches in width. Most of the pitchblende ore shipped from the region has been selectively mined and hand sorted and has ranged in grade from less than one per cent to as much as 65 per cent U_3O_8. The secondary uranium ores that have been shipped are quantitatively unimportant.

DISTRIBUTION OF URANIUM

More than 100 abnormally radioactive localities have been discovered during this investigation in an area of approximately 50 square miles, in the Central City region. Of the more than 100 localities, 40 per cent have material containing more than 0.10 per cent equivalent uranium, and about half of these localities are considered on the basis of geology to be potential sources of uranium ore. Most of the deposits that have been mined, and most of the significant prospects, are in the Central City district; a few promising occurrences are in the Lawson-Dumont-Fall River, Idaho Springs, and Chicago Creek districts.

The mines containing significant deposits of uranium occur in clusters or small groups that are closely spaced geographically, and most of the other localities having high abnormal radioactivity occur nearby.

Recent work has disclosed that the distribution of uranium deposits shows no distinct relation to the pattern of hypogene mineral zoning, contrary to the previous views of Leonard.[12]

MINERALOGY AND PARAGENESIS

Pitchblende is the primary uranium mineral in the vein deposits; in the oxidized parts of the veins this mineral has been altered to a variety of green and yellow secondary uranium-bearing minerals; principally torbernite, metatorbernite, and autunite. Uranium-bearing carbonaceous material, possibly thucolite, occurs sparsely at one mine in the Idaho Springs district.

The pitchblende ranges in all gradations from a hard, black, dense substance with a pitch luster and a colloform to massive texture, to a soft, porous, fine-grained, sooty material with a dull luster. Pitchblende occurs in veinlets, irregular aggregates of spheroidal grains, pellets, and irregular forms. The veinlets and spheroidal forms typically have shrinkage cracks, particularly radial cracks, that at places are filled with later vein minerals. All types of forms are locally fractured and brecciated.

The hard dense pitchblende occurs in the unaltered veins, and in certain mines it gives way to soft, porous pitchblende in the upper parts of the veins. X-ray diffraction powder photograph patterns are sharp for the hard dense pitchblende; but there is a loss of definition in the pattern of the soft sooty material. Brooker and Nuffield[13] concluded from a study of pitchblende in the Lake Athabaska region, Canada, that loss of definition in patterns was related to an increase in the UO_3/UO_2 ratio of the pitchblende.

The pitchblende in the Quartz Hill area of the Central City district contains unusual quantities of zircon; locally the pitchblende from this and other areas is relatively high in molybdenum. A pitchblende sample from the Fall River area contains several per cent of nickel.

In addition to the principal secondary minerals torbernite, metatorbernite, and autunite, small amounts of kasolite, dumonitite, and zippeite have been identified.

Aside from a local occurrence of pitchblende in the western part of the Idaho Springs district, pitchblende in the Central City region was the first metallic mineral to be deposited in the veins. It formed essentially contemporaneously with quartz; pyrite began to crystallize before all of the pitchblende was deposited. The other principal vein-forming minerals—sphalerite, chalcopyrite, tennantite, and galena—clearly are later than the pitchblende. The carbonate minerals, which at places form the gangue, all appear later in the paragenetic sequence than pitchblende.

STRUCTURE

Pitchblende is present in only a small per cent of the veins in the Central City region. Where present it occurs in ore shoots or smaller lenses and pods that are separated by vein material essentially barren of uranium. Within the shoots the pitchblende may be either in the principal sulfide ore-bearing veins or in subsidiary veinlets in the adjacent walls.

The uranium-bearing ore shoots in the Central City district are small, and although some have a systematic pattern of occurrence, others are erratically distributed along a vein. Little is known of the uranium-bearing ore shoots in the other districts. At some of the mines in the Central City district these shoots occur within zones of favorable ground (or zones of ore shoots) that rake in a westerly direction. The individual shoots vary somewhat in size but nevertheless have comparable dimensions. The larger shoot in one mine—the Carroll mine—has a horizontal (or stope length) of about 15 feet, height of more than 40 feet, and an average thickness of about 6 inches. The other shoots in this mine are slightly smaller. The ore shoots in the mine are arranged en echelon within the zone of favorable ground, and their axes plunge directly down the dip of the vein.

Within the shoots the pitchblende-bearing ore occurs in a variety of structures. Locally it forms tabular bodies as much as several tens of feet long and high in the plane of the vein, and with maximum widths of about 15 inches; but generally these bodies are smaller. At other places the pitchblende ore occurs as individual seams a few feet in maximum length and generally not more than an inch or two in width, or as local concentrations at the junction of two or more fractures.

RELATION OF DEPOSITS TO WALL ROCKS

The wall rocks of the pitchblende deposits in the Central City district and adjoining areas include a wide variety of Precambrian rocks and at one place a bostonite porphyry of Tertiary age. The most common wall rocks are felsic rocks—quartz monzonite gneiss, granite pegmatite, and biotite-quartz-plagioclase gneiss—but locally the wall rock is amphibolite or other mafic rocks. In the Fall River area, southwest of Central City, however, pitchblende deposits occur in three veins where they intersect a single type of lime-silicate gneiss wall rock that consists predominantly of garnet and quartz; uranium occurrences have not been found where the veins intersect other types of wall rock.

The altered wall rocks associated with the primary veins are characterized by pyritiferous, silicified, and sericitized rock adjacent to the veins surrounded by a broader outer zone of argillized rock. The width and mineralogy of the altered halo vary, but the differences cannot be correlated wholly with either the type of mineralization or the type of wall rock. Accordingly, altered rocks cannot be used effectively as a guide to primary uranium deposits.

LOCALIZATION OF ORE

The factors largely responsible for localizing the uranium-bearing ore were the character of the conduits followed by the ore-bearing fluids, structure and lithology of the wall rocks, and the composition and location of the source magma.

The significant uranium deposits occur along certain fracture sets and are absent in others. The important deposits in the Central City district, and also the adjacent Fall River area, occur in veins that trend northwest, west-northwest, east, or east-northeast. These veins occupy the oldest Laramide fractures in this part of the region. The younger northeast-trending fractures either were not in existence at the time of uranium mineralization or they were not open to provide access to the solutions.

The pitchblende filled openings in the pre-mineral fault fissures; there is little if any evidence of replacement. The openings were produced largely by shear but locally resulted from tension. Shear stresses produced open spaces at irregularities along both the principal fault fissures and the subsidiary branching fractures that extended for short distances into the walls. Tension fractures were formed principally in wall rock horses between splits in veins.

Another factor that affected the localization of all types of ore was the structure and lithology of the wall rocks. In many places a vein is tight in one rock but is open and ore-bearing in another rock. This control of the ore is related principally to the relative competency of the different rocks and is dependent upon the physical behavior of the rocks to stresses that produced the fractures. The differences in the width of the fracture zones is most marked where the wall rocks differ greatly in lithology and where the foliation and layering in these rocks are intersected by the fractures at a large angle. At many mines in Central City the veins are wide and ore-bearing in quartz monzonite gneiss or pegmatite wall rock but are weak and nearly barren in biotite-quartz-plagioclase gneiss wall rock.

Calcium-rich or iron-rich wall rocks may have been favorable chemically for the deposition of some of the uranium-bearing ores in the Front Range.[14] The marked association of uranium with garnet and quartz-rich lime-silicate rocks in the Fall River area is thought to have resulted from the chemical control of uranium deposition but may be due in part to the relative competency of the rock to fracturing. It has been inferred in other areas throughout the

world that wall rocks of similar composition to those in the Fall River area have been largely responsible for the precipitation of uranium from ore-forming fluids.

The uranium-bearing veins in the Central City district are closely related in space to one type of Tertiary intrusive rock, quartz bostonite. Because of this association Alsdorf.[7] Lovering and Goddard,[8] and Phair[15] have concluded that bostonite magma was the probable source for the uranium-bearing ore fluids. Phair has demonstrated a magmatic enrichment in both uranium and thorium in the quartz-bostonite, and he has proposed a possible mechanism that would account for the concentration of uranium with respect to thorium in the derived residual aqueous fluids. The clustering of significant uranium deposits in relatively small areas and the apparent lack of correlation between the uranium deposits and the pattern of hypogene mineral zoning together with the data presented by Phair, suggest to the writer that the uranium deposits very likely had a source different from that of the precious metal and base-metal ores.

SUPERGENE ALTERATION

In the oxidized parts of the veins pitchblende was leached and altered where the meteoric waters were acid, and green-colored secondary uranium minerals were deposited where the solutions were nearly neutral. For the most part the oxidized portions of the veins were impoverished, but locally, particularly in the lower part of the oxidized zone, the veins were enriched in uranium.

The meteoric waters were relatively acid along veins of the pyritic- and composite-types, and the pitchblende was leached and dissociated and uranium was not reprecipitated as secondary minerals. The solutions were only slightly acid along veins of the galena-sphalerite type, because these sulfides provide less acid than pyrite on weathering. By reaction with the wall rocks the solutions were locally neutralized and uranium was reprecipitated at places as secondary minerals.

One vein on Nigger Hill belonging to the galena-sphalerite type, which has been opened from the surface to a depth of about 250 feet, shows that pitchblende was completely leached from surface to a depth of about 100 feet. At a depth of approximately 100 feet, and possibly above this depth, the uranium was reprecipitated from the supergene solutions as torbernite, an unidentified yellow uranium-bearing mineral, and an unknown form. In this environment the uranium was dispersed through the vein by the supergene solutions and, except locally, the tenor was decreased below that of the primary deposits. Below a vertical depth of about 100 feet, pitchblende was not dissociated but it was locally leached to variable degrees; the uranium content of the leached material is far below the equivalent uranium content, indicating relative enrichment in radium and other disintegration products. In the transition zone between leached and unaltered pitchblende, the pitchblende is partly to completely converted to a soft, sooty, porous substance.

Along two other uranium-bearing veins on Nigger Hill, metatorbernite occurs throughout the lower part of the oxidized zone, but nothing is known concerning the unaltered vein material. One of the veins is barren to a depth of about 25 feet; from depths of 25 feet to the bottom of the deepest workings at 43 feet, metatorbernite occurs sporadically along the vein zone, primarily replacing montmorillonite in the altered amphibolite wall rocks. Metatorbernite is sparse within the sulfide-bearing vein, and all of the pitchblende has been dissociated in this environment. Dump samples from the oxidized part of another vein show that the kasolite is present locally where the vein has been almost entirely altered to limonite. Several samples of altered biotite-quartz-plagioclase gneiss wall rock found on the same dump contain abundant metatorbernite. The metatorbernite replaced the altered gneiss adjacent to the vein and was concentrated in the transition zone between moderately and intensely altered gneiss—in the zone where biotite is bleached and partly altered to illite-montmorillonite type clay minerals.

The work of Phair and Levine[16] on the differential leaching of uranium, radium, and lead from pitchblende in H_2SO_4 solutions clearly demonstrates the processes that take place in the oxidized zone. In an oxidizing acid environment uranium is leached and both radium and lead tend to be fixed approximately proportionately. During the alteration, pitchblende, which consists of variable proportions of UO_2 and UO_3 is oxidized; UO_3 forms at the expense of UO_2; and UO_3, being more soluble than UO_2 in dilute acid solutions, is preferentially leached with respect to UO_2, radium, and lead. After dissociation of the pitchblende the uranium presumably can be precipitated only by neutralizing the solutions. Neutralization of the slightly acid solutions in the supergene zone of veins of the galena-sphalerite type was accomplished largely by reaction with the wall rocks, and the uranium was reprecipitated as metatorbernite and other secondary minerals. The supergene solutions in veins of the pyritic and composite types, however, originally highly acid because of the abundance of iron-sulfide, were not neutralized, and the dissolved uranium was carried out and probably dispersed in surface waters.

GRADE OF PRIMARY AND SECONDARY DEPOSITS

The pitchblende in the primary deposits generally is in small, high-grade seams that are much narrower than mining widths, and the grade of the shipping ore is variable, depending to a large extent upon the care taken in mining and in sorting. Where the pitchblende bodies are on the vein walls adjacent to the country rock, they generally can be mined separately, commonly by stripping. Probably this type of ore accounted for most of the shipping product from the mines on Quartz Hill. Pitchblende seams that are intimately mixed with other ore minerals in the vein, however, cannot be mined separately, and sorting is

tedious. The pitchblende seams that are present in the walls of the sulfide-bearing veins can be mined profitably only where the seams are moderately continuous and are closely spaced over mining widths. The uranium ore that was shipped prior to 1952 was produced largely as a byproduct of gold mining and was concentrated by hand sorting. Some of it contained as much as 65% U_3O_8. The primary ore shipped recently is much lower in grade and seldom exceeds 2% U_3O_8; some is recovered by gravity separation on Wilfley concentrating tables, and some crudely hand-sorted and shipped direct from mines.

The grade of the secondary uranium deposits commonly is lower than that of the primary deposits. These occurrences generally have not been prospected or mined, however, and little is known concerning the grade of individual deposits. At least one secondary deposit—at the Two Sisters mine—has substantial ore grade material. The secondary minerals for the most part coat fracture surfaces in and adjacent to the veins. At the Martha E mine in the Chicago Creek area, torbernite and autunite occur as pods or flakes along joints or foliation planes in the footwall of a moderately dipping shear zone containing sooty pitchblende and hydrous iron oxide. The average grade of 21 samples is 0.031 per cent uranium. A shipment of 2920 pounds which was selected by hand-sorting assayed 0.14 per cent uranium. Secondary uranium minerals at the McKay shaft workings, R.H.D. mine, on Nigger Hill, replace altered amphibolite; the average grade of the ore is approximately 0.10 per cent uranium, but several tons containing approximately 0.20 per cent uranium could be hand-picked. Samples of metatorbernite-bearing altered biotite-quartz-plagioclase gneiss from the dump of the Two Sisters mine, Nigger Hill, contain as much as 6.11 per cent uranium. The metatorbernite replaces the gneiss and locally coats fractures. 510 lb. from the dump assayed 1.53% uranium.

AGE AND ORIGIN

Age determinations by the Pb^{206}/U^{238} and Pb^{207}/U^{235} methods upon pitchblende samples from the Wood and Iron mines, in the Central City district, indicate a range in age for the deposits of from 55 to 70 million years.[17] Holmes[18] based the beginning of the Tertiary period on similar ages from Pb/U ratio determinations.

Phair[15] concluded that the uranium is genetically related to quartz bostonite magma, and the writer is in general agreement with this hypothesis. Phair proposed that uranium-rich solutions given off by a cooling quartz bostonite magma at depth rose along planes of weakness provided by porphyry dikes and deposited the uranium in the veins.

FUTURE OF DISTRICT

The uranium-bearing ore bodies that have been found in the Central City district and adjoining areas are small but generally high in grade. They have been mined largely in conjunction with precious-metal and base-metal ores, mostly as a byproduct of gold mining. There is little reason to expect the discovery of bodies that are larger than those previously mined, and accordingly future production of uranium from this region can be expected to come from scattered small pods and ore shoots distributed through the uranium-bearing veins. These bodies can be mined most economically together with the precious- and base-metal ores.

REFERENCES

1. Bastin, E. S. and Hill, J. M., *Economic Geology of Gilpin County and Adjacent Parts of Clear Creek and Boulder Counties, Colorado,* US Geological Survey Professional Paper 94 (1917).
2. Spurr, J. E., *et al., Economic Geology of the Georgetown Quadrangle,* US Geological Survey Professional Paper 63 (1908).
3. Lovering, T. S. and Goddard, E. N., *Geology and Ore Deposits of the Front Range, Colorado,* US Geological Survey Professional Paper 223 (1950).
4. Pearce, Richard, *Some Notes on the Occurrence of Uraninite in Colorado,* Colorado Scientific Society Proceedings 5: 156–158 (1895).
5. Moore, R. B. and Kithil, K. L., *A Preliminary Report on Uranium, Radium, and Vanadium,* US Bureau of Mines Bulletin 70, Mining Technology 2: 43–67 (1913).
6. Rickard, Forbes, *Pitchblende from Quartz Hill, Gilpin County, Colorado,* Mining and Scientific Press, 106, 23: 851–856, San Francisco (1913).
7. Alsdorf, P. R., *Occurrence, Geology and Economic Value of the Pitchblende Deposits of Gilpin County, Colorado,* Economic Geology 11: 266–275 (1916).
8. Bastin, E. S., *Geology of the Pitchblende Ores of Colorado,* US Geological Survey Professional Paper 90 (See p. 1–5) (1914).
9. Bastin, E. S., *Discussion. Occurrence, Geology, and Economic Value of the Pitchblende Deposits of Gilpin County, Colorado,* Economic Geology II: 681–685 (1916).
10. Lindgren, Waldemar, *Mineral Deposits,* 4th edition, McGraw-Hill Co., Inc., New York (p. 530–2) (1953).
11. Harrison, J. E., *Relation Between Fracture Pattern and Hypogene Zoning in the Freeland-Lamartine District, Clear Creek County, Colorado,* Geological Society of America Bulletin 64: 1431 (1953).
12. Leonard, B. F., *Relation of Pitchblende Deposit to Hypogene Zoning in the Front Range Mineral Belt, Colorado [abstract],* Geological Society of America Bulletin 63: 1274–1275 (1952).
13. Brooker, E. J. and Nuffield, E. W., *Studies of Radioactive Compounds: IV—Pitchblende from Lake Athabaska, Canada,* American Mineralogist 37: 362–385 (1952).
14. Adams, J. W. and Stugard, Frederick, Jr., *Wall rock control of certain pitchblende deposits in Golden Gate Canyon, Jefferson County, Colorado* (in preparation).
15. Phair, George, *Radioactive Tertiary Porphyries in the Central City District, Colorado, and Their Bearing upon Pitchblende Deposition,* US Geological Survey Trace Elements Investigations Report 247, (TEI-247, US Atomic Energy Commission Technical Information Service, Oak Ridge, Tennessee) (1952).
16. Phair, George and Levine, Harry, *Notes on the Differential Leaching of Uranium, Radium, and Lead from Pitchblende in H_2SO_4 Solutions,* Economic Geology 48: 358–369 (1953).
17. Phair, George, written communication.
18. Holmes, Arthur, *The Construction of the Geological Time Scale,* Geological Society of Glasgow Transactions 21, pt. 1: 17–152 (1946).

Uranium Deposits of the Boulder Batholith, Montana

By G. E. Becraft,* USA

The Boulder batholith in western Montana extends from a few miles south of Helena to about 20 miles south of Butte, and covers an area of about 1500 square miles. Although the area is mountainous, the topography is not rugged but is characterized by smoothly rounded ridges commonly about 1000 feet above the major valleys. Most of the higher valleys were occupied by glaciers in the Pleistocene epoch, but typical alpine cirques are rare.

Early in the spring of 1949, uranium minerals were discovered in veins in the batholith near Boulder, Montana (Fig. 1), and subsequently, more than 100 radioactivity anomalies have been detected. Detailed geologic mapping of the batholith and a study of the uranium deposits were begun in 1950. Previous geologic work done in the vicinity of the uranium deposits had been of a reconnaissance nature in connection with studies of the mineral deposits in and near the batholith. The most complete studies are by Knopf,[1] Billingsley and Grimes,[2] and Pardee and Schrader.[3] The author is indebted to the geologists of the US Geological Survey who have mapped in the area and have made their information available to him for this report, and particularly to D. M. Pinckney, S. Rosenblum, and D. Y. Meschter for their aid in the study of the uranium deposits.

GEOLOGY

The principal rocks of the area are quartz monzonite and granodiorite of the Boulder batholith. These rocks, with a few notable exceptions, do not have a great range in mineralogic or chemical composition, but they have a considerable range in texture and fabric. In the detailed mapping the batholith was divided into 23 units based principally on the textural differences apparent in hand specimens.

The rocks of the batholith cut sedimentary rocks ranging from Precambrian to Mesozoic in age near the northern margin of the batholith, and elsewhere the batholith cuts Cretaceous volcanic rocks. The volcanic rocks consist of coarse- and fine-grained fragmental rocks, mainly of andesitic composition, tuff flows[4] of quartz latitic composition, and subordinate lava flows. Associated with the volcanic rocks are numerous diorite porphyry intrusive bodies. The distribution of the prebatholithic volcanic rocks suggests that only the upper part of the batholith has been uncovered in the area of the uranium deposits.

The batholithic rocks and locally the older volcanic rocks near the margin of the batholith have been intruded by silicic rocks—including aplite, alaskite, alaskite-porphyry, and pegmatite—all designated as alaskite on Fig. 1. The silicic rocks occur principally as dikes, but gently dipping sheets are common, and a few large bodies of irregular shape have been recognized. Most of the alaskite is confined to a moderately well-defined, northeastward-trending zone that approximately parallels the eastern boundary of the batholith.

The youngest igneous rocks in the area are rhyolite and dacite. The rhyolite in the western part of the area occurs almost exclusively as flows, remnants of which now cap mountains and ridge crests, whereas most of the small rhyolite bodies shown in the northeastern part of Fig. 1 are plugs or dikes. The dacite occurs as tuff beds and dikes. Almost all of the dikes are in a northeastward-trending zone somewhat more sharply defined than the zone of alaskite intrusions (Fig. 1). The large area of dacite near the center of the map consists mainly of tuff and other fragmental rocks and is cut by many small dacite dikes. Most of the dacite tuff in the area occurs as valley fill or as remnants on valley walls. The surface on which the dacite tuffs and rhyolite flows rest indicate that extensive erosion took place between the intrusion of the batholith and the extrusion of the volcanic rocks.

There is no direct evidence of the relative ages of the dacite and rhyolite because the two rocks have not been observed in contact, but geomorphic evidence suggests that the rhyolite may be older than the dacite. The rhyolite, which appears to be more resistant to erosion than the rather poorly consolidated dacite tuff, caps ridge crests and appears to have been deposited on a surface of relatively low relief. The dacite tuff appears to have accumulated in valleys at a somewhat later stage of erosion.

STRUCTURE

Detailed mapping in the batholith has shown many strong northeast- and east-trending structures. Several gross features of the area, such as the long dimension of the batholith, the zone of alaskite intrusions, the belt of dacite dikes, and many of the larger stream valleys, are oriented N 20° E to N 30° E. Numerous veins, shear zones, and faults fall into two dominant sets—a generally east-trending set, and a N 60° E-trending set, both of which dip

* US Geological Survey.

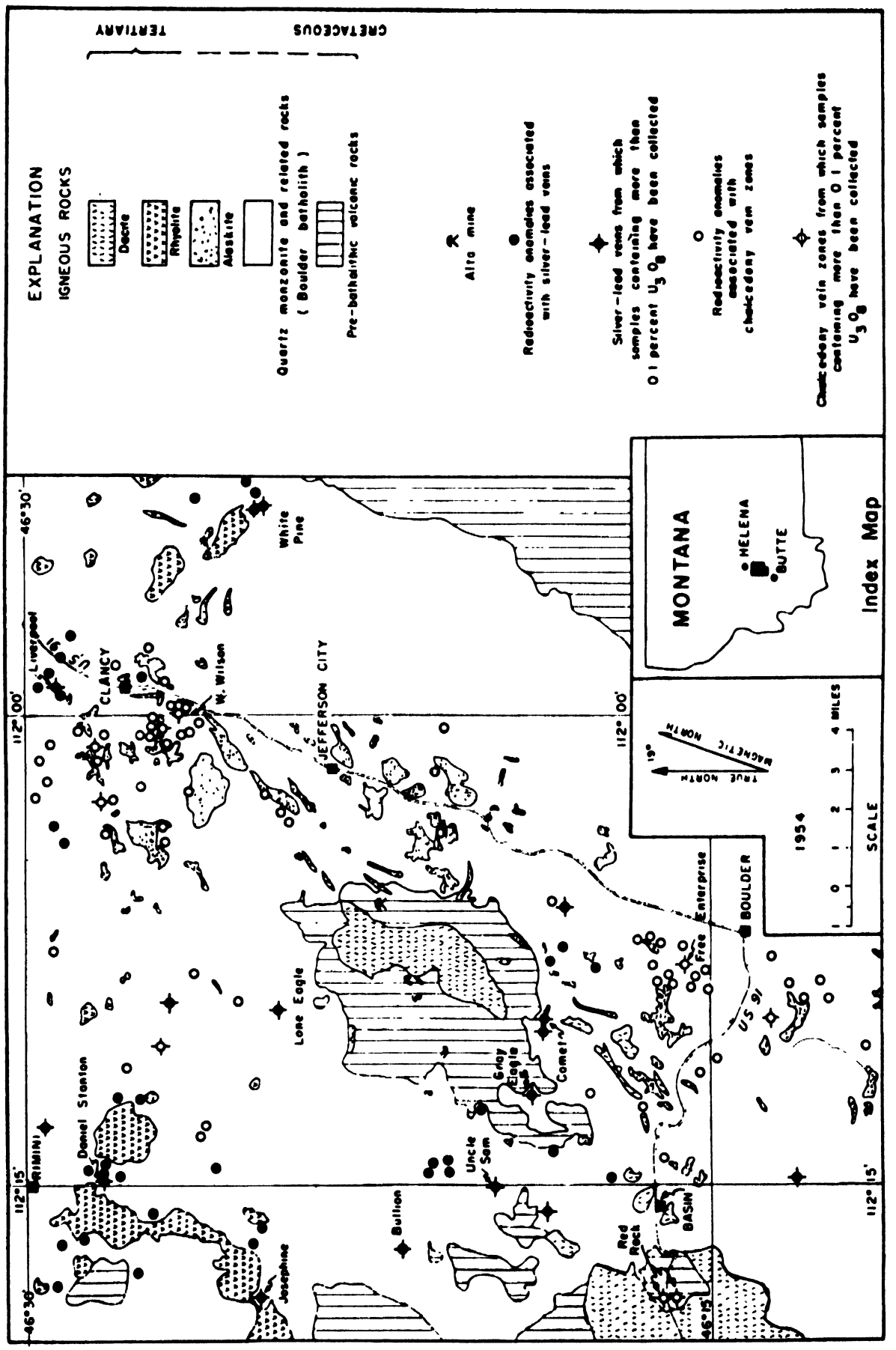


Figure 1. Generalized geologic map of the northern part of the Boulder batholith, Montana, showing uranium deposits and radioactivity anomalies

steeply. Almost all the shear zones, which locally contain silver-lead veins, are east-trending. These zones are as much as 200 feet wide, but there is no evidence of large-scale lateral displacement. Many faults in the vicinity of Clancy and Boulder are occupied by chalcedony veins. These faults near Boulder and west of Clancy have a predominantly N 60° E trend; those east of Clancy have a predominantly east trend.

MINERAL DEPOSITS

The mineral deposits in the northern part of the batholith are probably of at least three different ages. The oldest deposits, which include all of the deposits that have yielded substantial amounts of metals, occur in the east-trending shear zones and are common in the batholith and in the prebatholithic volcanic rocks. These are principally silver-lead deposits, but some contain important amounts of gold and zinc and minor amounts of copper. Typical examples of this type of deposit are the Alta mine in the prebatholithic volcanic rocks and the Comet mine in the quartz monzonite of the batholith.

Dacite dikes cut several of the silver-lead veins, and dacite tuffs and rhyolite flows rest on erosional surfaces developed after the formation of the veins.

A distinctly different and probably younger type of deposit is represented by the chalcedony veins and vein zones that locally contain a little silver but no important concentrations of base metals. The vein zones consist of one or more discontinuous stringers and veins of chalcedony and microcrystalline quartz in altered quartz monzonite and granodiorite and in alaskite that has not been strongly altered. The zones have been repeatedly brecciated and silicified along predominantly northeast-trending, steeply dipping faults. Crosscutting relations of several chalcedony and microcrystalline quartz veinlets in a few vein zones indicate as many as four distinct periods of brecciation and silicification.

All of the chalcedony vein zones are younger than the alaskite, and most of them are older than the dacite. Dacite dikes cutting the vein zones are relatively common, but in a few locations chalcedony vein zones cut dacite dikes. Crosscutting relations at one location suggest that a dacite dike was intruded during the formation of a chalcedony vein zone. The dike appears to cut the early microcrystalline quartz and the later dark-gray to black chalcedony; in turn the dike is cut by a small light-gray chalcedony veinlet that may represent the final phase of silicification in the formation of the chalcedony veins and the vein zones took place over a considerable period of time.

The chalcedony vein zones are localized in two distinct areas of several square miles each, one near Clancy and one near Boulder, and are relatively rare throughout the remainder of the northern part of the batholith.

The youngest mineral deposits in the northern part of the batholith are small deposits of gold in Tertiary rhyolite near Rimini. The rhyolite is intensely altered and cut by many small quartz veinlets. The gold is disseminated throughout the rhyolite and concentrated in limonite-filled fractures.

URANIUM DEPOSITS

Radioactivity anomalies have been detected at many places in the northern half of the batholith, but very few have been found elsewhere in or around the batholith. One exception is a small uranium deposit associated with a chalcedony vein zone a few miles west of Butte. In the Butte district only very slight radioactivity and traces of pitchblende have been detected scattered at random throughout the extensive mine workings, although the production of other metals from the Butte district far exceeds the total production from all the other mining districts in the batholith.

All but two of the known radioactivity anomalies are in the rocks of the batholith. Uranium minerals and anomalous radioactivity has been found in and adjacent to the silver-lead deposits and in the chalcedony veins and vein zones. No apparent structural or mineralogical differences were noted between the silver-lead deposits in the batholith and those in the prebatholithic volcanic rocks, except that uranium minerals have been found only in the silver-lead deposits in the batholith.

Moderate to high radioactivity anomalies have been detected as several places on the dump of the Comet mine, and samples containing as much as 0.52 per cent uranium have been collected. The Comet mine is in a shear zone in quartz monzonite near the roof of the batholith. The shear zone, which dips steeply and trends about N 80° W, has been traced for a distance of about six miles. It cuts intensely altered prebatholithic volcanic rocks and quartz monzonite, and slightly altered alaskitic rocks; displacement along it has been slight. Several dacite dikes cut the zone and are not sheared or altered. Several silver-lead mines, of which the Comet is the largest, are situated along the zone. Radioactivity anomalies have been detected on the dumps of five of these mines, but Geiger-counter and scintillation-counter traverses along the entire length of the zone failed to disclose any radioactivity anomalies along the trace of the outcrop. The absence of radioactivity anomalies may be the result of thick cover and thorough leaching of the uranium from the zone near the surface.

In the Comet mine three principal veins that follow the trend of the shear zone and dip steeply to the south and several splits of these veins were explored. Ore minerals included galena, sphalerite, tetrahedrite, and chalcopyrite. The gangue consists chiefly of quartz and altered wall rock. A part of the quartz is a clear crystalline variety and a part is a dark bluish-gray, fine-grained variety. The wall rock is dominantly quartz monzonite and subordinately alaskite. Adjacent to the vein the quartz monzonite has been strongly silicified and sericitized.

At the Gray Eagle mine about 1½ miles west of the Comet mine, a sooty black mineral, identified as

pitchblende, occurs intimately intermixed with pyrite in gray crystalline quartz. Wright and Bieler[5] state that uraninite has extensively replaced pyrite.

Selected samples that contain more than 0.1 per cent U_3O_8 have been collected from the dumps of many other silver-lead mines in the batholith rocks. Among these are the Josephine, Daniel Stanton, Liverpool, Bullion, Uncle Sam, White Pine, and several unnamed properties (Fig. 1). Radioactivity anomalies have been detected on many other mine dumps.

Many radioactivity anomalies have been detected in and adjacent to chalcedony vein zones in the batholith. Uranium ore has been produced from two mines in these zones; the Free Enterprise mine has produced a few tons of high-grade ore and about 150 tons of low-grade ore,[6] and the W. Wilson mine has produced several hundred tons of moderately high-grade ore.

The W. Wilson mine is about a mile and a half southwest of Clancy. The geology of a few square miles in the vicinity of the mine was mapped in 1950 by Roberts and Gude, and subsequently detailed studies of the mine were made by Meschter and by Wright *et al.*[8]

The dominant rock type in the vicinity of the W. Wilson mine is quartz monzonite with an approximate composition of 45 per cent plagioclase (An_{30-35}), 25 per cent potash feldspar, 20 per cent quartz, 7 per cent biotite and 3 per cent hornblende. Adjacent to each chalcedony vein, the quartz monzonite is typically altered in poorly defined gradational zones of decreasing intensity outward from the vein. The innermost zone immediately adjacent to the vein is characterized by silicification; sericitization characterizes an intermediate zone, and beyond that lies a zone of kaolinization. This alteration is similar to that accompanying the silver-lead veins and nonuraniferous chalcedony veins; no particular feature of the alteration was recognized as specifically diagnostic of or peculiar to the uranium mineralization.

The W. Wilson vein zone consists of from 1 to 5 veins of chalcedony and microcrystalline quartz, locally as much as 3 feet thick but averaging only a few inches thick. The interlacing of individual veinlets of quartz and chalcedony along the strike and dip of the vein has resulted in a pattern that resembles crude netting. Uranium minerals were first discovered at the W. Wilson mine in two ore bodies that contained sparse nodules and veinlets of pitchblende and relatively abundant yellow and orange secondary uranium minerals: uranophane, phosphuranylite, uranocircite, meta-autunite, and a mixture of oxides referred to as gummite. A few secondary minerals, mainly metatorbernite, meta-autunite, and uranophane, are sparsely distributed along and adjacent to fractures outside of the ore bodies, indicating the transportation and redeposition of some of the uranium by meteoric water. Meschter[9] stated that at least three periods of silicification in the W. Wilson mine can be recognized. The first period is represented by clear microcrystalline quartz, the second by black to dark-gray chalcedony, and the third by clear microcrystalline quartz. He concluded that pyrite, chalcopyrite, and pitchblende are essentially contemporaneous with the dark-gray to black chalcedony.

One of the occurrences of uranium minerals in the prebatholithic volcanic rocks is at the Red Rock mine about 1½ miles west of Basin. The batholith is exposed about 3000 feet northeast of the mine but may underlie the volcanic rocks at the mine at a relatively shallow depth. The vein consists of light-gray chalcedony in intensely silicified, sericitized, and brecciated volcanic rocks. The entire altered zone is about 300 feet wide and forms a conspicuous northeast-trending ridge. The Red Rock vein differs from the typical chalcedony vein zone of the batholith in that it is a single vein of chalcedony with gradational margins, rather than a series of anastomosing veinlets with sharp boundaries.

Uranium minerals and radioactivity anomalies have been found in and adjacent to a few veins that have some characteristics of both the silver-lead veins and the chalcedony veins and vein zones. They contain abundant amounts of lead and silver minerals and small amounts of sphalerite in a gangue that is predominantly microcrystalline quartz and chalcedony. The mineral assemblage of these veins suggests that they were formed either during an intermediate period of mineralization or during both of the periods described above. A quartz vein in the Lone Eagle mine is an example of a vein of mixed type. The vein is in intensely altered quartz monzonite in which biotite is altered to chloride, and the feldspars are altered to a light-gray to greenish-gray mixture of clay and sericite. Silicified zones of quartz monzonite adjacent to the quartz vein range from less than an inch to several feet in thickness. Faulting and shearing are common throughout the mine. Uranium is present in two forms: as small irregular blebs of pitchblende in the vein, and as a sooty black material coating irregular fractures in the vein and in the altered wall rock adjacent to the vein. Wright *et al.*[8] state that pitchblende has extensively replaced pyrite, and in some places has replaced chalcedony and sphalerite that filled fractures in pyrite. They also observed a second generation of sphalerite and pyrite as veinlets cutting the pitchblende.

AGE OF THE URANIUM DEPOSITS

All the known uranium deposits are post-alaskite and pre-dacite. Data obtained by measuring the lead-alpha activity ratio in zircon suggests an age of about 60 million years for the alaskite—late Upper Cretaceous or Paleocene.[10] Weed[11] reports that dacite tuffs in the Deer Lodge Valley, about 30 miles west of Boulder, are contemporaneous with Miocene lake beds, but in the Townsend Valley, about 30 miles east of Boulder, quartz-bearing tuffs in a similar setting are lower Oligocene in age. These two observations

indicate that the dacite may be either Miocene or Oligocene in age.

In the chalcedony vein zones the uranium was deposited with the dark-gray to black chalcedony, which was deposited late in the formation of the vein zones but before the intrusion of the dacite. In the silver-lead veins also, the uranium appears to be intimately associated with dark-gray to black chalcedony or microcrystalline quartz. In several of the silver-lead veins, the chalcedony cuts quartz veins containing galena and sphalerite and therefore is interpreted to be later than the sulfide mineralization. The intimate association of uranium with dark-gray to black chalcedony or microcrystalline quartz in the chalcedony-vein zones and in the silver-lead deposits suggests that most of the uranium mineralization may be of the same age and that many of the silver-lead veins were reopened during the period of uranium mineralization.

REFERENCES

1. Knopf, A., *Ore deposits of the Helena Mining Region, Montana,* US Geological Survey Bulletin 527 (1913).
2. Billingsley, P. and Grimes, J. A., *Ore Deposits of the Boulder Batholith of Montana,* American Institute of Mining Engineers Transactions 58: 284–368 (1918).
3. Pardee, J. F. and Schrader, F. C., *Metalliferous Deposits of the Greater Helena Mining Region, Montana,* US Geological Survey Bulletin 842 (1933).
4. Fenner, C. N., *Incandescent Tuff Flows in Southern Peru,* Bulletin, Geological Society of America 59: 879–893 (1948).
5. Wright, H. D. and Bieler, B. H., *An Investigation of the Mineralogy of the Uranium-Bearing Deposits in the Boulder Batholith, Montana,* US Atomic Energy Commission RME–3041 (1953).
6. Roberts, W. A. and Gude, A. J., III, *Geology of the Area Adjacent to the Free Enterprise Mine, Jefferson County, Montana,* US Geological Survey Bulletin 988–G: 143–155 (1953a).
7. Roberts, W. A. and Gude, A. J., III, *Uranium-Bearing Deposits West of Clancey, Jefferson County, Montana,* US Geological Survey Bulletin 988–F: 69–87 (1953b).
8. Wright, H. D., Bieler, B. H., Shulhof, W. P. and Emerson, D. O., *Mineralogy of Uranium-Bearing Deposits in the Boulder Batholith, Montana,* US Atomic Energy Commission RME–3095 (1954).
9. Meschter, D. Y., written communication.
10. Chapman, R. W., written communication.
11. Week, W. H., Geology and *Ore Deposits, of the Butte District, Montana,* US Geological Survey Professional Paper 74 (1912).

Uranium in the Fluorspar Deposits of the Thomas Range, Utah

By M. H. Staatz and F. W. Osterwald,* USA

The largest known uraniferous fluorspar deposits of the United States are in the western part of the Thomas Range (lat 39° 45′ N, long 113° 10′ W), Juab County, Utah, but like the other known uraniferous fluorspar areas in the United States, this district has not been important as a source of uranium. The term "fluorspar" applies to the deposit as a whole or the mined product as differentiated from the mineral fluorite (CaF_2). A fluorspar deposit is made up chiefly of fluorite.

The Thomas Range is a northwest-trending group of mountains in the eastern part of the Basin and Range physiographic province. It consists of an eastern block 12 miles long by 3 to 6 miles wide composed of Tertiary (?) rhyolites and tuffs, and a western rugged mountain mass called Spors Mountain,[1] which is about 6 miles long and a mile and a half to 2 miles wide and which is composed mainly of extensively faulted early to middle Paleozoic sedimentary rocks. The uraniferous fluorspar deposits are restricted to the western part of the range.

The first fluorspar was produced in 1943 from the Floride mine near the southern end of Spors Mountain. No other deposits were known until 1948 when the Blowout, Dell Nos. 1, 2, and 5, Eagle Rock, Fluorine Queen, Hilltop, Lost Sheep, Nonella, and Oversight deposits were discovered in the northern part of the mountain. The Lucky Louie was found in southern end of Spors Mountain in 1948, and the Bell Hill and Harrisite bodies were discovered in 1949.

Total production from the district to January 1, 1953 was 75,000 short tons of ore containing from 65 to 94 per cent fluorite. The ore was used for metallurgical purposes and was not milled before shipment. Mining was by both open-cut and underground methods.

GEOLOGY

The rocks of Spors Mountain are chiefly marine limestone, shale, quartzite, and dolomite ranging in age from Lower Ordovician to Middle Devonian.[2] The complete sequence consists of limestone of Lower Ordovician age overlain conformably by shale and quartzite of Middle Ordovician age, dolomite of Upper Ordovician age, five dolomite formations of Silurian age in an apparently conformable sequence, dolomite of Lower Devonian age, and dolomite of Middle Devonian age. These rocks are cut by Tertiary (?) plugs and dikes of latite, rhyolite, and dellenite; volcanic explosion pipes filled with breccia are common along the east side of Spors Mountain. Volcanic flows and tuffs of probable Tertiary age surround the Paleozoic sedimentary rocks.

All Paleozoic and Tertiary rocks strike northeast and dip gently northwest. The district is cut by at least five sets of closely spaced faults, but no folds have been recognized. Three sets of faults are older and two sets are younger than the volcanic rocks.

ORE DEPOSITS

More than 40 fluorspar deposits, excluding small veins, are known on Spors Mountain. These deposits are divided into three types: pipelike bodies (Figs. 1A, 1B, and 1C), veins, and disseminated deposits. The fluorite in the ore bodies closely resembles brown, white, or purplish clay that occurs either as soft pulverulent masses or as boxworks. The most abundant ore is soft, white to dark purple, and pulverulent. Two small deposits in the northern part of the range are made up entirely of brown boxwork-type ore. Some deposits contain both boxwork and pulverulent ore; in these the boxworks are commonly pale purple.

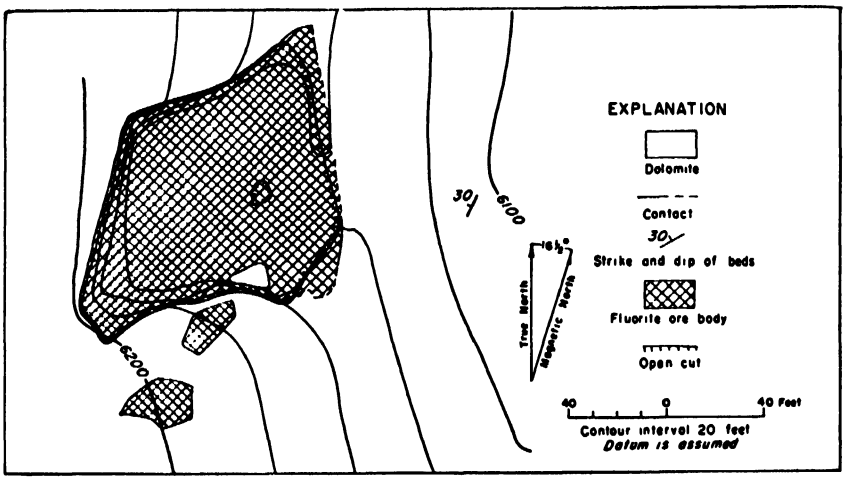
Individual fluorite grains approach clay particles in size. White waxy montmorillonite, well intermixed with fluorite, is the chief impurity; quartz, chalcedony, dolomite, calcite, and opal are the other gangue minerals. The assemblage of gangue minerals changes from deposit to deposit, and no deposit contains them all. Sulfide minerals are completely absent. Uranium occurs in carnotite, in an unknown uranium silicate, and in fluorite.

The fluorspar bodies have sharp contacts with adjacent dolomite; no alteration of country rock is recognizable even at the largest deposits.

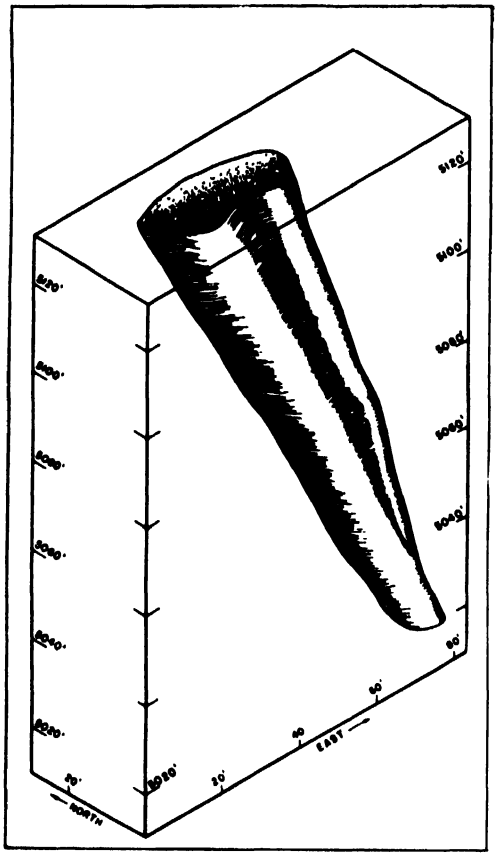
The pipelike bodies are by far the most important deposits in the district; 19 of the 21 deposits from which ore has been produced were of this type, and they yielded 99.95 per cent of the total production. The pipes are oval (Figs. 1A and 1B) to highly irregular (Fig. 1B) in plan. All pipes have steep walls and in many the walls are highly irregular. A few pipes are vertical, but most plunge steeply to the northeast or southeast. The Bell Hill ore body changed plunge about 100 ft below the surface from 52° N 62° E above that level to 70° S 81° E below.

At the surface the pipes range from less than a foot in diameter to 155 feet long and 106 feet wide (Fig. 1A). Although a few of the ore bodies are re-

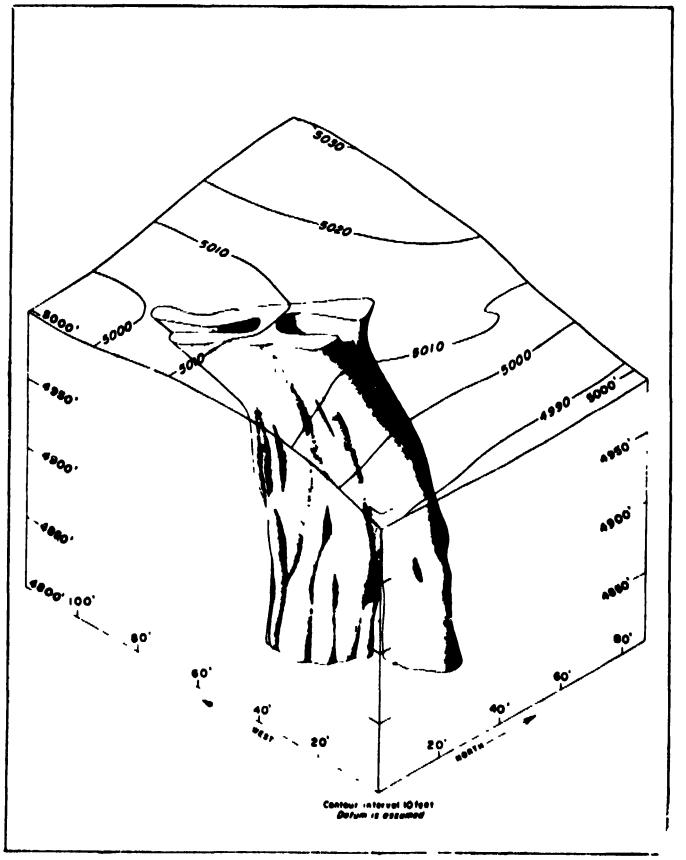
* US Geological Survey.



A - GEOLOGIC MAP OF THE EAST PIT OF THE FLUORINE QUEEN



B - BLOCK DIAGRAM SHOWING SHAPE OF THE LUCKY LOUIE PIPE



C - BLOCK DIAGRAM SHOWING SHAPE OF THE LARGE PIPE ON THE BELL HILL PROPERTY

Figure 1. Map and block diagrams of some fluorspar deposits, Thomas Range, Juab County, Utah

markably uniform in size and shape, most become smaller with increasing depth and a few pinch out abruptly. The Lucky Louie pipe (Fig. 1B) was 35 feet by 14 feet at the surface, but only 10 feet by 7.5 feet at a depth of 120 feet. The main ore body of the Bell Hill mine (Fig. 1B) is H-shaped in plan at the surface, but is lenticular on the 60-foot level. The shape of some deposits is changed by large horses of dolomite.

The pipes cut all dolomite formations older than Devonian and younger than the quartzite of Middle Ordovician age. Most pipes are either in or adjacent to faults or adjacent to intrusive breccia bodies. Pipes associated with faults are chiefly in the southern part of the district and tend to be irregular in shape; pipes associated with intrusive breccia bodies are in the northern part of the district and tend to be oval in shape. A few ore bodies, however, are not associated with either faults or intrusive breccia bodies. Pipes that go as deep as the contact of the quartzite of Middle Ordovician age do not end abruptly but join with anastomosing veins as much as 6 inches wide that penetrate the quartzite for several feet.

The character of the ore in some deposits changes with increasing depth. The fluorspar of the Blowout pipe contained few impurities near the surface, but at 240 feet the fluorspar contained such large masses of montmorillonite associated with lesser amounts of quartz, calcite, and dolomite that mining ceased to be profitable. The Lucky Louie deposit was composed almost entirely of fluorite at the surface, but it contained angular pieces of chalcedony at 90 feet in depth and consisted almost entirely of chalcedony at 120 feet in depth. The main pipe at the Bell Hill mine was uniform in composition to about 130 feet in depth, but below this level a hard, vuggy material consisting of quartz and light-colored dolomite appeared at either end of the ore body. Not all deposits, however, show these changes; the Dell ore body, for example, was mined to a depth of 200 feet with no reported change in composition.

Veins, extremely variable in shape, are common throughout Spors Mountain. They range from a few inches to 220 feet long and from less than an inch to 14 feet thick. Most veins cut the same Paleozoic rocks as the pipes, but a few cut tuff. Fluorspar was mined only from the Thursday and Eagle Rock veins, and neither produced over 55 short tons.

Disseminated deposits occur in volcanic rocks along the south and west sides of Spors Mountain. The fluorite content of these rocks rarely exceeds 30 per cent, and no attempt has been made to market ore from these deposits. The fluorite occurs in clay-rich layers in the tuff and in cavities and along fracture planes in rhyolite and latite. The deposits are poorly exposed and of little-known size and shape.

URANIUM MINERALS

Most of the fluorspar deposits are abnormally radioactive, but visible uranium minerals are scarce. Yellow powdery uranium minerals were observed at five deposits but were abundant only in the small Eagle Rock vein. These are secondary minerals consisting of at least two distinct species: carnotite, which was found at the Eagle Rock and Bell Hill properties, and an unknown uranium silicate obtained at the Harrisite property. Ordinarily these minerals coat fractures in dolomite or latite adjacent to the ore bodies; at only two properties did the fluorspar ore itself contain visible uranium minerals.

Vanadium and uranium have been found by analysis in fluorspar ore that contains no recognizable vanadium or uranium minerals. Ore from three pipes contained 2.5 to 6.5 times more vanadium than required to form carnotite with the available uranium, and hence some other vanadium mineral in addition to carnotite must be present. Ore from the main ore body of the Bell Hill mine, on the other hand, contained an excess of uranium with respect to vanadium, but the analyzed material from this mine was collected near the surface, where it may have been enriched in uranium by secondary processes. Autoradiographs of several ore specimens containing more than 0.10 per cent uranium showed no concentration of uranium, but a rather uniform haze was formed across the whole picture. Heavy-mineral separates, some of which were centrifuged, contained no recognizable uranium minerals. Therefore, most of the uranium is probably in a uranium mineral of clay-size dimensions scattered through the fluorspar, or it is contained within the fluorite lattice.

DISTRIBUTION OF URANIUM

The uranium content of veins and pipes varies considerably. Fluorspar samples from throughout the district range from less than 0.003 to 0.33 per cent uranium, but samples from only four deposits contained more than 0.10 per cent uranium. Three of these four deposits are small. The fourth deposit is the Bell Hill, which consists of at least eight closely related pipelike ore bodies. Only one of these pipes yielded samples with more than 0.10 per cent uranium, but this pipe is the only deposit in the entire district that has yielded a sample containing more than 0.20 per cent uranium.

Although the uranium content of an individual deposit varies from place to place even on the same level, the gross uranium content does not change significantly from one place to another except near the surface where it increases sharply. At the large Fluorine Queen deposit near the middle of Spors Mountain (Fig. 1A), three samples from an adit 64 feet below the surface contained 0.006 to 0.10 per cent uranium. A similar decrease in uranium content was recognized in many deposits where workings cut the ore body 30 feet or more below the surface. This increase in uranium content near the surface appears not to be primary zoning but to be a supergene effect related to the present topographic surface.

In both the main ore body of the Bell Hill mine and the east ore body of the Fluorine Queen mine this change in uranium content takes place near the sur-

face, despite the fact that one of these deposits crops out 1000 feet above the other. A similar change in uranium content has also been noted in the south ore body of the Lost Sheep mine and at the Oversight ore body, which crop out at intermediate altitude. Of these mines the Bell Hill was the only one developed on more than one level underground and was the only place where the relatively constant uranium content of the lower part of the ore body could be established. A series of samples was taken at the Bell Hill from the open cut, the six underground levels, and a drill hole. The samples from the drill hole and the six underground levels showed no greater deviation in uranium content than was found between individual samples from the same level. The samples from the uppermost level, 66 feet below the surface, and those from the open cut, 4 to 22 feet below the surface, showed a sharp and significant increase in uranium content above the 66-foot level.

Uranium is commonly dissolved in ground water and many of its salts are highly soluble. Sheridan[3] has observed that in the Red Desert of Wyoming, a uranium deposit containing schroeckingerite moves annually with the rise and fall of the water table. The upper surface of a cement slab at the Red Bluff mine, Arizona, used for sorting and loading uranium ore, became impregnated with yellow uranium minerals after an ore pile was left on it through one winter. Similarly, the near surface increase in uranium content of the Thomas Range deposits is probably caused by slow leaching of uranium from the upper part of the ore body, in part from material being actively eroded. The uranium is carried downward and redeposited in the dry underlying ore at some level between a few inches and approximately 30 feet below the surface. Yellow secondary uranium minerals occur only in the upper part of the ore bodies and are believed to have been formed during this secondary enrichment. As these minerals are scarce, however, part of the redeposited uranium is probably in other forms, possibly being adsorbed by the fluorite. Leaching would be slow because annual precipitation in the Thomas Range is small. Ives[4] reports about 5 inches of precipitation annually at Dugway, 32 miles to the northeast, the nearest place for which records are available.

Changes in uranium content cannot be connected with changes in grade of the fluorite ore. In fact, the uranium content of any two samples from any location within a pipe may vary in either direction with an increase in fluorite grade.

ORIGIN

The fluorspar deposits are believed to have been formed during the closing stages of the vulcanism that formed the plugs and dikes on Spors Mountain. Fluorspar veins cut intrusive breccia bodies and agglomerate in many places; one small fluorspar pipe partly replaces a small intrusive breccia mass; and a fluorspar vein follows the contact between latite and dolomite. On the other hand, in the Bell Hill mine an intrusive rhyolite breccia cuts the fluorspar body.

Available chemical analyses (Table 1) suggest that the intrusives of Spors Mountain and the volcanic rocks of the eastern part of the Thomas Range were derived from the same magma. This magma was rich in fluorine, as shown by the presence of topaz in both the intrusive and volcanic rocks. Topaz in vugs in rhyolite indicates that fluorine continued to be available after consolidation of the main rhyolite mass. Furthermore, secondary uranium minerals in the volcanic rocks in the eastern part of the Thomas Range suggest that the parent magma may also have been the source of the uranium.

Table I. Chemical Composition, in Weight Per Cent, of Rhyolites from the Thomas Range, Utah*

	a	*b*	*c*
SiO_2	73.30	76.54	74.49
Al_2O_3	14.27	12.16	14.51
Fe_2O_3	.34	.92	.57
FeO	1.89	.37	.32
MgO	.13	.14	Trace
CaO	.34	.78	1.03
Na_2O	3.86	3.50	3.79
K_2O	4.76	4.97	4.64
H_2O+	.39	.11	.64
H_2O-	.11	.05	–
TiO_2	.03	.09	–
CO_2	.06	.16	–
P_2O_5	.03	.02	–
MnO	.07	.05	Trace
	99.58	99.86	99.99

* *a* Rhyolite plug, Spors Mountain, Utah; L. M. Kehl, US Geological Survey, analyst. *b* Rhyolite flow, eastern part of the Thomas Range, Utah; L. M. Kehl, US Geological Survey, analyst. *c* Rhyolite flow, eastern part of the Thomas Range, Utah; L. G. Eakins, analyst.[5]

The fluorspar deposits are formed by the replacement of the dolomite wall rocks by fluorine-rich fluids derived from the magma that formed the volcanic rocks. Replacement as the dominant form of emplacement is indicated by relict structures. This is seen most clearly in the disseminated deposits, where the volcanic rocks are only partly replaced by fluorite. Chert layers in dolomite were traced without interruption into some ore bodies, and Silurian corals replaced by fluorite were found in three pipes.

The fluids that formed the fluorspar bodies could have been rather simple. Except for F, U, Al, and H, all the elements found in the uraniferous fluorite, montmorillonite, dolomite, quartz, chalcedony, and calcite that comprise the ore bodies, are abundant in the cherty dolomite wall rocks. Both Al and H are abundant in the underlying shale of Middle Ordovician age, however, so only F and U need be added from a magmatic source.

REFERENCES

1. Fitch, C. A., Quigley, James and Barker, C. S., *Utah's new mining district*, Eng. and Min. Jour. *150*: 63 (1949).
2. Thurston, W. R., *et al.*, *Fluorspar deposits of Utah*, US Geol. Survey Bull. 1005 (1954) (See p. 26–28).
3. Sheridan, D. M., oral communication (1953).
4. Ives, R. L., *Pleistocene valley sediments of the Dugway area, Utah*, Geol. Soc. America Bull. *62*: 781 (1951).
5. Washington, H. S., *Chemical analyses of igneous rocks*, US Geol. Survey Prof. Paper 199 (1917).

Wall-Rock Control of Certain Pitchblende Deposits in Golden Gate Canyon, Jefferson County, Colorado

By John W. Adams and Frederick Stugard, Jr.,* USA

Pitchblende and secondary uranium minerals are found in Golden Gate Canyon, Colorado. The deposits, which were discovered recently, occur in or near Laramide (earliest Tertiary) fault zones that cut gneisses, schists, and pegmatites of Precambrian age.

During a preliminary study of these deposits[1] it was noted that most of the occurrences of uranium minerals and of high radioactivity anomalies in the area were found where the fault zones cross hornblende gneiss, and, conversely, no significant radioactivity has been found along the same fault zones where they pass through other rocks. The distribution of the known uranium occurrences in relation to the hornblende gneiss and the faults is shown on Fig. 1. In the vicinity of the deposits, quartz-biotite gneiss is adjacent to hornblende gneiss.

The fault zones, or "breccia reefs", are extensive structures as much as 20 feet wide and possibly many miles long. In the area studied, they consist of carbonates and potash feldspar as a fine-grained groundmass enclosing rock fragments that have been replaced in varying degrees by these minerals. Ankerite is the most abundant carbonate mineral in the reefs, and with potash feldspar appears to be the product of widespread introduction of hydrothermal solutions into the faults.

At the Union Pacific prospect (Fig. 2) pitchblende and base-metal sulfides occur along the hanging wall of a carbonate-potash feldspar reef cutting hornblende gneiss. The pitchblende occurs as thin films or more commonly as colloform masses less than 0.1 mm in diameter that densely coat crystals of ankerite of comparable size. The pitchblende-ankerite veinlets are irregularly distributed through intensely altered wall rock and are replaced in varying degrees by later sulfides. Both pitchblende and hematite have been noted coating crystals of potash feldspar that have grown from the walls of fractures. The deposition of potash feldspar, pitchblende, hematite, and ankerite was followed by the introduction of sulfides which in turn gave way to a final carbonate stage.

The first process in the development of the ore is thought to have been propylitization of the hornblende gneiss. This resulted in the partial conversion of hornblende to chloride and some sericitization of plagioclase. The sulfide ion concentration of the solutions was probably low as very little pyrite was formed from the breakdown of the iron-bearing minerals, thus permitting any excess iron to deposit as hematite.

Following or perhaps during propylitization, solutions were introduced that raised the potash content of the gneiss from less than 1 to more than 3 per cent (Fig. 3). The added potash is in part contained in small clear crystals of orthoclase that line fractures in the rock, but as much or more potash may have replaced the soda of the original plagioclase. This feldspathization of the plagioclase is supported by the distribution of potassium as shown by staining and also by the decreased soda content of the gneiss after alteration (Fig. 3).

The precipitation of uranium followed potassic alteration and coincided with the beginning of a carbonate phase. This is shown by the deposition of pitchblende on orthoclase crystals and its intergrowth with ankerite. The precipitation of uranium is thought to have been caused by the reduction of U^{6+} ions to U^{4+} by the Fe^{2+} ions released by the breakdown of hornblende and chlorite. Gruner[2] has experimentally produced pitchblende and hematite by reduction of U^{6+} by Fe^{2+}; hematite formed only when the pitchblende was synthesized in an H_2S-free environment. In the ore deposit, pitchblende and hematite (later ankerite) were deposited at essentially the same time, before the formation of all sulfides, with the exception of the very minor pyrite formed during propylitization.

After depletion of the available uranium, several simple copper sulfides and sphalerite, galena, and emplectite (?) were deposited in an intricate network of fractures that follow only in part the original pitchblende-bearing veinlets. Deposition of these sulfides was followed by tennantite replacement. It is questionable whether this replacement was part of a continuous period of sulfide deposition or whether a "rest interval" took place. Polished-section relationships favor discontinuity with a new wave of solution containing arsenic and antimony in addition to copper and iron migrating along the margins of pre-existing veinlets. On the depletion of the arsenic and antimony, sufficient copper remained so that chalcopyrite formed locally throughout the tennantite and along grain boundaries of tennantite and other

* US Geological Survey.

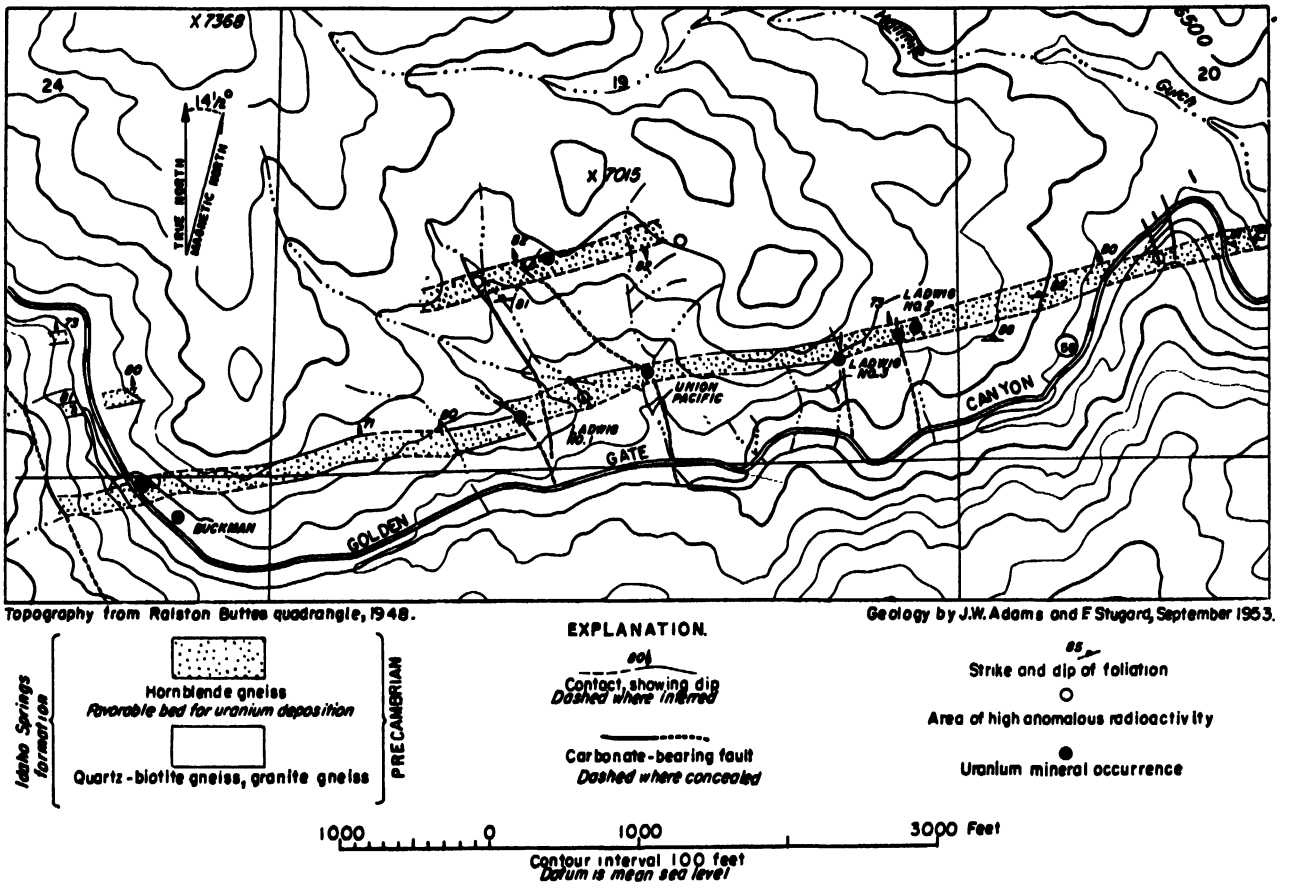


Figure 1. Geologic sketch map showing distribution of uranium occurrences in the Golden Gate Canyon area, Jefferson County, Colorado

minerals. With the deposition of chalcopyrite the sulfide mineralization waned, and a vigorous carbonate phase began which was to continue until the close of hypogene activity. The bulk of the carbonate deposited was extremely fine grained ankerite, succeeded at the last by somewhat coarser grained calcite. The calcite, which is sparse, forms veinlets and fills cavities in the ankerite. Minute pyrite crystals that developed along the edges of the calcite-filled openings indicate that a very weak sulfide phase marked the transition point between the two carbonates.

Figure 4 shows a graphical representation of the paragenesis of the deposit.

The ore deposit at the Union Pacific prospect is, so far as is known, confined to hornblende gneiss wall rocks. This localization, repeated at several other uranium occurrences in the area, appears to be largely the result of the composition and texture of the wall rock.

As previously discussed, the deposition of uranium probably was effected by the oxidation of ferrous to ferric iron. Analyses of the two rock types involved showed that the hornblende gneiss contains almost four times as much ferrous iron as the biotite gneiss. Field observations and thin section studies indicate that the hornblende gneiss was readily altered by the solutions introduced along the fault, and that hornblende, the dominant iron-bearing mineral of the rock, was especially subject to attack. It is believed that the release and subsequent reprecipitation of iron from hornblende provided an effective mechanism for uranium deposition.

The nature of the iron-bearing mineral probably was of little consequence, providing it was reactive and present in sufficient quantity. Thus a rock rich in biotite might be just as effective a precipitant as one containing its iron equivalent as hornblende. In the Joachimsthal district, Czechoslovakia, pitchblende has been observed to be more abundant where the wall rocks of the veins were rich in biotite.[3]

A direct comparison of the iron content of rocks as a measure of their effectiveness in uranium deposition should be qualified by a consideration of the availability of the iron-bearing mineral to contact with the vein fluids.

Although the rocks classed as biotite gneiss in this report contain layers that are markedly gneissic, they are for the most part granoblastic. In contrast, the hornblende gneiss is quite uniformly foliated, with closely spaced layers of light and dark minerals. It would seem reasonable that where vulnerable minerals are aligned in more or less continuous planes, as in the hornblende gneiss, they would be far more accessible to the invading solutions than when randomly distributed throughout the rock.

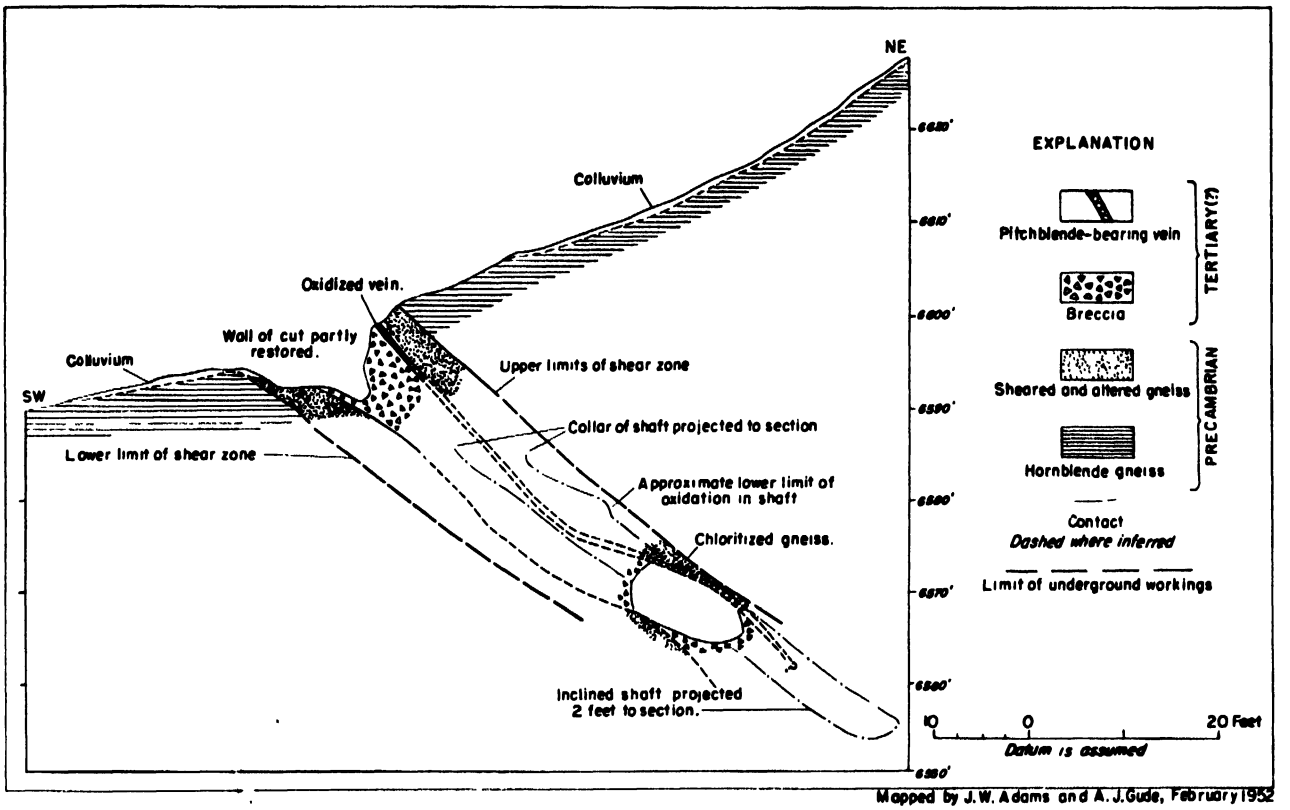


Figure 2. Geologic section of the Union Pacific prospect, Jefferson County, Colorado

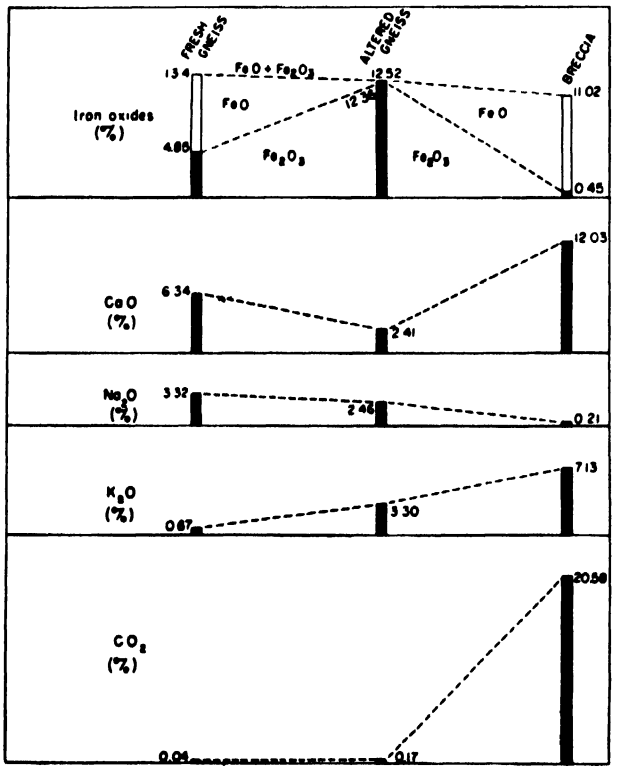


Figure 3. Chemical changes during alteration of gneiss

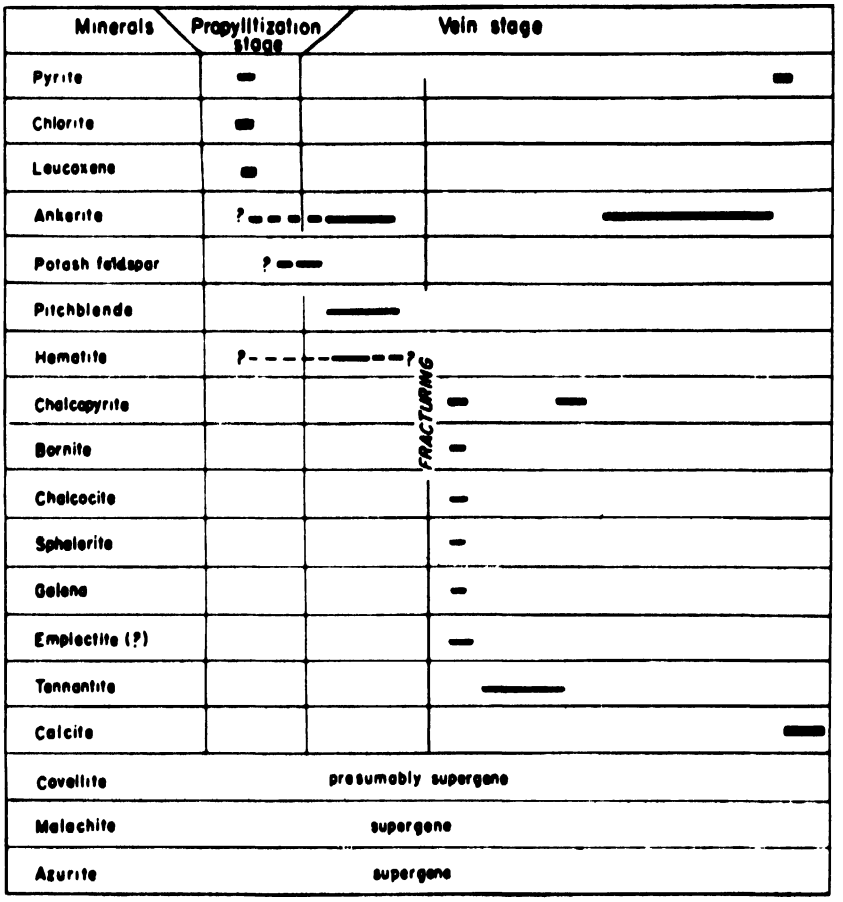


Figure 4. Paragenesis of the minerals at the Union Pacific prospect

CONCLUSIONS

The studies made during this investigation lead to the conclusion that pitchblende-bearing veins of the carbonate type can be expected where ample ferrous iron is available in the wall rocks. The difference in the available ferrous iron of the hornblende gneiss and biotite gneiss is thought to have resulted in the localization pattern exhibited by the pitchblende occurrences in the Golden Gate Canyon area.

This conclusion may be of some value in prospecting for uranium in areas of comparable geologic environments; the nature of the ferrous iron-bearing mineral is probably unimportant so that no special significance should be placed on the presence of hornblende. Biotite, magnetite, tourmaline, and iron sulfides may be equally effective when present in sufficient quantity. In a sulfide environment, conditions resulting in the oxidation of either iron or sulfur may precipitate pitchblende. This implies that conditions are particularly favorable for uranium deposition where uranium-bearing solutions have access to rocks rich in ferrous iron or pre-existing sulfides.

REFERENCES

1. Adams, J. W., Gude, A. J., 3d and Beroni, E. P., *Uranium Occurrences in the Golden Gate Canyon and Ralston Creek Areas, Jefferson County, Colorado*, US Geological Survey Circular 320 (1953).
2. Gruner, J. W., *New Data of Synthesis of Uranium Minerals, Part 1*, US Atomic Energy Commission Technical Information Service, RMO-983 (1953).
3. Everhart, D. L. and Wright, R. J., *The Geologic Character of Typical Pitchblende Veins*, Economic Geology, *48*: 77-96 (1953).

Relation of Secondary Uranium Minerals to Pitchblende-Bearing Veins at Marysvale, Piute County, Utah

By G. W. Walker and F. W. Osterwald,* USA

Pitchblende- and fluorite-bearing hydrothermal veins at Marysvale, Utah, grade upward into a complex assemblage of secondary uranium phosphate, silicate, carbonate, oxide, sulfate, molybdate, and vanadate minerals. Rocks in which the deposits occur are of Oligocene or younger age. Since discovery of the Marysvale deposits in 1948, large tonnages of ore have been mined from the zones of primary and secondary uranium minerals.

The principal uranium deposits are confined to an area of less than a square mile centered about 4 miles northeast of Marysvale, in Piute County. The Marysvale area, at an altitude of about 7000 feet, is in a series of hills in the Sevier River valley; the Tushar Mountains to the west reach an altitude of over 12,000 feet and the Sevier Plateau to the east reaches an altitude of 11,000 feet. The climate of the Sevier River valley is semi-arid.

GEOLOGY

The Marysvale ore is in and near the western edge of the High Plateaus division of the Colorado Plateaus physiographic province, and is contiguous with the Basin and Range physiographic province on the west. The Sevier River valley, in which the Marysvale area is located, represents a down-dropped fault block, or graben, between the upthrown Tushar Mountains to the west and the Sevier Plateau to to the east. The area is within an extensive region of Tertiary volcanic rocks; lesser amounts of Tertiary intrusive and Paleozoic and Mesozoic sedimentary rocks are exposed in a few places.

The rocks of the principal mining area are exclusively of igneous origin. Callaghan[1] separated the rocks into the Bullion Canyon volcanics of early Tertiary age, intrusive monzonite and associated rocks of post Oligocene (?) age, and the Mt. Belknap rhyolite of late Tertiary age. Additional information concerning these rocks and their relations has been obtained from descriptions by Taylor and others[2] and Kerr and others.[3] The Bullion Canyon volcanics consist chiefly of breccias, tuffs, and latitic to andesitic flows. According to Kerr (p. 14–15 of ref. 3), correlative volcanic rocks overlie sedimentary strata containing Oligocene fossils in south-central Utah. Small stocks of both porphyritic and nonporphyritic quartz monzonite and granite, presumably of post-Oligocene age, intrude the Bullion Canyon volcanics. Extensive erosion stripped most of the Bullion Canyon volcanites from the principal mining area at Marysvale and exposed the intrusive rocks prior to extrusion of the Mt. Belknap rhyolite of late Tertiary age; the pre-Belknap erosion surface had a relief of at least 500 feet. In the mine area, the Mt. Belknap rocks are mostly rhyolitic and from the base of the section upward, consist of thin, yellow, red, or black pitchstone layers, pyroclastic tuff breccias from 2 to 40 feet thick, and partly glassy red flows showing prominent flow banding and elongate flow vesicles. Partly glassy to devitrified and altered rhyolite dikes, thought by Taylor (p. 8 of ref. 2) to represent feeders for part of the Mt. Belknap rhyolite extrusives, crop out and are also exposed in underground workings in the north-central part of the area. Erosion subsequent to the extrusion of the Mt. Belknap rhyolite removed volcanic cover over much of the principal mining area leaving granitic rocks exposed at the surface.

Although no major faults have been recognized in the principal mining area, many small faults, shear zones, and fractures are exposed in open cuts and underground workings. The faults and shear zones show normal, reverse, and transverse displacements. Dominant trends of the faults and shear zones are northeast, northwest, and north; the north-trending set is less well developed than the other two sets. The northwest set dips about 40°–60° to the southwest whereas the other sets dip almost vertically. Several periods of movement are indicated by brecciation of wall rocks and early vein minerals and by minor displacement of vein structures following deposition of late vein minerals. The most active period of faulting and fracturing apparently followed the extrusion of the Mt. Belknap rhyolite and preceded the uranium mineralization; the faults and fractures probably are genetically related to the large high-angle faults that bound the Sevier River valley fault block. By analogy, these high-angle faults are correlative with other high-angle faults in central Utah which are of Pliocene age (p. 22–23 of ref. 4).

RELATION OF DEPOSITS TO GEOLOGY

Faults and fractures in the quartz monzonite, the dominant host rock, and in the volcanic rocks provided passageways for the ore-bearing solutions and controlled the deposition of the primary vein min-

* US Geological Survey.

erals. The wall rocks are commonly altered near the uranium-bearing structures particularly within a few hundred feet of the ground surface.

Pitchblende and secondary uranium minerals are most common in the northeast-trending faults, less common in the northwest-trending faults, and rare or absent in the north-trending faults. A few faults are continuously mineralized over horizontal distances of as much as 800 feet and vertical distances of more than 700 feet, although the uranium content varies from place to place. Within the faults and fractures, the uranium-bearing vein material commonly pinches and swells so that some ore is in pronounced shoots; locally, some of the best ore occurs in steeply plunging shoots at intersections of different fault sets or at places where faults change strike. Mineralization in faults occurs as narrow, locally siliceous, discontinuous veins separated by clay gouge or hydrothermally altered rock, or as breccia cemented by vein minerals.

Contacts between different rock types have influenced the localization of some of the uranium deposits. The contact between quartz monzonite and Mt. Belknap rhyolite is highly altered in places, but significant uranium mineralization has taken place only where the contact is slickensided in addition to the alteration. In a few places, ore bodies are enlarged beneath glassy agglomerate at the base of the Mt. Belknap rhyolite, and elsewhere uranium minerals are concentrated at the contact of quartz monzonite and rhyolite.

At least two main periods of hydrothermal alteration have affected the rocks of the Marysvale area. An early period of alteration, which is in no way related to the later primary uranium mineralization, is most pronounced in the Bullion Canyon volcanics and is characterized by the development of alunite. However, some hydrated, hexavalent-uranium minerals are associated with alunitic and clay-alteration zones in a few properties.[5,6] The quartz monzonite, granite, and Mt. Belknap rhyolite have been affected by a later period of hydrothermal alteration in which clay minerals were formed, chlorite was either introduced or formed at the expense of biotite, and locally the rocks were silicified. Although many uranium-bearing structures accompany or are enclosed by rocks showing this type of alteration, evidence for a genetic relation is either poor or lacking. Commonly the envelope of altered wall rock thins perceptibly with depth and in deeper workings is absent adjacent to most veins. The clay alteration may be a result of near-surface oxidation of pyrite. A thin alteration zone marked by red hematite around some ore bodies occurs principally in the primary zone; but, at places, it persists into the zone of supergene alteration.

Uranium mineralization is later than the Mt. Belknap rhyolite as indicated by the presence of fluorite, pyrite, and pitchblende in rocks of this sequence; the rocks also have been altered probably by the solutions that introduced the vein minerals. The deposits are thought to be of Pliocene age as the pitchblende and its associated minerals are localized in structures probably related to the large, high-angle, Pliocene faults.

PRIMARY ORE DEPOSITS

Pitchblende, associated principally with quartz or chalcedony, fluorite, pyrite, and adularia, occurs in several vein types and is known to have a vertical range of at least 2000 feet in the Marysvale area. Other minerals in or near the pitchblende-bearing veins are calcite, jordisite, hematite, magnetite, and marcasite. These minerals may have a more restricted distribution than the common gangue minerals.

Pitchblende has several modes of occurrence in the Marysvale area. Most of the pitchblende is associated intimately with fluorite, pyrite, and locally with molybdenum minerals in dark-purple to black veins, vein stockworks, lenticular and irregular masses, and breccia cement. In the dark vein filling, some of the pitchblende occurs as fine-grained, discontinuous thin veinlets alternating with thin layers of coarse purple fluorite and layers composed of fine-grained fluorite, pyrite, quartz, and adularia; and some occurs disseminated in a fine-grained, black, friable matrix composed of fluorite, pyrite, probably quartz and adularia, and clay or fault gouge. Pitchblende, associated with pyrite and adularia, is disseminated in a few brecciated, chalcedonic veins. Some of the richest pitchblende concentrations replace the matrix and fill interstices of brecciated fine-grained quartz. Pitchblende also occurs separately as isolated small pods, lenses, or disseminations in altered walls rocks, as fillings in elongate flow vesicles near the walls of late Tertiary rhyolite dikes, as thin coatings on joint and fracture surfaces, and, in small amounts, as replacements in hydrothermally altered wall rocks. The pitchblende occurs in a soft, powdery form and in hard, lustrous masses; some of the powdery pitchblende, particularly that on joint and fracture surfaces, is thought to be secondary, although none of its associated minerals show evidence of oxidation except near the boundary between the zones of secondary uranium minerals and primary pitchblende.

The dominant gangue minerals are quartz or chalcedony, fluorite, pyrite, and adularia. Most of the vein quartz in the principal mine area is clear to milky white, but near concentrations of pitchblende it is smoky to almost black in color. Purple to almost black fluorite, either in coarse crystals or in fine-grained powdery masses, is present in virtually all pitchblende-bearing veins; the fluorite content in most veins increases with depth. Colorless or pale green fluorite is present in alteration halos around uranium-bearing veins and also occurs in separate veins. Pyrite is much more widespread than the pitchblende, and locally unaltered masses remain scattered through the zone of supergene alteration almost to the ground surface. In general, pyrite pyritohedra occur in rocks near the veins and cubes near barren structures. Adularia occurs both

as a gangue mineral in the veins and as a devitrification product of the semiglassy groundmass of the Mt. Belknap rhyolite. At places adularia is associated closely with pitchblende and abundant fluorite in the dark-colored veins and at other places occurs as disseminated crystals in pitchblende-bearing chalcedonic veins in which fluorite is a miner constituent; locally, it is also found as euhedral crystals lining vugs in dark-purple fluorite.

Other gangue minerals associated with the pitchblende are magnetite, hematite, marcasite, and jordisite. Fine, granular magnetite and zones of red hematitic alteration in which hematite flakes have been deposited selectively on either feldspar grains or their alteration minerals are commonest near pitchblende-bearing ore shoots and veins. The hematite alteration zones are near concentrations of fluorite and pitchblende and are commonest within 5 feet of uranium ore. Marcasite, showing cockscomb structure, was identified only in one vein in which it was intimately banded with pitchblende and fluorite. The distribution and relations of tentatively identified siderite are but poorly recorded. Jordisite, black amorphous molybdenum disulfide, occurs close to several veins, particularly near vein pinchouts, and locally in the primary veins themselves.

SECONDARY MINERALS

The assemblage of secondary uranium minerals reported at Marysvale includes autunite, torbernite, metatorbernite, phosphuranylite, uranophane, β-uranotil, schroeckingerite, zippetite, johannite, uranopilite, tyuyamunite, and rauvite; other minerals that may be of secondary origin are sooty pitchblende and umohoite. Non-uranium secondary minerals, including iron and manganese oxides, ilsemannite, carbonates, and gypsum are locally present.

Ore-grade concentrations of secondary uranium minerals in the Marysvale area commonly represent the near-surface, altered extensions of pitchblende- and fluorite-bearing ore shoots or veins at depth. Alteration and solution of primary uranium minerals and redeposition of secondary ones occurred essentially in place. Most of the secondary uranium minerals occur within the vein structures although locally some concentrations are as far as 10 feet from the veins. The assemblage of secondary uranium minerals varies, in part, with respect to the type and degree of alteration of wall rocks, to the primary mineralogy of the veins, and to the depth beneath the ground surface. Some data on the distribution of the secondary uranium minerals has been obtained from reports by Kaiser,[7] Kerr *et al.*,[3,8] Taylor *et al.*,[2] Granger and Bauer[9] and Wyant.[5]

In some parts of the principal mining area, secondary uranium minerals extend to depths of as much as 400 feet beneath the ground surface, whereas in other parts of the area they extend only a few tens of feet. Throughout the area, the interface between the zones of hard pitchplende and of secondary minerals is extremely irregular and is probably related to fracture permeability associated with faults rather than to any static water table.

In general, the uranyl phosphate and silicate minerals are more abundant at Marysvale than are other secondary uranium minerals. Mostly they fill fractures or coat fracture surfaces, but some of the uranyl phosphates are disseminated in veins and wall rocks. These minerals, with the possible exception of phosphuranylite, are concentrated within a few feet of the originating pitchblende-bearing veins or their altered secondary counterparts. Phosphuranylite was identified from only one locality where it is in a zone of alunitic alteration in Bullion Canyon volcanic rocks; no primary uranium minerals were found at this locality. Autunite, torbernite, and metatorbernite, are rare or lacking in surface outcrops and are found principally as disseminations and fracture coatings in argillized quartz monzonite 10 feet or more beneath the ground surface. Autunite is one of the most abundant of the secondary minerals; it was identified in partly oxidized veins at a depth of 400 feet and hence has a relatively large vertical range. Although torbernite and metatorbernite commonly are intimately associated with the autunite, they have not been found over as great a vertical range nor are they as common in the oxidized veins.

Uranophane and β-uranotil occur only as fracture coatings and veinlets in quartz monzonite, granite, and rhyolite; they were not found disseminated in any of these rock types. Concentrations of these minerals occur from the surface to depths of 200 feet, and are most common within 10 feet of the originating vein. They are most abundant in surface or near-surface exposures, indicating that they are the most stable of the secondary minerals at Marysvale under near-surface weathering conditions. They are also abundant at the contact between quartz monzonite and the overlying rhyolites, in fractured quartz veins, and areas of wall-rock silicification. These two minerals are probably the most abundant of all secondary uranium minerals at Marysvale.

The uranyl sulfates, zippetite, uranopilite, and johannite, mostly form encrustations on mine walls; they are rare or absent in freshly broken ground. Schroeckingerite, a hydrated fluosulphocarbonate of sodium, calcium, and uranium, is commonest as fracture coatings, but in places it is disseminated in altered quartz monzonite. In a few places it has been found in altered rhyolite. Some schroeckingerite formed as post-mine encrustations and crystals on the walls of underground workings. Virtually none was found in surface outcrops, but it is a common constituent of oxidized veins from about 10 feet below leached outcrops to depths of about 100 feet.

The uranyl vanadates, tyuyamunite and rauvite, have not been found in the principal mine area, but have been reported from a prospect a few miles distant from the nearest known occurrence of pitchblende. At this prospect, minor amounts of the minerals are associated with uranyl phosphate minerals, principally as fracture coatings.

Some of the pitchblende is powdery black and occurs as fracture coatings, thin seams, and dustlike powder on primary vein minerals; pitchblende of this character is thought to be secondary. The sooty pitchblende occurs in quartz monzonite, granite, and rhyolite that show different degrees of argillic alteration or silicification. Although it has been found within 60 feet of the ground surface, most of the sooty pitchblende is concentrated near the interface between the oxidized and the unoxidized parts of the veins. Minerals associated with the powdery black pitchblende show little evidence of oxidation except near this interface.

A new mineral was discovered in the principal mine area at Marysvale in 1952 and was subsequently described and named umohoite by Kerr and others (ref. 8, p. 45–51). The mineral is hexagonal, black to bluish-black with a bright submetallic luster, and foliated or platy. The chemical composition indicates that it is essentially a hydrous uranium molybdate. It occurs as thin veinlets or disseminated specks in uranium-bearing veins associated either with (1) fluorite, pyrite, quartz, and pitchblende, or (2) with jordisite and ilsemannite, or (3) alone. Although very little is known concerning the distribution of umohoite, the principal occurrence is just below the oxidized zone in argillized quartz monzonite associated with a pitchblende- and fluorite-bearing vein that also contains jordisite and ilsemannite. Most of the umohoite does not occur with the other vein minerals, but has been preferentially deposited in thin veinlets and disseminated crystals in the altered quartz monzonite adjacent to the vein. Although Kerr and others[8] considered umohoite to be a primary uranium mineral, umohoite may be secondary because the uranium is hexavalent, it has a relatively high water content, and it is concentrated just below the zone of supergene alteration.

Supergene alteration of the pitchblende- and fluorite-bearing veins and of their enclosing rocks has produced, in addition to secondary uranium minerals, hydrated iron oxides, ilsemannite (a complex molybdenum sulfate), oxides of manganese, a pinkish carbonate, calcite, and gypsum. The hydrated iron oxides are distributed widely in the area, but commonly are lacking in the moderately altered quartz monzonite of the high-grade ore shoots; locally, hydrated iron oxides and secondary uranium minerals occur on the same joint. Gruner and others[10] have pointed out that some, if not all, of the hydrated iron oxides are goethite, and that most of the secondary uranium minerals are later than the goethite. The ilsemannite occurs closely associated with jordisite, from which it has been derived, in some of the pitchblende-bearing veins.

ORIGIN OF SOME URANIUM MINERALS

The near-surface ore-grade deposits of hydrated, hexavalent uranium minerals have been previously attributed solely to the oxidation of pitchblende-bearing veins, although available evidence suggests that some of these uranyl minerals and part, if not all, of the sooty pitchblende may have been deposited directly by warm solutions, either juvenile water or heated phreatic water.

The deposits of hexavalent-uranium minerals are the near-surface expression of quartz-fluorite-pyrite-adularia-pitchblende veins; the uranium content in both oxidized and unoxidized deposits is essentially the same. Some of the near-surface deposits of hexavalent-uranium minerals do not appear to contain as much fluorite and pyrite as do the pitchblende-bearing veins. In addition, hexavalent uranium minerals at Marysvale are not widely dispersed as might be expected if oxygenated circulating ground water had altered primary pitchblende and deposited the uranyl minerals.

The mineralogy and character of the pitchblende-bearing veins, particularly in their upper parts, indicate they probably were emplaced under a shallow cover and under conditions of low temperature and pressure.[10,2] Taylor[2] suggests that the near-surface deposits may be related to solfataric or fumarolic processes. Under these conditions, a change in the redox potential of rising, uranium-bearing, thermal solutions could cause reaction of uranium with available phosphate, sulfate, carbonate, or silicate anions derived through alteration of the wall rocks or from other sources. From such reaction, direct precipitation of uranyl phosphate, silicate, carbonate, or sulfate minerals might be expected.

Although some of the hexavalent-uranium minerals were undoubtedly derived essentially in place from oxidation of primary pitchblende ores, some are thought to have been deposited, where suitable conditions were met, by direct precipitation from the same solutions or ones similar to those that deposited pitchblende at depth under reducing conditions. A similar hydrothermal process of deposition for some uranyl minerals has been postulated by Kohl and Haller[11] for deposits at Wölsendorf.

GEOLOGICAL COMPARISON WITH OTHER AREAS

The uranium deposits at Marysvale have some characteristics in common with deposits in the Boulder batholith, Montana, and with deposits at Wölsendorf, Germany. Primary uranium ores at Marysvale and in the Boulder batholith are concentrated in siliceous veins and shoots within the veins. The mineralogy of the primary veins differs principally in (1) the relatively abundant fluorite and adularia at Marysvale, neither of which have been found in deposits in the Boulder batholith; (2) the greater abundance of pitchblende at Marysvale; and (3) the reported presence of minor amounts of galena, ruby silver, argentite, native silver, chalcopyrite, and arsenopyrite in the Boulder batholith deposits.[12,13,14] At both Marysvale and in the Boulder batholith a variety of hexavalent-uranium minerals, principally uranyl silicates, phosphates, and carbonates, appear to have formed by oxidation of primary ore essentially in place. The most abundant and widely distributed secondary

uranium mineral in the Boulder batholith deposits is uranophane; other secondary minerals include metatorbernite, metazeunerite, autunite, uranocircite (barium analogue of autunite), phosphuranylite, voglite, gummite, and rutherfordine. These minerals occur close to pitchblende-bearing veins or their altered secondary counterparts as does a somewhat similar assemblage of secondary uranium minerals at Marysvale. Phosphuranylite near primary pitchblende in the Boulder batholith deposits is the one notable exception; it is far removed from any known occurrences of pitchblende at Marysvale.

The siliceous veins at Wölsendorf, Germany, contain a relatively large amount of fluorite[11] and are reported to contain very minor amounts of chalcopyrite, bornite, sphalerite, pyrite, linnaeite(?) and stolzite. The fluorite contains pitchblende from which a series of secondary uranium minerals has formed. Kohl and Haller[11] separated the secondary minerals into two groups, those formed by ground-water alteration, including gummite, uranophane, fourmarierite, uranocircite, torbernite, and autunite, and those formed by hydrothermal alteration, including sooty pitchblende, ianthinite, uranophane, torbernite, autunite, and fourmarierite. The distinction between the two groups was made on the basis of paragenesis, distribution of minerals with respect to the water table and zone of oxidation, and the distribution of minerals with respect to cracks, fractures, holes, and druses. The ubiquitous uranophane, the sooty pitchblende, and the torbernite and autunite suggest a similarity to Marysvale, and it may be that the sooty pitchblende, umohoite, and part of the uranophane, autunite, and torbernite at Marysvale were also formed by hydrothermal alteration of primary pitchblende ores.

CONCLUSIONS

Concentrations of hexavalent uranium minerals at Marysvale are the near-surface extensions of pitchblende- and fluorite-bearing veins at depth. The veins, emplaced in faults and shear zones in Tertiary volcanic and intrusive rocks, are probably of early to middle Pliocene age. Some of the best ore, which is about the same grade in the oxidized and unoxidized parts of veins, occurs in steeply plunging shoots at intersections of different fault sets or at places where faults change strike; some ore is concentrated at the contact of the quartz monzonite and the overlying rhyolite. Hydrothermally altered wall rock accompanies some of the uranuim bearing structures, but, in general, the zones of alteration thin with depth and are absent adjacent to veins exposed in lower mine workings. Although most hexavalent uranium minerals are thought to have been derived essentially in place from oxidation of primary pitchblende some of the uranyl minerals, notably umohoite, and part of the uranophane, autunites, and torbernite, and some of the sooty pitchblende are thought to have resulted from the action of thermal solutions either by direct precipitation or by hydrothermal alteration of primary pitchblende.

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REFERENCES

1. Callaghan, Eugene, *Volcanic Sequence in the Marysvale Region in South-Central Utah*, American Geophysical Union Transactions, 20th Annual Meeting, Part 3: 438-452 (1939).
2. Taylor, A. O. *et al.*, *Geology and Uranium Deposits of Marysvale, Utah*, US Atomic Energy Commission RMO-896, Technical Information Service, Oak Ridge, Tennessee (1951).
3. Kerr, P. F. *et al.*, *Annual Report for July 1, 1951 to June 30, 1952*, US Atomic Energy Commission RMO-924, Technical Information Service, Oak Ridge, Tennessee (1952).
4. Eardley, A. J., *Structural Evolution of Utah*, in The Oil and Gas Possibilities of Utah, by G. H. Hansen and M. M. Bell; Utah Geological and Mineralogical Survey: 11-23 (1949).
5. Wyant, D. G., written communication.
6. Stugard, Frederick, Jr., Wyant, D. G. and Gude, A. J., 3d, *Secondary Uranium Deposits in the United States* in Selected Papers on Uranium Deposits in the United States, US Geological Survey Circular 220: 19-25 (1952).
7. Kaiser, E. P., *The Papsy's Hope Autunite Prospect, Marysvale District, Piute County, Utah*, US Geological Survey TEM-145A, US Atomic Energy Commission, Technical Information Service, Oak Ridge, Tennessee (1952).
8. Kerr, P. F. *et al.*, *Annual Report for June 30, 1952 to April 1, 1953*, US Atomic Energy Commission RME-3046, Technical Information Service, Oak Ridge, Tennessee (1953).
9. Granger, H. C. and Bauer, H. L., Jr., written communication.
10. Gruner, J. W., *et al.*, *The Uranium Deposits near Marysvale, Piute County, Utah*, Econ. Geol. *46*: 243-251 (1951).
11. Kohl, E. and Haller, H., *Die Mineralführung der Wölsendorfer Flusspatgange*, Zeitschrift Für Praktische, Geologie: 69-79 (1934).
12. Roberts, W. A. and Gude, A. J., 3d, *Uranium-bearing Deposits West of Clancey, Jefferson County, Montana*, US Geological Survey Bulletin 988-F: 69-87 (1953).
13. Thurlow, E. E. and Reyner, M. L., *Free Enterprise Uranium Prospect, Jefferson County, Montana*, US Atomic Energy Commission RMO-678, Technical Information Service, Oak Ridge, Tennessee (1950).
14. Becraft, G. E., *Preliminary Report on the Comet Area, Jefferson County, Montana*, US Geological Survey Circular 277 (1953).

Uranium Deposits at the Contact of Meta-Sediments and Granitic Intrusives in the Western United States

By Ernest E. Thurlow,* USA

Uranium deposits in close proximity to the contact of Paleozoic meta-sediments and granitic intrusives occur in at least two areas in the western United States: near Spokane, Washington and Austin, Nevada. Autunite is the principal secondary uranium mineral and uraninite has been tentatively identified from drill core. Concentrations of uranium minerals occur at the contact, in shear zones in the meta-sediments parallel with the contact, and also disseminated in small roof pendants of meta-sediments.

Nearby contact zones in each instance have yielded tungsten ores and each uranium deposit was discovered as a direct result of the fluorescence of autunite observed when searching for scheelite with an ultra-violet lamp. A zonal arrangement of metals is indicated in the Austin area and silicification is intense, whereas faulting and shearing were more pronounced at the Washington locality with little evidence of replacement of the country rock or introduction of quartz. Since exploration in these areas is not far advanced, observations recorded below are preliminary.

SPOKANE, WASHINGTON

Geography

A potentially important deposit of uranium is situated on the Spokane Indian Reservation in Stevens County, northwest of the city of Spokane (Fig. 1). It is in an area of low, rounded hills with local steep slopes not far from the confluence of the Columbia and Spokane rivers. Elevations in the general vicinity range from 2000 to 4000 feet above sea level. The district is named for the small town of Springdale, which lies to the east and has been known principally for its tungsten deposits. The climate is mild and total annual rainfall ranges from sixteen to twenty inches with about two-thirds of this falling during the winter season.

General Geology

The region is characterized by a diversity of rock types ranging from pre-Cambrian to Recent age. Nearly two-thirds of the area of Stevens County is composed of a thick series of metamorphosed sedimentary rocks of Paleozoic age which have been termed the Stevens series.[1] These have been intruded and, in places, greatly disturbed by batholithic masses of granite, syenite, and granodiorite. The predominant intrusive rock is the Loon Lake granite. Large areas are heavily covered with deposits of glacial drift and layers of soil. The Columbia basaltic lava plateaus so extensively developed south of the Spokane River extended northerly into this area as long, irregular shaped tongues.

A total of 40,000 to 50,000 feet of unfossiliferous sedimentary rocks of probable late Paleozoic age makes up the Stevens series. Seventeen formational units have been described from this series, although some duplication may exist because of difficulties in correlation.[1] The rocks are principally limestone, argillites, and quartzites. The Deer Trail argillite formation is in the lower part of the series and is the host for the uranium deposit. It measures approximately 3000 feet in thickness and at this locality is chiefly mica schist and phyllite with a few lenses of quartzite. Mica schist is predominant in the contact zone.

The Loon Lake granite is a coarse-grained holocrystalline, somewhat porphyritic intrusive with aplitic and pegmatitic facies. In the vicinity of the ore deposit an aplitic dike cuts both the argillite and the granite and appears to be an unfavorable host rock.

The meta-sediments generally lie in a series of northeasterly trending overturned folds which have been deeply truncated by erosion.[1] While no major tectonic structures cross the region, local faulting is common. The uranium deposit lies on the southeast flank of one of the major folds where the Deer Trail argillite is in contact with the Loon Lake granite.

Ore Deposits

Uranium occurs in shear zones at the contact of the Deer Trail argillite and the Loon Lake granite and also in a series of similar zones within the meta-sediments generally parallel with, and not far from, the contact (Fig. 2). The secondary uranium mineral autunite is also found in the granite as much as twenty feet from the contact where it may have been deposited by meteoric waters. No direct evidence of primary uranium mineralization is known within the granite.

Autunite and uranophane are the principal uranium minerals in the oxidized zone and uraninite associated with pyrite has been tentatively identified from drill

* US Atomic Energy Commission.

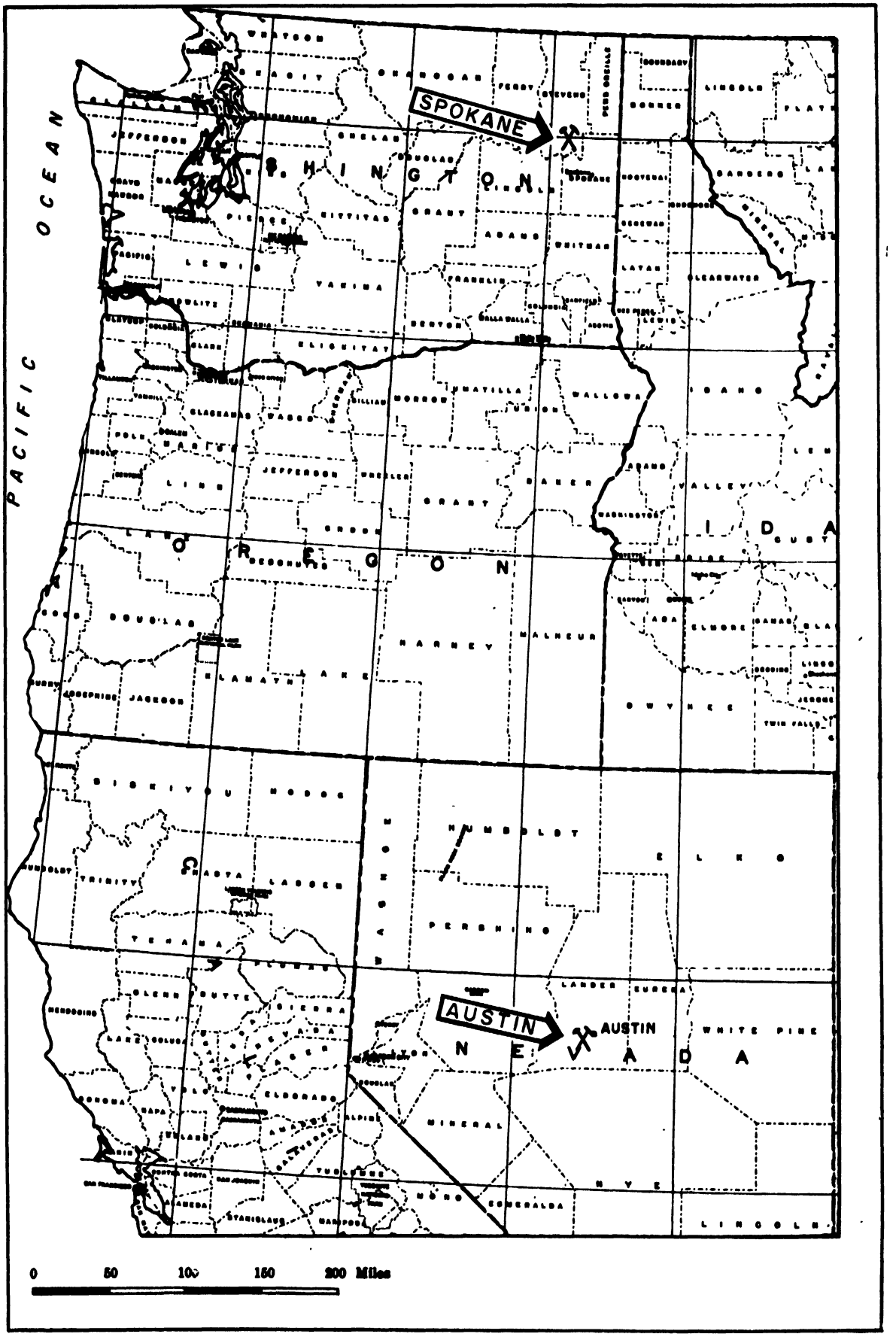


Figure 1. Index map of Western United States showing location of Spokane and Austin

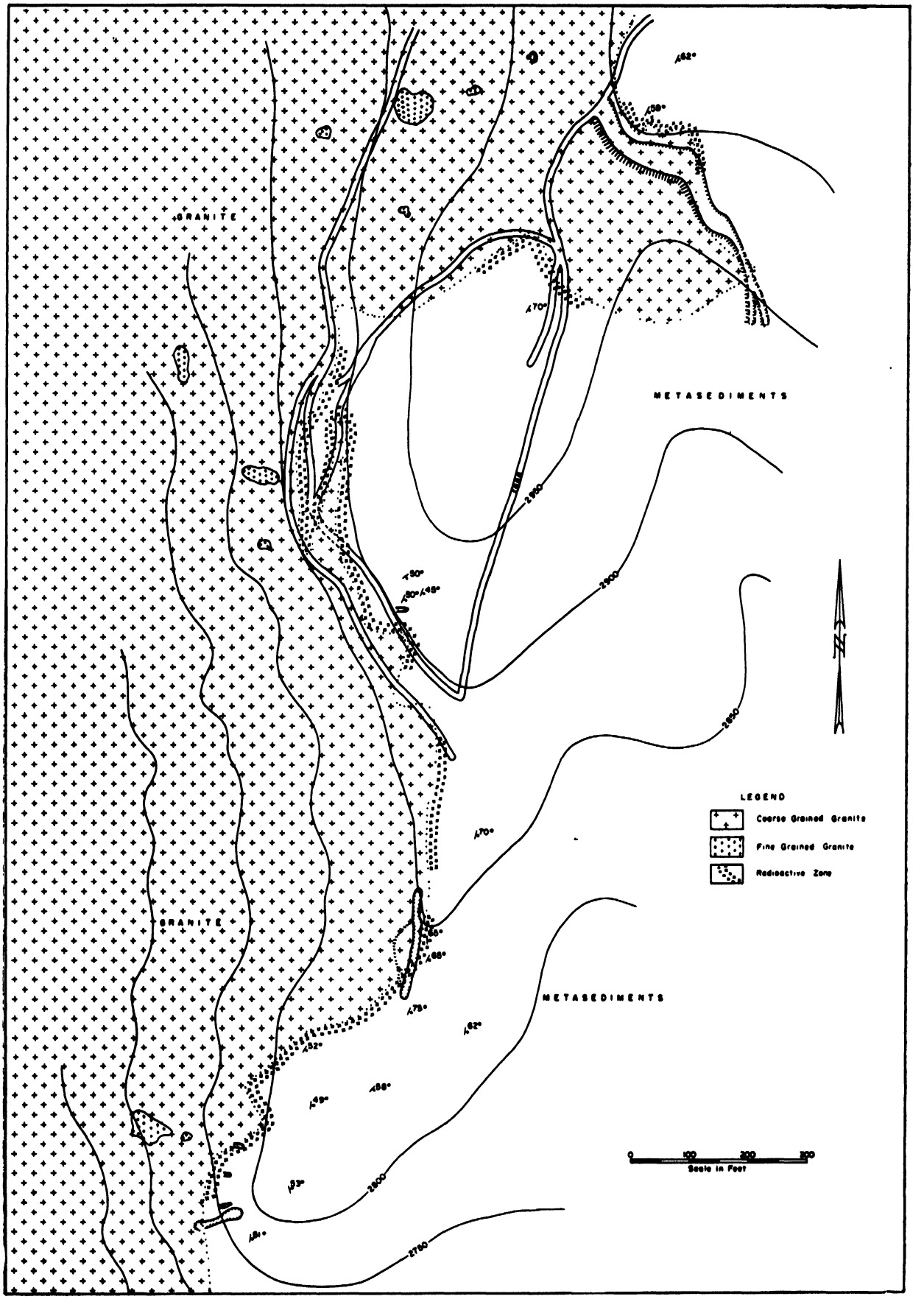


Figure 2. Geologic map of contact area, Spokane Indian Reservation

core recovered from a depth of 150 feet. Gangue minerals other than pyrite are almost completely lacking, and very little replacement of the host rock is apparent. The process of ore emplacement apparently involved only the filling of shear zones by deposition from ascending solutions. However, the original distribution of the primary ore is obscured by widespread oxidation and probable redistribution of the uranium as secondary minerals. The close association of the uranium with the Loon Lake granite suggests its derivation from the original magma.

The average dip of the contact at the outcrop is about fifty-five degrees in an easterly direction. Outcrops of the mineralized zone average about eight feet in width. There has not been sufficient exploration to determine the exact extent of the mineralized zone although the outcrop is mineralized for at least 2000 feet.

The general geologic environment at this deposit is repeated over a large area in northern Washington and a few other occurrences of uranium are known in the region.

AUSTIN, NEVADA

Geography

Austin, Nevada is in the Reese River silver mining district in Lander County near the center of the state. Uranium occurs apart from the silver ores near the southern edge of the district about three miles south of Austin.[2] Elevations range from 6000 to 7500 feet above sea level. Stream-cut canyons form rounded and moderate slopes and the foothills are covered by alluvium which is part of the eastern edge of a typical intermontane basin in the Basin and Range province. The climate is semi-arid to arid with most of the precipitation in the winter months. Vegetation consists of sage, pinion and juniper.

General Geology

The Reese River mining district is in the northern part of the Toyabe range and centers about a mass of quartz monzonite of probable Jurassic age. In the vicinity of the uranium occurrences, a series of sedimentary rocks is in contact with this intrusive body (Fig. 3). The meta-sediments are dominantly quartzites and phyllites with minor outcroppings of silicified limestones and hornfels. Fossils are lacking and the age of the rocks has been variously estimated as Cambrian or Silurian.[3,4]

The contact of the sedimentary rocks with the quartz monzonite dips about forty-five degrees to the south in Veetch Canyon. Roof pendants of metamorphosed sediments and irregularities in the contact appear to be the result of differential erosion of a flatter contact at higher elevations.

The quartz monzonite is host to narrow siliceous and intermediate dikes as well as to numerous mineralized fracture zones. A small area of extrusive rock near the head of Veetch Canyon is of dacitic composition and presumably Tertiary in age.

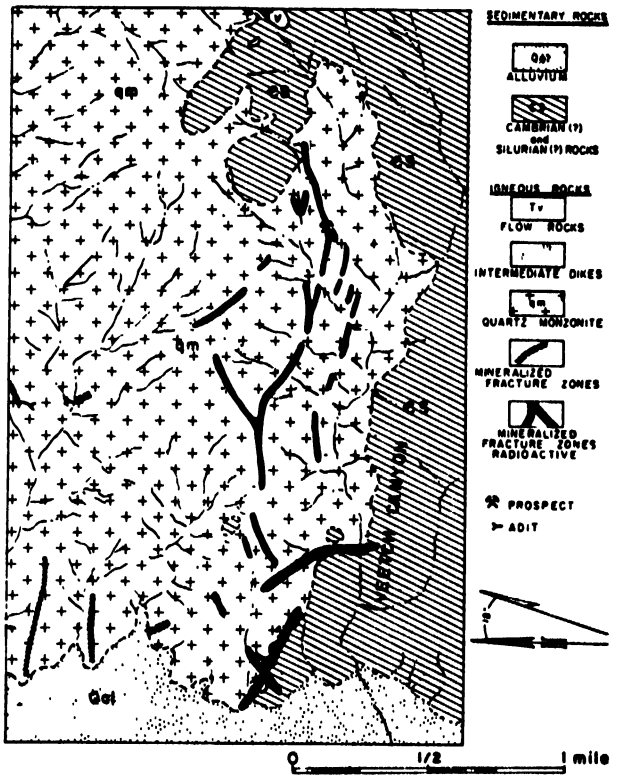


Figure 3. Geologic map showing a portion of intrusive contact south of Austin, Nevada

Ore Deposits

The secondary uranium minerals autunite and meta-torbernite occur in faults and fractures in both the intrusive and sedimentary rocks and are also disseminated in small roof pendants of meta-sediments near the contact of these units. The fracture zones apparently served as conduits for ascending uraniferous solutions which also contained silver, gold, and copper as well as silica and iron. They trend generally east-west and measure five to one hundred feet in width and fifty to several thousand feet in length. Dip of the mineralized zones varies from fifty degrees in a northerly direction to nearly vertical. In general appearance they resemble dikes and are composed principally of finely divided sericite with varying amounts of vein quartz. These veins form reef-like ridges in the intrusive rocks, whereas they are inconspicuous in the meta-sediments. The distribution of uranium along the fractures indicates that meta-sediments were the more favorable host rocks for mineral deposition. The best concentration of uranium minerals is in a fracture zone in meta-sediments near the intrusive contact.

Silver mines in the central and northern part of the district were developed along similar zones, but no abnormal radioactivity was detected in those areas. Quartz veins containing stibnite lie to the south of the uranium occurrences and scheelite has been mined from tactite zones to the east. A zonal arrangement of minerals outward from the central Austin area appears probable but more detailed study would be required to establish this concept.

REFERENCES

1. Weaver, Charles E., *The Mineral Resources of Stevens County, Washington,* US Geol. Survey Bull. 20 (1920).
2. Sharp, B. J. and Hetland, D. L., *Preliminary Report on Uranium Occurrences in the Austin Area, Lander County, Nevada,* US Atomic Energy Comm. RME-2010 (1954).
3. Ross, C. P., *The Geology and Ore Deposits of the Reese River District, Lander County, Nevada,* US Geol. Survey Bull. 997 (1953).
4. Ferguson, H. G., 1929, *The Mining Districts of Nevada,* Econ. Geol., 24: 115–148 (1929).

Relation of Tectonic Elements in Precambrian Rocks to Uranium Deposits in the Cordilleran Foreland of the Western United States

By F. W. Osterwald,* USA

The "Cordilleran Foreland" is a region containing distinctive structural elements that forms a broad north-south belt parallel to and east of the Cordilleran geanticline (Fig. 1). The predominate geological structure within the Foreland is a series of anticlinal mountains and broad asymmetric basins that contrast sharply with the folds and overthrusts related to the Cordilleran geanticline to the west. The mountains of the Foreland are bordered by flexures, and by high-angle normal and reverse faults. Many structures are covered by nearly flat-lying sedimentary rocks of Tertiary age. The eastern margin of the Foreland is beneath the Tertiary rocks of the Great Plains and has not been defined.

The discovery of uranium deposits within the Foreland led to a study of where and why uranium is concentrated in this tectonic environment. Deposits of metallic minerals other than uranium minerals are few and widely scattered, and most are in outcrop areas of Precambrian rocks. Uranium deposits, however, are widely distributed throughout the region as disseminated uranium and uraniferous lignites in the sedimentary rocks of the basins, and as veins in the crystalline cores of mountain ranges.

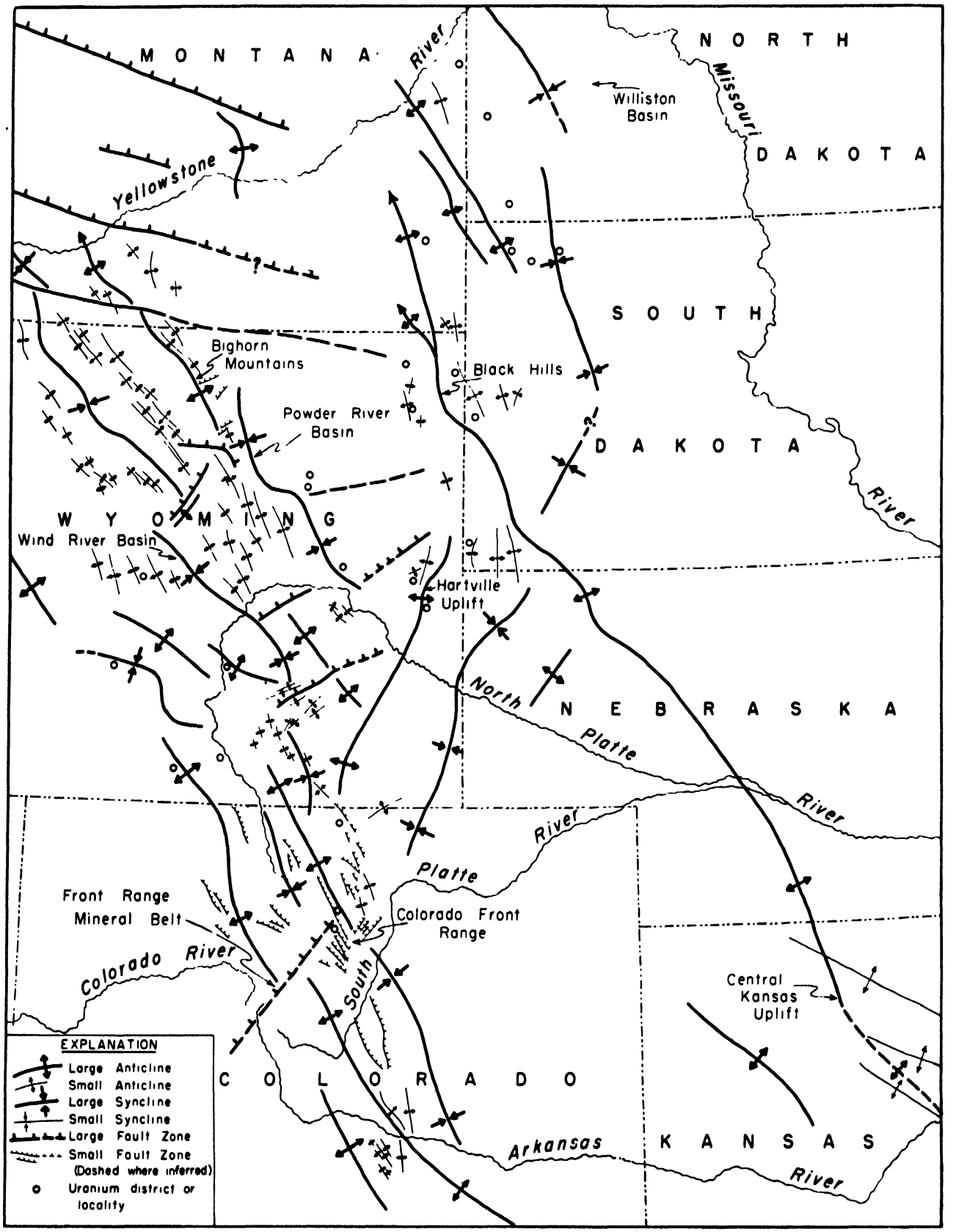
Through the studies that are still in progress it is hoped that criteria of tectonic and structural favorability will be developed to aid in the search for new uranium districts. Structure contour maps showing the configuration of the top of the Precambrian rocks are being compiled for a large part of the Cordilleran Foreland. Such maps, based on available geophysical or well-log data, enable one to project structures for considerable distances, even under a thick cover of nearly flat-lying Tertiary rocks. It is believed that use of the Precambrian datum plane eliminates most of the effects of unconformities. In addition, structures of Precambrian age undoubtedly have influenced the location and direction of later structures that are fundamental controls for localization of uranium districts. Therefore, by obtaining an accurate picture of the basement configuration beneath known uranium districts, one might pick out other areas of similar configuration.

* US Geological Survey.

TECTONIC HISTORY AND DEVELOPMENT

Many large-scale and small-scale structures of the Foreland record earth movements at various times during geologic history. In many places preexisting structures controlled the pattern of later structures.[1] These major controlling structures include: (1) the ancestral Rocky Mountains, which formed during the Pennsylvanian period, on the site of the present Colorado Front Range (Fig. 1) and adjacent ranges (Ref. 2, p. 230–233); (2) the central Kansas uplift (Fig. 1), which was elevated in pre-Mississippian time, in Pennsylvanian time, and in Late Cretaceous or early Tertiary time (Ref. 3, p. 49); (3) the Williston basin of western North Dakota and eastern Montana (Fig. 2), which occupies about the same position as an early Paleozoic depositional basin (Ref. 3, p. 61); (4) the large east-west trough in central Montana, which was filled with a thick series of sedimentary rocks in late Precambrian time and also in Mississippian time (Ref. 2, p. 287). Movements during the Late Cretaceous, apparently along steep fractures bordering the old trough, produced a belt of *en echelon* faults on the north side, and sharp flexures on the south side of the trough (Ref. 2, p. 341–342); (5) the prominent Laramide anticlines in Wyoming, which began to form early in geologic time (Ref. 4, p. 2155); and (6) the Tertiary uplifts in the Beartooth and Bighorn Mountains and in the Black Hills that coincide with Precambrian structures.[5]

Precambrian structure also influenced later deformation on a small scale; only a few examples are given here. Pre-Oligocene faults and folds in the Bighorn Mountains (Fig. 1) follow the trend of primary foliation planes and joints in Precambrian granitic rocks.[6,7] Precambrian fractures in granitic rocks of the Colorado Front Range (Fig. 1) were reopened during Pennsylvanian time and filled with sandstone dikes;[8,9] repeated movement during Tertiary time, as shown by correlation of Tertiary erosion surfaces, has sheared the sandstone filling. Isopachous contours of Pennsylvanian rocks in southeastern Wyoming show that some tectonic trends during the Pennsylvanian period had about the same trends as the present tectonic units and occupied about the same position.



Modified from Tectonic Map of the United States Am Assoc Petroleum Geologists, 1944

Figure 1. Structural trends of the Cordilleran Foreland

Widely scattered observations indicate that the predominating structural trends in the Precambrian rocks are northeast and northwest. Near the Front Range mineral belt (Fig. 1), early lineation and foliation in Precambrian rocks trend northeast, and later lineation trends northwest.[10] Precambrian structures in rocks of the Medicine Bow Mountains of southern Wyoming trend northeast;[11] similar trends are found in the Laramie Range, Wyoming, and in the Hartville uplift, Wyoming (Fig. 1). Metamorphic rocks in the Bighorn Mountains, Wyoming, have pronounced lineation and probable zones of overthrusting that trend northeast, but somewhat younger Precambrian granitic rocks have northwest-trending structure.[6] The tectonic pattern of present structures parallels these Precambrian trends (Fig. 1).

The distribution of mountain ranges in the Foreland is related in part to the distribution of Precambrian granite massifs.[1] Precambrian cores of many ranges in the Foreland, and also in Kansas and Oklahoma,[12] consist of granitic rocks in the center and metamorphic rocks around the margins.

The thrust or reverse faults marginal to many ranges have led some authors, for example Beckwith,[13] to postulate that horizontal compressive stresses caused much of the deformation within the region. The marginal thrusts, however, may be produced by the vertical or near-vertical uplift of rigid blocks of Precambrian rocks, together with a slight amount of rotation of individual blocks during the uplift. The thrusts may be partly similar to the thrust that is marginal to a salt dome at Boling Dome, Texas,[14] to the marginal upthrusts around plutonic intrusions,[15] and to the fractures produced in pressure-box model experiments by Link.[16]

INFLUENCE OF STRUCTURE ON LITHOLOGY

The lithology of some Mesozoic rocks of the Foreland exhibits a close relation to structure on both regional and local scales. The clastic material composing the rocks was derived, in large part, from the rising Cordilleran geanticline to the west; the result is a gradation from coarse-grained sediments to the west into finer grained rocks to the east. Local uplifts (Ref. 2, plate 16) probably influenced the sedimentation in their immediate areas by locally providing coarser grained clastic material. Because some of these rocks provide favorable hosts for uranium deposition, the structural influence on lithology is important in the localization of uranium deposits. An example of regional influence is the Morrison formation of Jurassic age, which in the Foreland consists of siltstone and other argillaceous material with lenses of sandstone and fresh-water limestone, but which grades westward into sandstone. Though uranium minerals and radioactivity highs are widely scattered throughout the Morrison rocks in Wyoming, important uranium deposits are known only in the Colorado Plateau region, where sandstone is most abundant. Clastic rocks resulting from local uplifts provide favorable hosts for uranium deposits in the Black Hills.

The influence of local structures on lithology is illustrated best by some of the Lower Cretaceous sandstones in the southern part of the Powder River Basin, Wyoming (Fig. 1), which thicken near the axial parts of anticlines;[4] the thickest part is slightly down structure from the crest of the anticline. The thickening is repeated in several stratigraphic units of different ages on the same structure, and deposition of the standstones was influenced by repeated uplift of the growing structure. Similar thickening is probable on many anticlinial structures in the region. In the Black Hills the heavy-mineral suite of some sandstones of Lower Cretaceous age contains minerals similar to those found in Precambrian rocks, suggesting that the sandstone formed during uplift of the Black Hills and that the Precambrian rocks were being eroded at that time.[17] Similar Cretaceous rocks contain commercial uranium deposits in this area. Because of the lithology of the beds and the mineral suites, in these areas, were influenced by structures, it is believed that regional tectonics also were important in controlling the location of uranium districts by determining the location of favorable host rock.

Paleocene sediments in some basins of the Foreland are thickest in structural troughs, near and parallel to uplifts.[18,19] Early Tertiary conglomerates at the edges of some basins in south-central Wyoming grade rapidly into shale and coal beds,[20] as a result of abrupt changes in the tectonic conditions—rapidly rising mountains at the basin margins and more slowly subsiding basin centers. Stable areas bordering downwarped, unstable troughs, where rocks of dominantly medium-grained sediments are abundant, seem to be favorable localities for uranium deposition, as in the Williston Basin region (Fig. 1) and the Great Divide Basin, Wyoming.

Relatively young tuffaceous rocks crop out in some basin interiors, partly because the interiors suffer less erosion than the margins of the basins, and partly because thicker sedimentary sections are deposited in the basin troughs. As tuffs are possible source rocks of uranium, their presence in basins is favorable for the occurrence of ore deposits. Examples are small patches of tuffaceous sedimentary rocks of Oligocene age in the Powder River Basin (Fig. 1), which may have been source rocks for the uranium deposits in underlying rocks of Eocene age.[21] Favorable beds in the underlying rocks, equally necessary for the localization of deposits, were probably controlled by the tectonic conditions during Eocene time. Regional unconformities beneath tuffaceous sediments probably controlled movement of uranium; disseminated deposits and uraniferous lignites commonly are parallel to and beneath such unconformities.[22]

TECTONIC ANALYSIS OF THE REGION

The various structures of the Foreland can be divided into three large classes to show the relation of uranium deposits to the structural pattern. (1) Large-scale structures include large mountain ranges, major basins, and fault zones with structural relief as much as a few tens of thousands of feet;

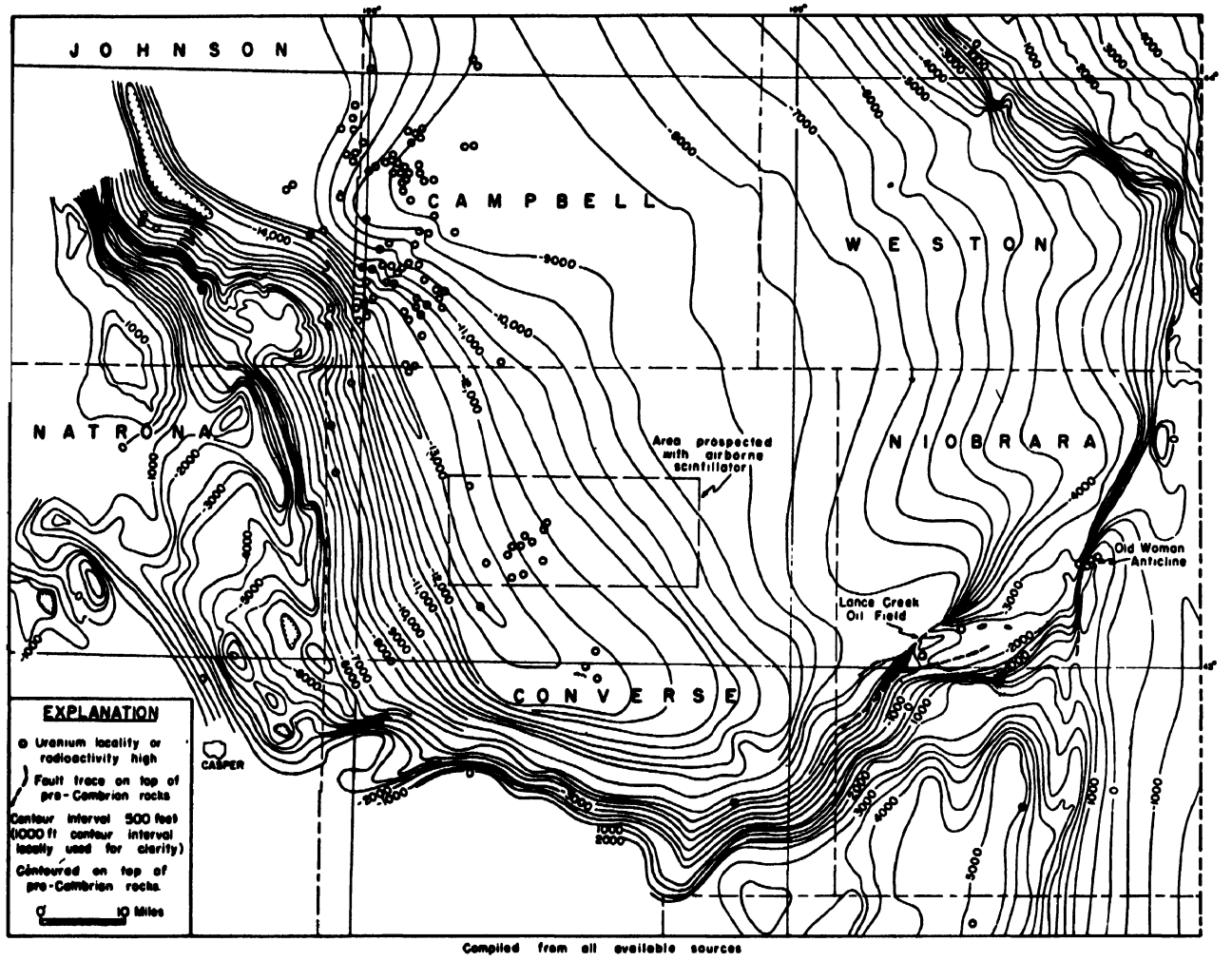


Figure 2. Structure contour map of southern Powder River Basin, Wyoming

some are several hundred miles long. (2) Intermediate-scale structures are large folds and faults superimposed on large-scale structures. These have a structural relief of a few hundred feet; few exceed several tens of miles in length. (3) Small-scale structures are folds, faults, and joints of lesser size which, though not important in the localization of uranium districts, nevertheless may be very important controls of individual deposits.

Large- and intermediate-scale structures within the Cordilleran Foreland are outlined on Fig. 1. The three sets of large-scale structures, which trend northwest to north-northeast and west-northwest, are of Precambrian age. The northwest set is the most pronounced but is disrupted in part by the northeast set, which is probably younger. The west-northwest set appears only in central and southern Montana, and consists of long, almost-parallel faults or fault zones in Precambrian rocks,[23] that apparently offset the northwest- and northeast-trending large-scale structures of Precambrian age.

Most of the known uranium districts within the Foreland are in four structural environments: (1) areas near major basin axes along northwest-trending large-scale structures; (2) areas in which northwest- and northeast-trending large-scale structures intersect; (3) areas in which groups of *en echelon,* northwest-trending intermediate-scale structures are superimposed on northwest-trending large-scale structures; and (4) areas over or near large faults or fault zones in Precambrian rocks, associated with northeast-trending large-scale structures.

Uranium districts near major basin axes are best illustrated by the Powder River Basin (Fig. 2), Williston Basin (Fig. 1), and Great Divide Basin of Wyoming. Most of the deposits in the Powder River Basin are located east of the basin axis, drawn on the Precambrian surface. Many are located along a zone in which the slope of the surface increases. Most of the known deposits are at the north end of the group of deposits shown on Fig. 2, where the basin floor is interrupted by a northeast-trending large-scale structure that has little or no surface expression. Little information is available concerning the northeast-trending structure, but it is probably a belt of fault blocks in Precambrian rocks. Figure 2 also shows the outline of an area which was prospected with airborne scintillation counters. Anomalies and deposits were found only in the western end of the area near the basin axis; the eastern end is barren.

Uranium districts in areas of intersecting northwest- and northeast-trending large-scale structures include vein deposits in the Hartville Uplift (Fig. 1),[24,25] and in the northern Laramie Range, Wyoming, and disseminated deposits in south-central Wyoming.[26]

Uranium deposits in or near zones of *en echelon* intermediate-scale structures superimposed on northwest-trending large-scale structures include the vein deposits in the Colorado Front Range (Fig. 1), the disseminated deposits in the Black Hills (Fig. 1), and the disseminated deposits along the southwest margin of the Wind River Basin (Fig. 1).

Uranium districts over or near zones of large steep fractures associated with northeast-trending large-scale structures are illustrated by the deposits on the flank of Old Woman anticline, Wyoming (Fig. 2).

LOCALIZATION OF URANIUM DISTRICTS BY TECTONIC ELEMENTS

The intersections of two major tectonic elements trending northwest and northeast, which seem to be favorable for localization of uranium districts, may be areas in which the energy levels were slightly raised by an increase in the geothermal gradient, by faulting and folding, or by a combination of the two factors. The slight increase caused uranium, probably dispersed through the rocks as adsorbed ions, to be expelled, moved, and later concentrated.

Margins of major tectonic units may be places in which the energy levels are changed by the same factors mentioned for intersections of elements, allowing uranium to be released and concentrated in smaller structures. However, the uranium probably would be merely moved upward and laterally, and be redispersed in another place if favorable environments providing local points of low-energy level were not met. These environments are provided by structures such as *en echelon* faults along the east margin of the Colorado Front Range (Fig. 1), and the anticlinal noses that localize deposits on the flanks of the Black Hills (Fig. 1). The ore is localized however, not in the intermediate-scale structures, but in small-scale structures probably related to them. The uranium in the Front Range pitchblende vein deposits may have been dispersed originally in Precambrian igneous and metamorphic rocks, and the uranium in the Black Hills disseminated deposits may have been dispersed in sedimentary rocks of younger age. The forces that expelled, mobilized, and concentrated the uranium in both areas were probably similar and were probably active during Cretaceous or Tertiary time.

The repeated deformation along Precambrian structural trends and the gradual, long-continued growth of structures may have caused nearly flat-lying Tertiary rocks to be slightly bent and jointed. Gentle folds and associated joints in Pliocene rocks in southern Wyoming indicate that at least some deformation took place late in Tertiary time. These minor structures in Tertiary rocks may have provided places of low-energy level to localize uranium mobilized by larger structures below. A possible example is the deposits in Tertiary rocks overlying the flanks of the Lance Creek oil field (Fig. 2).

Clusters of small plugs, dikes, necks, sills, and flows crop out in the Black Hills of South Dakota and Wyoming, in the Sweetwater arch of central Wyoming, and in the Leucite Hills of south-central Wyoming. Others that do not crop out are known from geophysical exploration. Most of the volcanic rocks are Tertiary in age and some may have been the source for much of the pyroclastic material found in widespread sediments of Tertiary age (Ref. 33, p. 34). These alkaline volcanic clusters seem to be related to tectonic features in a manner very similar to that of the uranium deposits. The areas in which the energy levels were relatively high may have been raised locally even higher to permit small bodies of magma to form. Burbank[28] pointed out that the formation of magma is a special case in which the energy level necessary for energy flow is so high that the flow results in a silicate liquid, and that previously mobilized elements may become mixed with material of the silicate melt. For these reasons, some of the bodies of igneous and pyroclastic rock may have provided uranium, which was later concentrated into deposits.

REFERENCES

1. Thom, W. T., Jr., *Structural Features of the Bighorn Basin Rim,* University of Wyoming, Wyoming Geological Association and Yellowstone Bighorn Research Association, Field Conference in the Bighorn Basin, Guidebook: 176–177 (1947).
2. Eardley, A. J., *Structural Geology of North America,* Harper and Brothers, New York (1951).
3. King, P. B., *The Tectonics of Middle North America East of the Cordilleran System,* Princeton University Press, Princeton, New Jersey (1951).
4. Curry, W. H., Jr. and Curry, W. H., III, *South Glenrock, A Wyoming Stratigraphic Oil Field,* American Association of Petroleum Geologists Bulletin 38: 2119–2156 (1954).
5. Cloos, Ernst and Cloos, Hans, *Pre-Cambrian Structure of the Beartooth, the Big Horn, and Black Hills Uplifts and its Coincidence with Tertiary Uplifting,* Geological Society of America Proceedings 1933: 56 (1934).
6. Osterwald, F. W., *Structure and Petrology in the Northern Bighorn Mountains, Wyoming,* Geological Survey of Wyoming Bulletin (in press).
7. Osterwald, F. W., *Structure of the Tongue River Area, Bighorn Mountains, Wyoming,* Wyoming Geological Association, 4th Annual Field Conference in the Powder River Basin, Guidebook: 37–38 (1949).
8. Vitanage, P. W., *Sandstone Dikes in the South Platte Area, Colorado,* Journal of Geology 62: 493–500 (1954).
9. Crosby, W. O., *Sandstone Dikes Accompanying the Great Fault of Ute Pass, Colorado,* Essex Institute Bulletin 27: 113–147 (1897).
10. Sims, P. K., Osterwald, F. W., and Tooker, E. W., written communication.
11. Blackwelder, Eliot, *Pre-Cambrian Geology of the Medicine Bow Mountains,* Geological Society of America Bulletin 37: 615–658 (1926).

12. Hiestand, T. C., *Regional Investigations, Oklahoma and Kansas,* American Association of Petroleum Geologists Bulletin 19: 948–970 (1935).
13. Beckwith, R. H., *Structure of the Elk Mountain District, Carbon County, Wyoming,* Geological Society of America Bulletin 52: 1445–1486 (1941).
14. Halbouty, M. T. and Hardin, G. C., Jr., *Thrust Fault at Boling Dome, Texas,* American Association of Petroleum Geologists Bulletin 38: 1725–1741 (1954).
15. Cloos, Hans, *Plutone und ihre Stellung im Rahmen der Krustenbewegungen,* 16th International Geological Congress, Proceedings I: 235–253 (1933).
16. Link, T. A., *Experiments Relating to Salt-Dome Structures,* American Association of Petroleum Geologists 14: 483–503 (1930).
17. Crowley, A. J., *Possible Lower Cretaceous Uplifting of Black Hills, Wyoming, and South Dakota,* American Association of Petroleum Geologists Bulletin 35: 83–90 (1951).
18. Mackin, J. H., *Altitude and Local Relief of the Bighorn Area During the Cenozoic,* University of Wyoming, Wyoming Geological Association, Yellowstone-Bighorn Research Association, Field Conference in the Bighorn Basin, Guidebook: 103–119 (1947).
19. Van Houten, F. B., *Origin of Red-Banded Early Cenozoic Deposits in the Rocky Mountain Region,* American Association of Petroleum Geologists Bulletin 32: 2083–2126 (1948).
20. Knight, S. H., *The Late Cretaceous-Tertiary History of the Northern Portion of the Hanna Basin—Carbon County, Wyoming,* Wyoming Geological Association, 6th Annual Field Conference in South-Central Wyoming, Guidebook: 45–53 (1951).
21. Love, J. D., *Preliminary Report on Uranium Deposits in the Pumpkin Buttes Area, Powder River Basin, Wyoming,* US Geological Survey Circular 176 (1952).
22. McKay, E. J., oral communication.
23. Chamberlin, R. T., *A Peculiar Belt of Oblique Faulting,* Journal of Geology 27: 602–613 (1919).
24. Ball, S. H., *Contributions to Economic Geology, 1906, Part I, Copper Deposits of the Hartville Uplift, Wyoming,* US Geological Survey Bulletin 315–B: 93–107 (1907).
25. Larsen, E. S., Hess, F. L. and Schaller, W. T., *Uranium Minerals from Lusk, Wyoming,* American Mineralogist 11, number 6: 155–164 (1926).
26. Love, J. D., *Preliminary Report on the Uranium Deposits in the Miller Hill Area, Carbon County, Wyoming,* US Geological Survey Circular 278 (1953).
27. De Vore, G. W., *The Role of Adsorption in the Fractionation and Distribution of Elements,* Journal of Geology 63: 159–190 (1955).
28. Burbank, W. S., written communication.
29. Ramberg, Hans, *The Thermodynamics of the Earth's Crust; I. Preliminary Survey of the Principal Forces and Reactions in the Solid Crust,* Norsk Geologisk Tidsskrift, Bd. 24: 98–111 (1944).
30. Ramberg, Hans, *Relation Between External Pressure and Vapor Tension of Compounds and Some Geological Implications,* Norske Videnskaps-Akadami Auhandlinger Matematisk-Naturvidenskapelig Klasse 3, Oslo (1944).
31. Barth, T. F. W., *The Distribution of Oxygen in the Lithosphere,* Journal of Geology 56: 41–49 (1948).
32. Barth, T. F. W., *Theoretical Petrology,* John Wiley & Sons, New York (1952).
33. Carey, B. D., *A Brief Sketch of the Geology of the Rattlesnake Hills,* Wyoming Geological Association, 9th Annual Field Conference in the Casper Area, Guidebook (1954).
34. Blackstone, D. L., Jr., *Tectonic Map of Southern Wyoming and Northern Colorado,* Wyoming Geological Association, 8th Annual Field Conference, Guidebook (1953).
35. Lovering, T. S. and Goddard, E. N., *Geology and Ore Deposits of the Front Range, Colorado,* US Geological Survey Professional Paper 223 (1950).

Influence of Regional Structure upon the Origin and Distribution of Uranium in the Colorado Plateau

By Vincent C. Kelley,* USA

The Colorado Plateau is located in the western United States and is a part of the grand cordillera of North America (Fig. 1). It embraces an area of about 140,000 square miles and geologically is a segment of broad, general structural stability within the great mountain systems known as the Rockies.

The Colorado Plateau structural province is bounded on the east by the Eastern Rockies orogenic belt; on the north by the Uinta uplift; on the west by the High Plateaus; and on the south by the northwesterly trending Basin-Range fault-block belt of Arizona and New Mexico (Figs. 1, 3, 4).

The primary rock masses that have been involved in the modern deformation of the Plateau consist principally of a considerably deformed, dominantly crystalline Precambrian complex and a Paleozoic-Mesozoic blanket of variably bedded sedimentary rocks. There is, however, little in either the gross form of the sedimentary wedge on the dominant northeasterly trend of the Precambrian foliation that appears to have guided the modern structural trends. Locally, however, certain northwesterly trending positives and accompanying sags developed across the Plateau region during Pennsylvanian and Permian times which appear to have controlled some of the later Laramide tectonic trends (Fig. 2). Furthermore, this early deformation may have initiated a northwesterly trending grain of lesser fractures and folds which together with the dominant positives of the late Paleozoic Ancestral Rockies form what may be termed lineaments (Fig. 3). Within the central (San Juan) segment formed by these lineaments, there is also a northwesterly alignment of the principal Laramide laccolithic centers into what are termed the Porphyry lines (Fig. 3).

The principal Laramide structural features of the Plateau consist of a number of extramontane uplifts and basins whose locations, trends, and forms appear to be closely related to the mechanics of the Laramide orogeny of the Central Rockies to the west of the Plateau and the Eastern or Colorado Rockies to the east.

The basins of the Colorado Plateau constitute one-third of the total area. There are seven large basins which range considerably in size, shape, and structural relief. Three major basins (Uinta, Piceance, and San Juan) lie in the northeastern diagonal part of the Plateau and four minor basins (Kaiparowits, Henry, Blanding, and Black Mesa) lie in the southwestern part (Fig. 4).

The uplifts of the Colorado Plateau may be grouped into those that are caused by tangential compression and those caused by igneous intrusions. Exclusive of the bounding orogenic uplifts such as those of the Eastern Rockies or the Uinta Mountains there are nine principal tectonic uplifts (Fig. 4). The total area of the uplifts is only about 20 per cent of the area of the Plateau.

Two rather distinctively oriented groups of uplifts can be recognized—those of northerly trend and those of northwesterly trend. All are asymmetrical; a southwestern group is asymmetrical to the east, and an eastern group is asymmetrical to the west.

The igneous domal uplifts on the Plateau are shown in Fig. 4. The large plugs, stocks, and associated laccoliths have given rise to doming which extends some distance from the intrusive centers. The general uplifts around such igneous centers as the La Sal, Henry, and Abajo were not caused by compression, but rather by the igneous upthrust.

Among the basins and uplifts of the Plateau are a number of other structural elements more or less intermediate in tectonic magnitude. These include such features as platforms, slopes, benches, saddles, arches, and sags (Fig. 4). These tectonic features constitute nearly 50 per cent of the area of the Plateau and, because they are commonly areas of somewhat lesser deformation, they may be regarded as the essence of Plateau structure. It is difficult, however, to place the tectonic emphasis upon these features that may be attributed to the "nodes" of deformation that are represented by the basins and uplifts.

Most of the deformation on the Plateau has occurred along monoclines and these generally form the demarcation between uplifts and adjoining basins (Fig. 4). The structural relief along the steep portion of a typical monoclines is commonly five times, and as much as ten times, that in the adjoining uplift or basin.

In addition to the larger uplifts and basins there are hundreds of smaller anticlines and synclines in and marginal to the Colorado Plateau, some very long and broad, others very short and narrow.

* University of New Mexico.

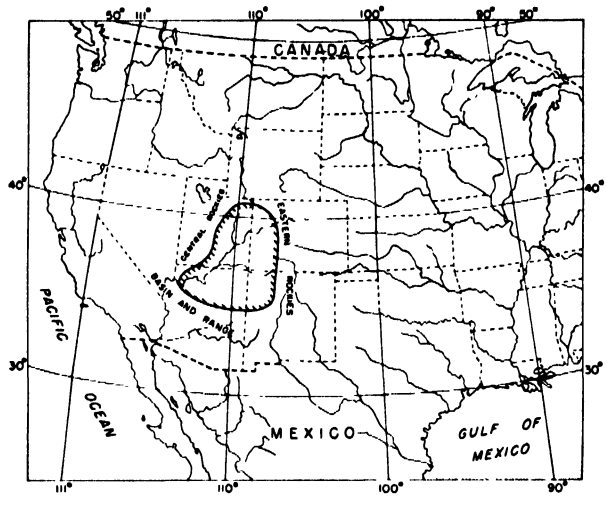


Figure 1

The salt anticlines and piercements of the Paradox fold and fault belt are the most unique structures on the Plateau. Fundamentally they consist of long nearly parallel anticlines and synclines. Prominent valleys have been eroded along the crests of the anticlines where they have been pierced by the Paradox formation of Pennsylvanian age and subsequently collapsed in long irregular grabens. Most of the greatest uranium and vanadium deposits occur within this tectonic division.

Although the broad general structure is fairly simple, the piercement and graben structures along the crests of the anticlines are very complex. Collapse is abundantly evident in most of the mapped surface structures; Jurassic and Cretaceous rocks are commonly displaced downward against rocks in normal position as old as the Pennsylvanian Paradox formation.

Piercement, which began in Permian time, continued intermittently until Laramide time. Laramide compression probably accentuated the structural relief. The cause of collapse may be partly related to isostatic balance and load support relations.[1] Thus, with the accumulation of 7000 feet of late Cretaceous sediments over the area, the ratio of the density of the column of rock overlying the base of the Hermosa formation above the salt piercement to that of the sedimentary columns on either side would have increased, during burial, causing downward flow and collapse. The salt column may have been in part pressed downward and back into the flanking synclines, but escape longitudinally and upward by additional piercement seems also very likely.

Diverse forms of igneous intrusions are present in and around the Colorado Plateau, namely; plugs, dikes, stocks, plugdomes, sills, and laccoliths. So far as is known all are Laramide or younger.

The most numerous and distinctive are intrusive centers such as plugs, plugdomes, small stocks, and associated laccoliths and sills. The most significant of these is the porphyry laccolith type, as the La Sal and Abajo centers. The porphyry laccolith centers lie mostly in the central part of the Plateau, within the San Juan segment (Fig. 3) and they are located regionally along three northwesterly trending lines. None of the porphyry centers is located on a tectonic uplift; instead they are located either in or near sedimentary or structural basins, or in platform areas.

The regional tectonic pattern has only little direct relationship to the distribution of uranium and related deposits in the Plateau. However, indirectly the tectonic events of the past, probably as far back as Permian time, have had a most important bearing on the distribution of deposits through other geologic factors which may have contributed more directly to the distribution of ore. The principal factors of direct control are (1) provenances and environments of sedimentation, (2) paleohydrology, (3) igneous activity, (4) erosional history.

Although mineralization occurs in almost every formation of the stratigraphic section the great preponderance of known commercial reserves and output of ore are from three relatively thin stratigraphic intervals within the Morrison, Chinle, and Shinarump formations.

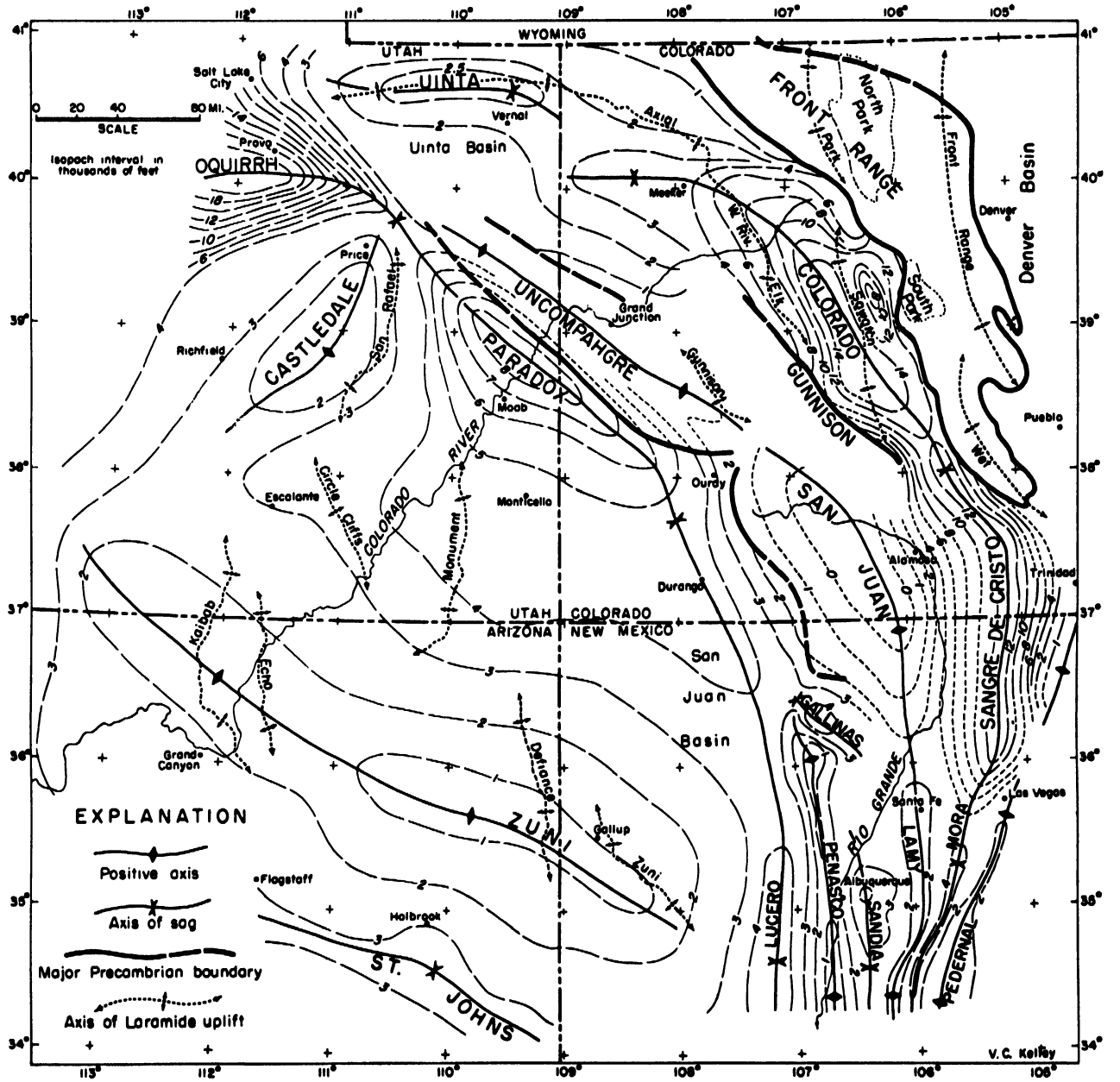
In general, uranium occurrences fall into nearly every standard genetic type that has been proposed for mineral deposits. However, the great majority of deposits on the Plateau may be one or another of the following genetic types: (1) syngenetic, in sandstone, claystone, coal, tuff; (2) ground water; and (3) hydrothermal.

Most of the deposits have been oxidized or modified to some extent by ground water. In some instances this may have involved only chemical rearrangement *in situ* or migration and concentration a few feet or a few tens of feet away. Elsewhere leaching from up-dip or near-surface outcrops or from overlying beds may have been effective in ore concentration. It is also considered possible that ground water may have brought the ore from considerable distance.

There are few deposits on the Plateau that are unquestionably hydrothermal by reason of being on fissures or connected directly to mineralized fissures. Yet in spite of this there remains the possibility that every deposit on the Plateau is indirectly of hydrothermal origin. This possibility is unlikely to be disproved so long as conclusive evidence of a syngenetic origin is lacking.

Past hydrologic conditions are one of the most important of the problems controlling origin and distribution of ore on the Plateau. As with the present, the principal controls for the ancient hydrology are structure, geomorphology, and climate.

Radioactive age determinations indicate a Laramide age for Plateau uranium ores. However, because these determinations may not be entirely conclusive and because ground water might have concentrated ore earlier, only to be reworked and redeposited during Laramide time, the earlier hydrodynamics should be considered.


WYOMING
UTAH
COLORADO
UINTA
Uinta Basin
OQUIRRH
CASTLEDALE
UNCOMPAHGRE
PARADOX
FRONT RANGE
North Park
Middle Park
South Park
Denver Basin
COLORADO
GUNNISON
SAN JUAN
SANGRE DE CRISTO
San Juan Basin
ZUNI
ST. JOHNS
GALLINAS
LUCERO
PENASCO
SANDIA
LAMY
MORA
FEDERAL
Rio GRANDE
Axial
Salt Lake City
Provo
Vernal
Meeker
Denver
Price
Richfield
Grand Junction
Gunnison
Pueblo
Ouray
Moab
Monticello
Escalante
Durango
Alamosa
Trinidad
Santa Fe
Las Vegas
Albuquerque
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Flagstaff
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0 20 40 80 MI.
SCALE
Isopach interval in thousands of feet
EXPLANATION
Positive axis
Axis of sag
Major Precambrian boundary
Axis of Laramide uplift
V.C. Kelley

Figure 2

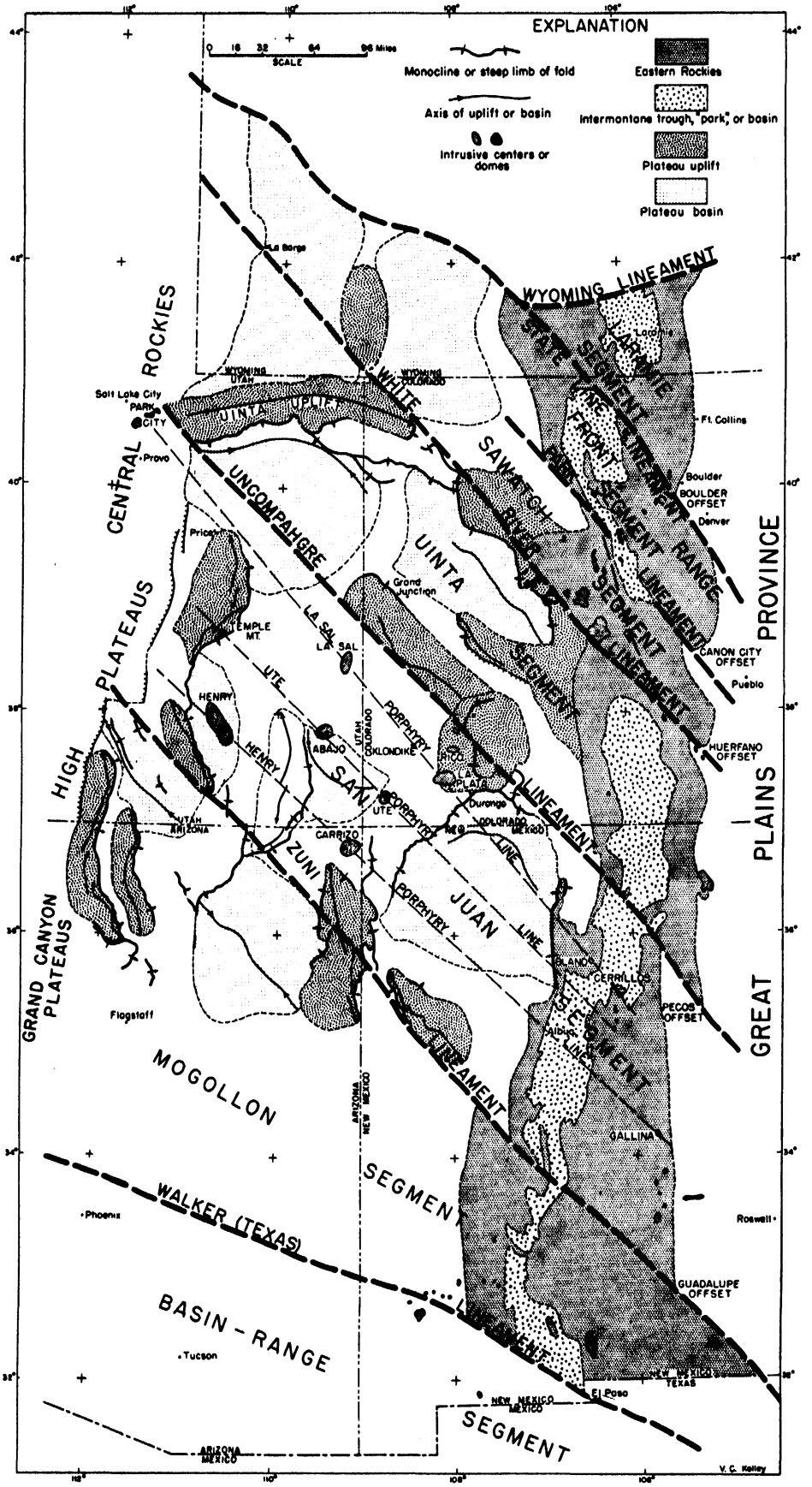

Figure 3. Great Plains Province

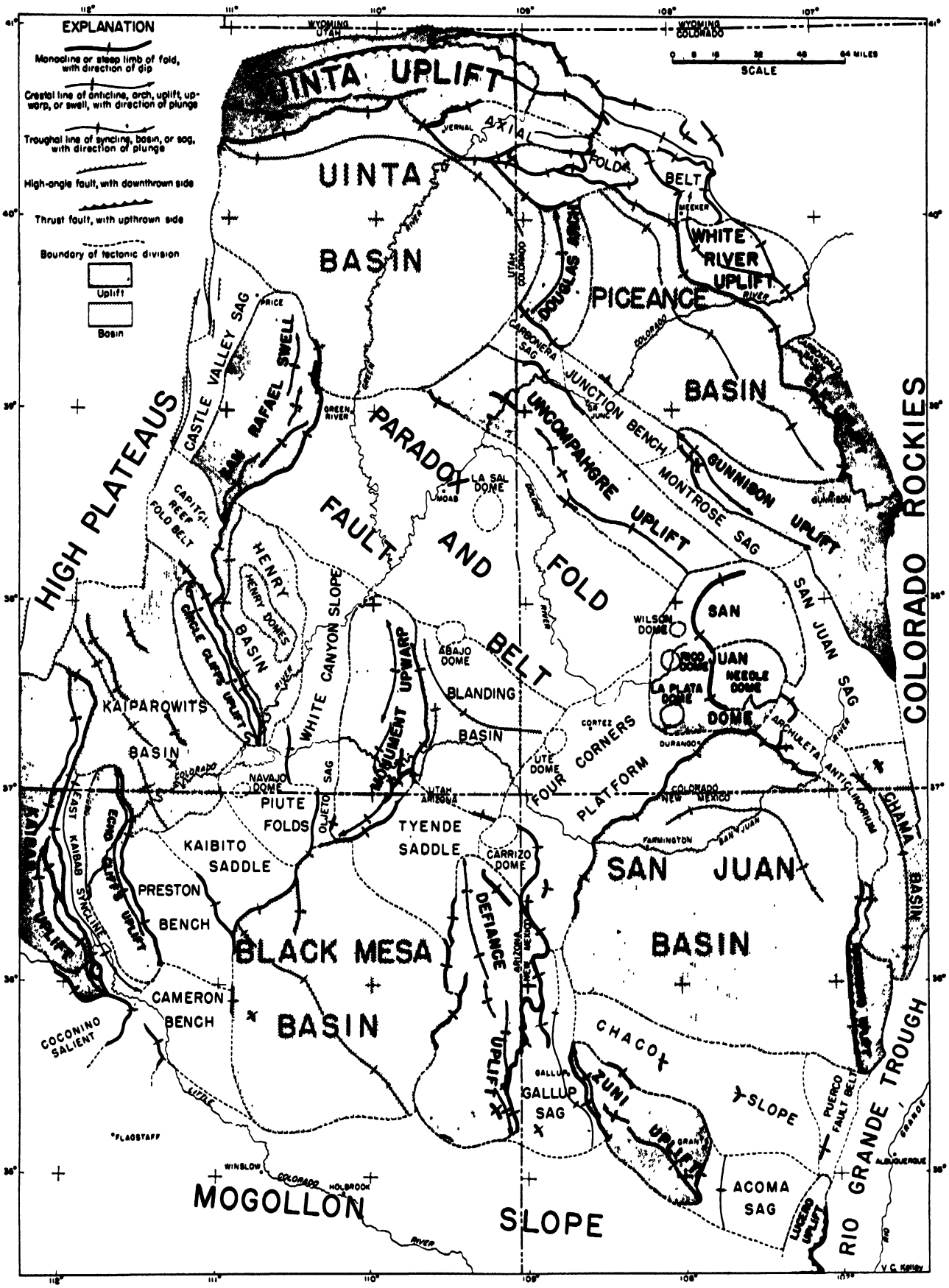
EXPLANATION
Monocline or steep limb of fold, with direction of dip
Crestal line of anticline, arch, uplift, upwarp, or swell, with direction of plunge
Troughal line of syncline, basin, or sag, with direction of plunge
High-angle fault, with downthrown side
Thrust fault, with upthrown side
Boundary of tectonic division
Uplift
Basin
SCALE
UINTA UPLIFT
UINTA BASIN
WHITE RIVER UPLIFT
PICEANCE BASIN
UNCOMPAHGRE UPLIFT
GUNNISON UPLIFT
CASTLE VALLEY SAG
SAN RAFAEL SWELL
PARADOX FAULT AND FOLD BELT
JUNCTION BENCH
MONTROSE SAG
SAN JUAN SAG
HIGH PLATEAUS
COLORADO ROCKIES
CAPITOL REEF FOLD BELT
HENRY BASIN
WHITE CANYON SLOPE
MONUMENT UPWARP
BLANDING BASIN
FOUR CORNERS PLATFORM
KAIPAROWITS BASIN
PIUTE FOLDS
KAIBITO SADDLE
TYENDE SADDLE
PRESTON BENCH
BLACK MESA BASIN
CAMERON BENCH
DEFIANCE UPLIFT
SAN JUAN BASIN
CHACO SLOPE
GALLUP SAG
ZUNI UPLIFT
ACOMA SAG
MOGOLLON SLOPE
RIO GRANDE TROUGH
COCONINO SALIENT
LA SAL DOME
ABAJO DOME
WILSON DOME
LA PLATA DOME
NEEDLE DOME
ARCHULETA ANTICLINORIUM
CHAMA BASIN
CARRIZO DOME
UTE DOME
NAVAJO DOME
PUERCO FAULT BELT
LUCERO UPLIFT
FLAGSTAFF
WINSLOW
HOLBROOK
GALLUP
FARMINGTON
ALBUQUERQUE
DURANGO
V. C. Kelley

Figure 4

During Shinarump time hydrodynamic conditions were very favorable for concentration of ore in the channel bottoms owing to the unconfined occurrence of the water. With the widespread and commonly deep burial by the Chinle and Jurassic sandstone formations, Shinarump hydrodynamics may have changed significantly. Recharge would have diminished because of overlap of the Shinarump, aridity, and deep burial. Furthermore, in the middle part of the Plateau the Shinarump may have been unwatered and some unconfined "puddling" in channels and other low areas may have occurred.

During Morrison time marked fluvial and lacustrine conditions, probably indicating at least moderate surface-water supplies, returned to the Plateau. The highland areas were principally along the southern rim and to the west of the present Plateau although some lesser highlands probably existed in parts of the present Eastern Rockies of Colorado. Surface and ground-water flow may have discharged to great playas and lakes at various places in the east-central part of the Plateau.

The gentle warping that may have gone on during Morrison time was accentuated in late Jurassic and early Cretaceous times. Along the southern rim of the Plateau erosion truncated successively older beds southward. Surface recharge of all the exposed permeable units must have been widespread. Uranium derived from the eroding outcrops could have been introduced into the Shinarump and Morrison beds at this time. Furthermore, since much volcanic activity took place to the south, as is shown by the composition of the thick early Cretaceous rocks of southern New Mexico, hydrothermal additions to the early Cretaceous ground-water system of the Plateau region could have been made.

Throughout most of Triassic and Jurassic times ground-water flow in the central part of the Plateau was generally northwesterly toward a discharge area along the Cordilleran geosyncline.

During late Cretaceous time the entire Plateau subsided greatly as a part of the Rocky Mountain geosyncline. The Cordilleran geanticline west and southwest of the Plateau rose continuously and furnished sediment together with abundant supplies of water. By middle Cretaceous time the magnitude of the uplifts in the Central Rockies may have been sufficiently great to reverse the direction of subsurface flow in formations of the western part of the Plateau. Toward the end of late Cretaceous deposition, the Shinarump and Morrison formations of the San Rafael Swell and Henry Mountains areas were buried and probably below sea level by 10,000 and 7000 feet respectively. Similar deep burial of the principal ore-bearing intervals existed over most of the rest of the Plateau. Temperature in the ground water at these depths may have been about 150°F. In order for eastward flow in the ore-bearing formations to have occurred there would have to be an upward escape of ground water through the overlying units by slow mass permeation and movement along fissures to the surface, especially in the low areas near sea level. Theoretically at least, ground water would flow no farther east than the coast line of the marine sea. Beneath this sea it is likely that all the ground water would be stagnant and saline. The dense saline water would form a steep barrier across the formations[2] blocking eastward flow of fresh water from the source areas. As the late Cretaceous shoreline fluctuated slowly east and west across a low-gradient surface so would the subsurface interface between fresh and saline water. It is interesting and perhaps significant to note that the areal band, in which fluctuation of the interface between fresh and salt water occurred, includes most of the large orebodies on the Plateau. In this area ground water in the Morrison and Shinarump may have been 120°–170°F. It was very slowly "surging" east and west with the shoreline above, and changing repeatedly from fresh to saline. The effect this may have had upon ore concentration is primarily a problem of geochemistry. Within the band of the fluctuating interface the pH and other chemical features of ground water probably would change repeatedly.

The comparatively simple tectonic and hydrologic conditions that prevailed on the Plateau during most of late Cretaceous time were changed greatly with the onset of the Laramide deformation of the Plateau and adjoining areas in late Montanan, Lance, and Paleocene times. Deformation, uplift, and erosion in the Central Rockies continued to provide recharge of the aquifers and a hydrostatic gradient eastward in the western part of the Plateau. New sources of water and hydrostatic head developed in the Uinta uplift, Eastern Rockies, and probably also along the southern rim of the Plateau as it was given a broad general tilt northward. In the early stages while Cretaceous rocks still blanketed the uplifts, changes in the hydrodynamics of the Morrison and Shinarump would have been slight. Gradually, however, and even before complete removal of the thick Cretaceous some recharge in these newly uplifted areas probably would have occurred. This would have first stopped the eastward ground-water flow and then reversed it along the eastern and southern sides. The Uinta uplift diverted the flow southward. The earliest effect of the orogenies would have been to concentrate the flow inward toward the central part of the Plateau probably in a north-northwesterly trending ground-water basin centering around the Blanding basin. Some of the relatively dense connate sea water would have been pushed into deep basins such as the Uinta, Piceance, and San Juan where it may have remained a longer time or even to the present. Much saltwater flushing may have been accomplished by Paleocene time.

As erosion and truncation proceeded in the uplifts around and within the Plateau, successively older formations would have been exposed to recharge thereby rejuvenating the ground-water flow. Wherever this occurred reversal of direction of former ground-water flow on one side of the uplift took place.

It may be observed from the above descriptions that the paleohydrology of the Plateau is complicated and that fluids in the principal ore-bearing units have moved in numerous different directions and with differing flow potentials in the various uplifts, basins, and other structural divisions of the Plateau. Temperatures rose, with burial, to those of epithermal conditions during the time when the primary ores formed and then declined slowly with unloading and exposure in outcrop. Salinity and probably the pH of the fluids may have changed many times in the central Plateau as salt water and fresh water alternately replaced one another while the areal distribution of the late Cretaceous seaway expanded and contracted.

Although tectonic controls on the distribution of hydrothermal activity are implied from discussions above, certain special aspects related in particular to the hydrodynamics will be discussed further. A great deal of hydrothermal action very likely occurred in source areas of the Chinle and Morrison formations. Furthermore, the great amount of fine volcanic material in several of the late Cretaceous formations suggests the possibility of hydrothermal activity during that time to the west and along the southwestern side of the Plateau. Hydrothermal fluids coming into the epithermal zone become considerably diluted by ground water and the introduced metals may be moved far and remain in the meteoritic system for long periods. Thus, uranium introduced by hydrothermal fluids during Chinle or Morrison times may have stayed in solution until the period of falling temperature which ensued with Laramide erosion.

It is abundantly clear from field relations that a great deal of hydrothermal activity occurred on the Plateau during Laramide and succeeding times. Alteration in and around the porphyry stocks and laccoliths suggests that a considerable volume of hydrothermal fluid was introduced into the ground water by the surrounding area.

With the emplacement of a porphyry center is established an outward radial flow potential in the associated ground water that is of two derivations. With intrusion and crystallization a vapor pressure center is built up and super-imposed upon the pre-existing ground-water gradient. At the same time or after this pressure subsides, a radial flow potential is maintained by reason of the structural high and high ground from which meteoritic ground-water penetrations will radiate. The tectonic modifications of the ground-water flow by the Uncompahgre, San Juan, and Monument uplifts probably caused a flow to concentrate along the Utah-Colorado line. Also the La Sal, La Plata, Abajo, and Ute centers would further accentuate the flow in this area. In general the uplifts, the flow directions, and hydrothermal sources highly favor the area amongst these intrusive centers and this is where most of the uranium and vanadium of the Plateau occurs. Greater concentration of ore is found nearer to the La Sal center than to others, perhaps because ground-water flow, lithology, and local structural channels (salt piercements) were more favorable, together with a greater release of uranium from the La Sal center.

Hydrothermal introductions into the ore-bearing formations may have been made through (1) surface flow, (2) lineal flow from fissures, (3) pipelike conduits of diatremes and fissure intersections, and (4) wide-area pervasions. In general, "pin-point" or pipe-like feeding of ore beds by hydrothermal fluids is probably the most common entry. This, of course, is much more difficult to detect on the surface and conduits may not crop out. Underground mining likewise does not ordinarily reveal them, especially if they only enter the bed from below but do not transect it.

If there is relatively strong meteoric flow along a bed and past a point of only mildly disturbing hydrothermal entry then the hydrothermal material may be swept in a path along the direction of flow in the bed. If the hydrothermal entry was lineal, and not parallel to the ground-water flow lines, a wide band of hydrothermal contamination would result. A lineal entry parallel to the direction of meteoric flow would produce a streak of narrow band of hydrothermal contamination. Streaks of ore-bearing hydrothermal fluid in an otherwise barren ground-water system might not encounter many favorable sedimentary channels, organic debris, or favorable minor structural traps.

Another variable that may operate during hydrothermal introductions arises from the possibility that the hydrothermal fluid is sufficiently denser than the meteoric water to maintain a gravity separation between the two within a permeable layer. If a dense hydrothermal fluid enters a bed at its base and remains unmixed, it may underflow the lighter fluid either up dip or down dip. Under these conditions the heavy ore-bearing fluid might accumulate in stagnant pockets near the bottoms of channels, synclines, or the downthrown side of faults. Thus with east-to-west flow the lower west sides of certain north-trending channels or troughs and the bases of small faults downthrown on the east would "puddle" the heavy solution under favorable relationships of dip and flow potentials, and result in concentration of ore.

In summary, an indirect tectonic control may be deduced for any of the commonly postulated origins of uranium. Syngenetic deposits as well as favorable rock compositions, which may precipitate ore from solution, are reflections in part of the tectonics of the time. The principal problem within the tectonic control is the history of the circulation of ground water. This is influenced or controlled by past climate and geomorphology as well as the structure. Repeated changes in direction of ground-water flow have resulted from orogenic and intrusive tectonics.

There is no doubting the fact that hydrothermal emanations have been added to the ground-water system of the plateau. There have been several times

of such addition since the Triassic. They may or may not have brought in much of the ore, but the introduction of fluids regardless of uranium content during Laramide time probably considerably modified the ground-water flow potentials. Hydrothermal contamination of the meteoric ground-water systems was most commonly centralized in its entry and linear in its movements, and expansive spreading of hydrothermal introductions in Shinarump of Morrison sandstone beds probably occurred only rarely.

A general consideration of the paleohydrodynamics of ground water in the Plateau makes the greater concentration of ore in the area amongst the several uplifts and igneous domes appear logical. This area includes the so-called Uravan mineral belt and in it there appears to have been an unusual concentration of ground-water and hydrothermal contamination.

REFERENCES

1. Kelley, V. C., *Regional tectonics of the Colorado Plateau and relationship to origin and distribution of uranium:* Univ. New Mexico Pub. in Geol. No. 5 (1955).
2. Hubbert, M. K., *The theory of ground-water motion:* Jour. Geol. 48, 785–944 (1940).

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Age, Environment and Production of Uranium Host Rocks on the Colorado Plateau

By Hiram B. Wood,* USA

Tables presented with this paper illustrate the widespread geographic and geologic distribution of uranium in the United States and the variety of depositional environments of host rocks. For a rapid summary, the map location, a typical mine or mining area, and the important uranium minerals of area are listed for each unit. An index to the production of each is given in the last column of Tables I, III, and IV and the relative production of all units is given in Table I. The wide stratigraphic range of the deposits makes it impossible to state the exact age of each and only the approximate chronologic position of each host is given under the heading "Age".

Forerunner of this compilation was under the joint authorship of Isachsen, Mitcham and Wood.[1]

The number and variety of uraniferous units have increased tremendously in the last five years; uranium host rocks include representatives of all eras, although most ore is from the Mesozoic. Depositional environments of hosts include fluvial, lacustrine, littoral, marine, paludal, igneous and metamorphic. Of the ore produced to date, about 90 per cent comes from fluvial sediments of Triassic and Jurassic age from deposits on the Colorado Plateau (Table III). Although many new vein deposits of potential richness have been found in igneous and metamorphic rocks throughout the United States, no increase in proportionate production is anticipated. In the last year many new deposits have been discovered in paludal and lacustrine sediments and an increase in proportional production from these types of sediments is probable.

Table I lists the major uranium ore producing rock units, the regions from which the greatest production has come, and the approximate percentage of the total uranium oxide produced for the eighteen-month period from July 1, 1953 to January 1, 1955.

* US Atomic Energy Commission.

REFERENCES

1. Isachsen, Y. W., Mitcham, T. W. and Wood, H. B., Econ. Geol. *50*, 127–37 (1950).

Table I. Uranium-Producing Rock Units of the United States (Compiled by Florence P. Berg)

Unit	*Region*	*Percentage*
Salt Wash sandstone	Colorado Plateau, some from Black Hills	40.9
Chinle formation and Shinarump conglomerate	Colorado Plateau	38.7
Brushy Basin shale	Colorado Plateau	9.2
Todilto limestone	Colorado Plateau	7.4
Vein deposits	Western United States	1.4
Inyan Kara group*	Black Hills	0.6
Carlile shale	Black Hills	0.6
Dakota sandstone	Colorado Plateau, Black Hills, and Wyoming	0.4
Fort Union formation (trace from the Lance formation)	Wyoming and the Dakotas	0.3
Recapture shale (includes the Westwater Canyon sandstone)	Colorado Plateau	0.2
Entrada sandstone	Colorado Plateau	0.1
Dripping Springs quartzite	Southern Arizona	0.1
Cutler formation	Colorado Plateau	0.1
Others†	Colorado Plateau, Wyoming, the Dakotas and New Mexico	Trace

* Includes the Fall River sandstone and Dakota sandstone.
† Includes the Wingate sandstone; Uinta formation; Mesaverde group; Browns Park, Sante Fe, Bidahochi, Hermosa and Wind River formations.

Table II. Age, Environment and Production of Uranium Host Rocks West of the Continental Divide and Outside the Colorado Plateau

Map No. (See Fig. 1)	Age	Uranium host rocks: Unit	Uranium host rocks: Depositional environment	Uranium ore mineralogy	Approximate location	Production category*
1	Early pre-Cambrian	Gneisses and schists	In biotite schist	Unknown	San Bernardino Mtns., Calif. Sec. 28, T. 2N., R. 2 E.	2
2	Late pre-Cambrian	Belt series	Marine; quartzites, argillites and slates	Pitchblende	9 miles E of Kellog, Coeur d'Alene Co., Idaho	2
3	Late pre-Cambrian	Pinal schist	Quartz sericite schist	Pitchblende, fluorite	30 miles NE of Tucson, Pima Co., Arizona	2
4	Late pre-Cambrian	Dripping Spring quartzite	Slate, argillite and quartzite	Torbernite, uraninite	35 miles N of Glove, Cherry Creek District, Gila Co., Arizona	3
5	Ordovician	Laketown Dol. and Fish Haven Dolomite	Marine dolomite	Uraninite (?) fluorite	30 mile N of Delta, Juab Co., Utah	2
6	Silurian	Meta-sediments	Quartzites and argillites	Autunite, metatorbernite	3 miles S Austin, Lander Co., Nevada	2
7	Silurian	Deer Trail argillite	Schists, phyllites and quartzites	Autunite, uraninite (?)	Midnight Mine, Southern Spokane Indian Reservation, Wash.	2
8	Permian & Penn. (?)	Supae formation	Littoral-Fluvial; bleached, gray-green sandstone and shale along Cu vein	Torbernite, metazeunerite	30 miles N of Peach Springs, Mohave Co., Arizona	1
9	Permian	Hermit shale	Fluvial sandstone	Torbernite, autunite	Hacks Canyon, 30 mi. SW Fredonia, Mohave Co., Ariz.	2
10	Permian	Kaibab limestone	Marine; dark gray, dense, fossiliferous limestone	Autunite	6 miles S of Kanarraville, Washington Co., Utah	2
11	Permian	Phosphoria formation; Park City formation	Marine; dark, fine-gr. phosphatic sediments	Fluorapatite, carnotite, autunite	Bear Lake District of NE Utah, SE Idaho and SW Wyoming	1
12	Triassic	Moenkopi formation	Fluvial siltstones and mudstones	Cu-U	Lees Ferry area, Coconino Co., Ariz.	1
13	Triassic	Shinarump formation	Fluvial; basal Chinle sandstone and congl.	Autunite	Lees Ferry area, Coconino Co., Ariz.	1
14	Triassic	Chinle formation	Fluvial; interbedded gray-green sandstone and shale with carbonaceous debris	Torbernite, autunite, carnotite	Leeds, Washington Co., Utah	3
15	Jurassic (?)	Hualapai intrusive	Igneous; granitic	Pitchblende	15 miles N of Kingman, Mohave Co., Arizona	1
16	Jurassic (?)	Idaho batholith	Igneous; quartz monzonite	Uraninite	9 miles W of Hailey, Blaine Co., Idaho	1
17	Jurassic	Sierra Nevada batholith	Igneous; granodiorite; along shear fractures	Carnotite	Miracle Mine, 30 miles E of Bakersfield, Kern Co., Calif.	2
18	Cretaceous	Dakota sandstone	Fluvial-littoral; coarse to med-gr., friable sandstone and cgl. with coal and plant remains	Carnotite	W end of Zion National Park, Kane Co., Utah	2
19	Lower Cretaceous	Comanche Series	Littoral-paludal; interbedded sandstone, shale, and limestone	Uranophane, kasolite, autunite	21 miles N of Nogales, Santa Cruz Co., Ariz.	3
20	Upper Cretaceous	Bear River formation	Paludal; disseminated in lignitic coal, interstratified clay, limestone, sandstone, marl and bituminous shale	Unknown	Sec. 4, T. 1 S., R42E Fall Creek, Idaho	1

Table II. Age, Environment and Production of Uranium Host Rocks of the Continental Divide and Outside the Colorado Plateau (continued)

Map No. (See Fig. 1)	Age	Uranium host rocks: Unit	Uranium host rocks: Depositional environment	Uranium ore mineralogy	Approximate location	Production category*
21	Lower Tertiary	Bullion Canyon series	Igneous; veins in quartz monzonite and fine-grained aplite, hydrothermally altered	Uraninite, torbernite, autunite, fluorite	Bullion Monarch Mine 2 miles NE of Marysvale, Paiute Co., Utah	3
22	Lower Tertiary	Andesite	Igneous; Andesite dikes and volcanic tuffs	Autunite	Rosamond, Kern Co., Calif.	1
23	Miocene	Undifferentiated	Marine; interbedded sandstone and siltstone	Autunite (?)	30 miles W of Bakersfield, Kern Co., Calif.	1
24	Miocene	Acid extrusives	Igneous; fault zone in rhyolite	Autunite, torbernite, gummite, uraninite	74 miles N of Winnemucca, Humboldt Co., Nevada	2
25	Miocene	Tuffaceous sandstone	Lacustrine	Unknown	10 miles SE of Hawthorne, Mineral Co., Nevada	2
26	Miocene	Sheeprock intrusive	Igneous; granite	Unknown	25 miles W of Eureka; Erickson District, Tooele Co., Utah	1
27	Miocene	Barrett formation	Paludal; lignite	Unknown	Goose Creek Area, Idaho (Utah-Nevada Corner)	1
28	Upper Miocene	Siebert Lake beds (Esmeralda formation) (?)	Lacustrine; stratified tuffs, pyroclastics and diatomaceous earth, with lenses of uraniferous opal	Unknown	3 miles W of Tonopah, Esmeralda Co., Nevada	2
29	Pliocene	Coso Lake beds	Lacustrine; tuffs altered to green clay	Autunite	5 miles E of Olancha, Inyo Co., California	1
30	Pliocene	Virgin Valley opal	Lacustrine; opalized portions of tuff and diatomaceous earth beds	Carnotite	T. 45 N., R. 26 E., Humboldt Co., Nevada	1
31	Pliocene (?)	Panaca formation	Lacustrine; white to brown, stratified tuffs	Carnotite (?)	1½ miles NE of Panaca, Lincoln Co., SE Nevada	2
32	Recent	Alluvium	Fluvial; unconsolidated sands and gravels	Samarskite, euxenite	55 miles NE of Boise, Boise Co., Idaho	2

*1. Production less than 25 tons; 2. Production 25 to 1,000 tons; 3. Production over 1,000 tons.

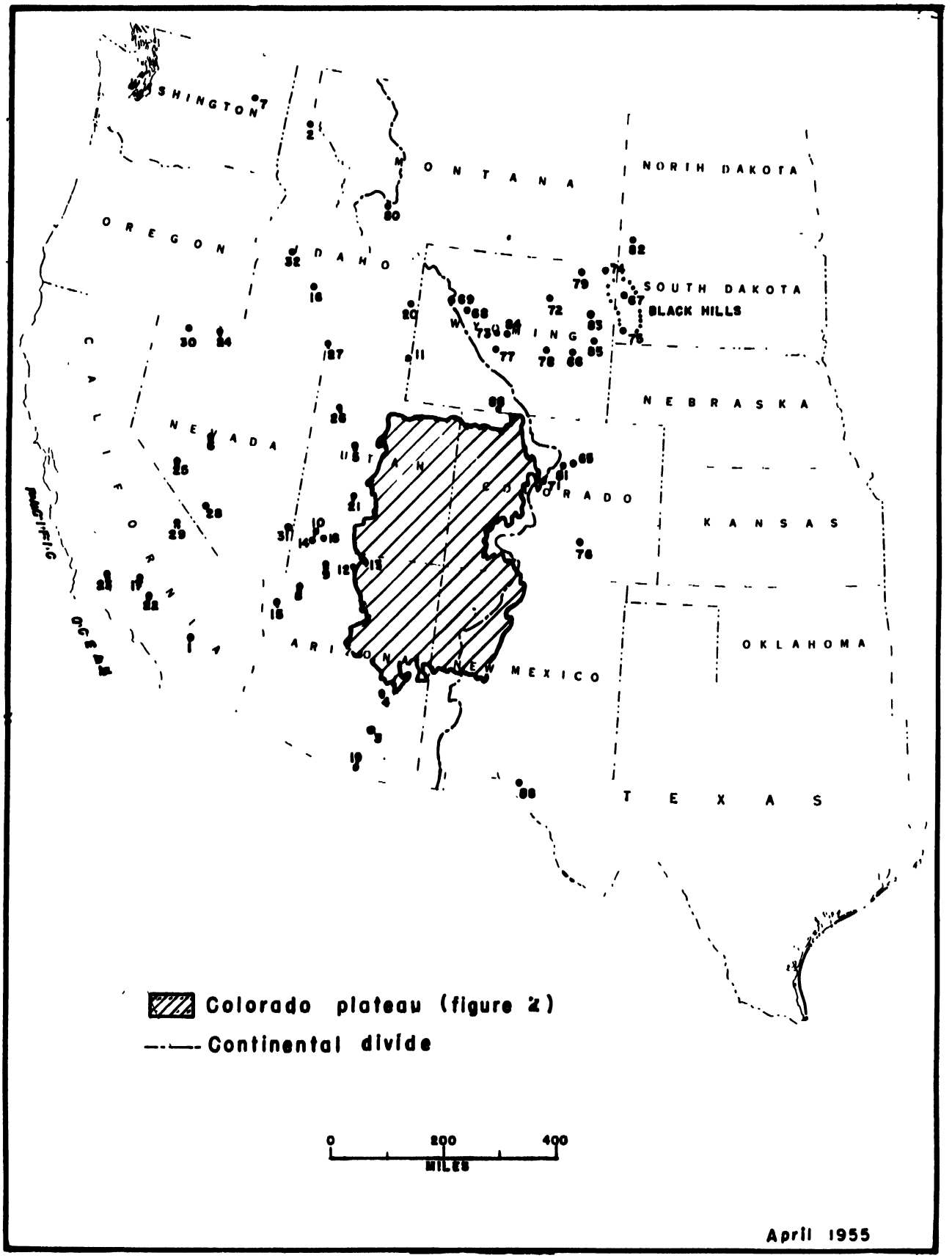


Figure 1. Western United States

Table III. Age, Environment and Production of Uranium Host Rocks of the Colorado Plateau

Map No. (See Fig. 2)	Age	Host rocks: Unit	Host rocks: Depositional environment; Ore occurrence	Major ore minerals	Approximate location	Production category[a]
33	Pre-Cambrian	Metamorphic Complex	Metamorphosed sediments; shear zones and faults in quartzites and schists	Uraninite	Los Ochos Mine, Cochetopa mining district, Saguache Co., Colorado	3
34	Pennsylvanian	Weber quartzite	Littoral; disseminated in argillaceous quartzite	Carnotite	6 miles NE of Skull Creek, Moffat Co., Colorado	2
35	Pennsylvanian	Hermosa formation	Marine; along closely spaced fracture planes in limestone	Carnotite	13 miles SW Naturita, Montrose Co., Colorado	3
36	Permian	Rico formation	Fluvial; impregnations in bleached sandstone along fault	Unidentified uranium-vanadium minerals	10 miles SW of Moab, San Juan Co., Utah	1
37	Permian	DeChelly sandstone (Cutler formation)	Eolian; disseminated in cross-bedded sandstone beneath paleostream channel in Shinarujo formation	Carnotite	Monument No. 2 Mine, 30 miles NE of Kayenta, Apache Co., Arizona	3
38	Permian	Cutler formation	Fluvial; disseminated and in concretions in arkosic lenses. Enrichment along fractures	Carnotite, becquerelite	Big Buck claims, 32 miles SE of Moab, San Juan Co., Utah	3
39	Permian	Kaibab limestone	Residual; disseminated in conglomerate and breccia	Uranium-vanadium, associated with asphaltite	Temple Mt. collapse, 44 miles SW of Greenriver, Emery Co., Utah	1
40	Triassic	Moenkopi formation	Fluvial; disseminated in fine-grained gray sandstone with mud galls	Uraninite associated with hydrocarbons	Elk Ridge, 34 miles W of Blanding, San Juan Co., Utah	3
41	Triassic	Shinarump formation	Fluvial; disseminated in coarse-grained, cross-bedded, friable sandstone	Uraninite and Cu-uranium sulphates	White Canyon, San Juan Co., Utah; Monument Valley, Navajo Co., Arizona	3
42	Triassic	Chinle formation (Moss back sandstone member)	Fluvial; medium-grained, arkosic cross-bedded sandstone	Uraninite, montroseite	Big Indian Wash, San Juan Co., Utah; Temple Mt., San Rafael Swell, Emery Co., Utah	3
43	Triassic	Wingate sandstone	Eolian; scattered disseminations in thin lenses of bleached, dolomitized sandstone	Pitchblende with asphaltite	Temple Mt. collapse, 44 miles SW of Greenriver, Emery Co., Utah	2
44	Jurassic(?)	Kayenta formation	Fluvial; disseminated in fine to medium-grained cross-bedded sandstone and along fractures	Carnotite	Big Chief claims, 11 miles NW of Naturita, Montrose Co., Colorado	2
45	Jurassic	Navajo sandstone	Eolian; disseminated in massive, gray sandstone along fractures and along walls of basic dike	Copper-uranium and vanadium minerals	Garnet Ridge, 10 miles N of Dinnehotso Trading Post, Apache Co., Arizona	1
46	Jurassic	Carmel formation	Littoral; scattered disseminations in greenish-gray siltstone	Unidentified	Saucer Basin, 30 miles S of Greenriver, Emery Co., Utah	
47	Jurassic	Entrada formation	Eolian; disseminated in upper 30 feet of cross-bedded sandstone, highly fractured	Carnotite and black vanadium minerals	Joker Mine, 21 miles W of Naturita, Montrose Co., Colorado	3
48	Jurassic	Todilto limestone	Lacustrine; disseminated in dense, gray limestone and in minute silty laminae on crest of minor folds	Tyuyamunite, uraninite	Gay Eagle and Black Hawk Mines, 9 miles N of Grants, Valencia Co., New Mexico	3
49	Jurassic	Curtis formation	Marine; disseminated in thin-bedded sandstone	Unidentified uranium, vanadium minerals	2 miles NW of Skull Creek, Moffat Co., Colorado	

Table III. Age, Environment and Production of Uranium Host Rocks of the Colorado Plateau (*continued*)

Map No. (See Fig. 3)	Age	Host rocks: Unit	Host rocks: Depositional environment; Ore occurrence	Major ore minerals	Approximate location	Production category[a]
50	Jurassic	Summerville formation	Lacustrine; disseminated in sandstone	Carnotite, uraninite	Haystack Butte, NW of Grants, McKinley Co., New Mexico	3
51	Jurassic	Bluff sandstone	Eolian; disseminated in cross-bedded sandstone	Carnotite and unidentified vanadium minerals	2 miles NW of Carrizo Mtns., Apache Co., Arizona	1
52	Jurassic	Morrison formation Salt Wash member	Fluvial; disseminated in fine to medium-grained, cross-bedded, gray carbonaceous sandstone with interbedded mudstone	Carnotite, tyuyamunite, uraninite	Uravan mineral belt, Mesa, Montrose and San Miguel Cos., Colorado	3
53	Jurassic	Morrison formation Recapture shale	Fluvial; disseminated in interbedded sandstone and mudstone	Carnotite and vanadium minerals	Enos Johnson claim 8 miles W of Sanastee, San Juan Co., New Mexico	3
54	Jurassic	Brushy Basin shale member	Fluvial; disseminated in massive sandstone	Carnotite, corvusite	Jackpile Mine, 6 miles N of Laguna, Valencia Co., New Mexico	3
55	Cretaceous	Burro Canyon formation	Fluvial; disseminated in carbonaceous, conglomeratic sandstone, with thin lenses of green mudstone	Carnotite	Berties Beauty No. 1 claim, 7 miles NW of Naturita, Montrose Co., Colorado	1
56	Cretaceous	Cedar Mountain formation	Lacustrine; disseminated in dark gray siltstone lenses interbedded with bentonitic shales	Unidentified	Cedar Mountain, 10 miles E of Huntington, Emery Co., Utah	2
57	Cretaceous	Dakota sandstone	Paludal – lagoonal; black, carbonaceous shale beds, interbedded with sandstone	Carnotite	Silver Spur No. 5, E of Gallup, McKinley Co., New Mexico	3
58	Cretaceous	Mesa Verde Group Toreva sandstone	Fluvial-marginal marine; disseminated in gray to buff, arkosic sandstone, interstitial clay and woody trash	Carnotite, meta-hewettite	Black Mesa, 12 miles NW of Black Mtn. Trading Post, Apache Co., Arizona	2
59	Cretaceous	Fruitland formation	Littoral; arkosic sandstone filling a scour in underlying shale	Unidentified	Boyd claims, 10 miles NW of Farmington, San Juan Co., New Mexico	2
60	Eocene	Wasatch formation	Fluvial; disseminated in cross-bedded, poorly sorted, sandstone lenses filling scours, with carbonaceous debris	Carnotite	6 miles N of Thompson, Book Cliffs area, Emery Co., Utah	2
61	Eocene	Uinta formation	Fluvial; disseminated in gray carbonaceous sandstone lenses interbedded with shales	Metatorbernite	Myton and Ouray; Uintah and Duchesne Cos., Utah	2
62	Pliocene	Bidahochi formation	Lacustrine; disseminated in tuffaceous pyroclastics and travertine beds in diatremes	Carnotite	40 miles N of Holbrook, Navajo Co., Arizona	2
63	Pliocene	Browns Park formation	Fluvial; along fractures and disseminated in sandstone	Meta-autunite; sabugalite reported	½ mile N of Juniper Springs, Moffat County, Colorado	2
64	Tertiary	Monzonite porphyry	Igneous; veinlets, monzonite porphyry plug	Uraninite, uranophane in fluorite and quartz veinlets	Henry Mtns., 30 miles E of Ranksville, Garfield Co., Utah	1

[a] Refers to total production from specified host rock; minimum grade of ore is 0.10% U_3O_8. 1. Production less than 25 tons; 2. production 25 to 1000 tons; 3. production over 1000 tons.

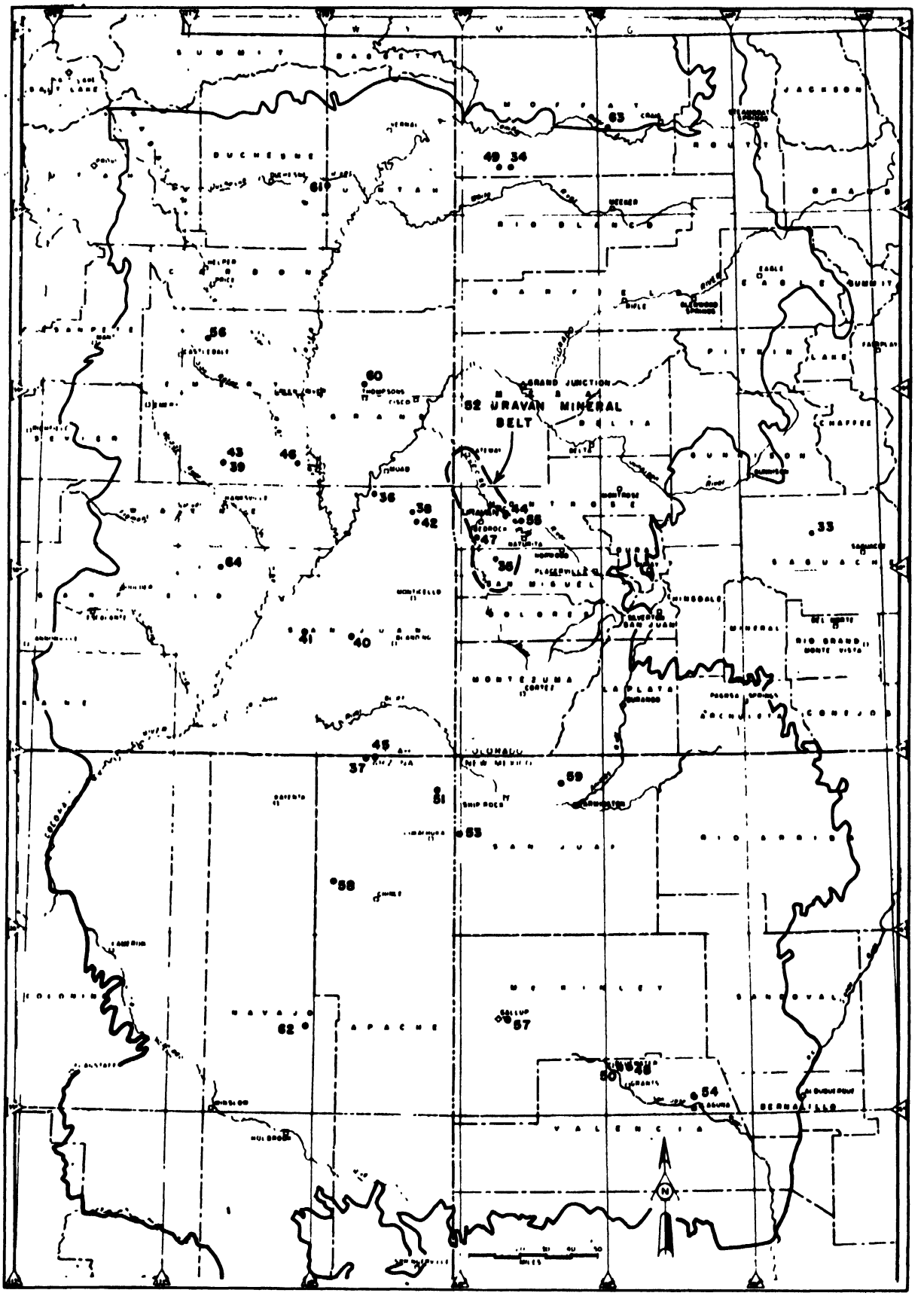


Figure 2. Colorado Plateau, United States

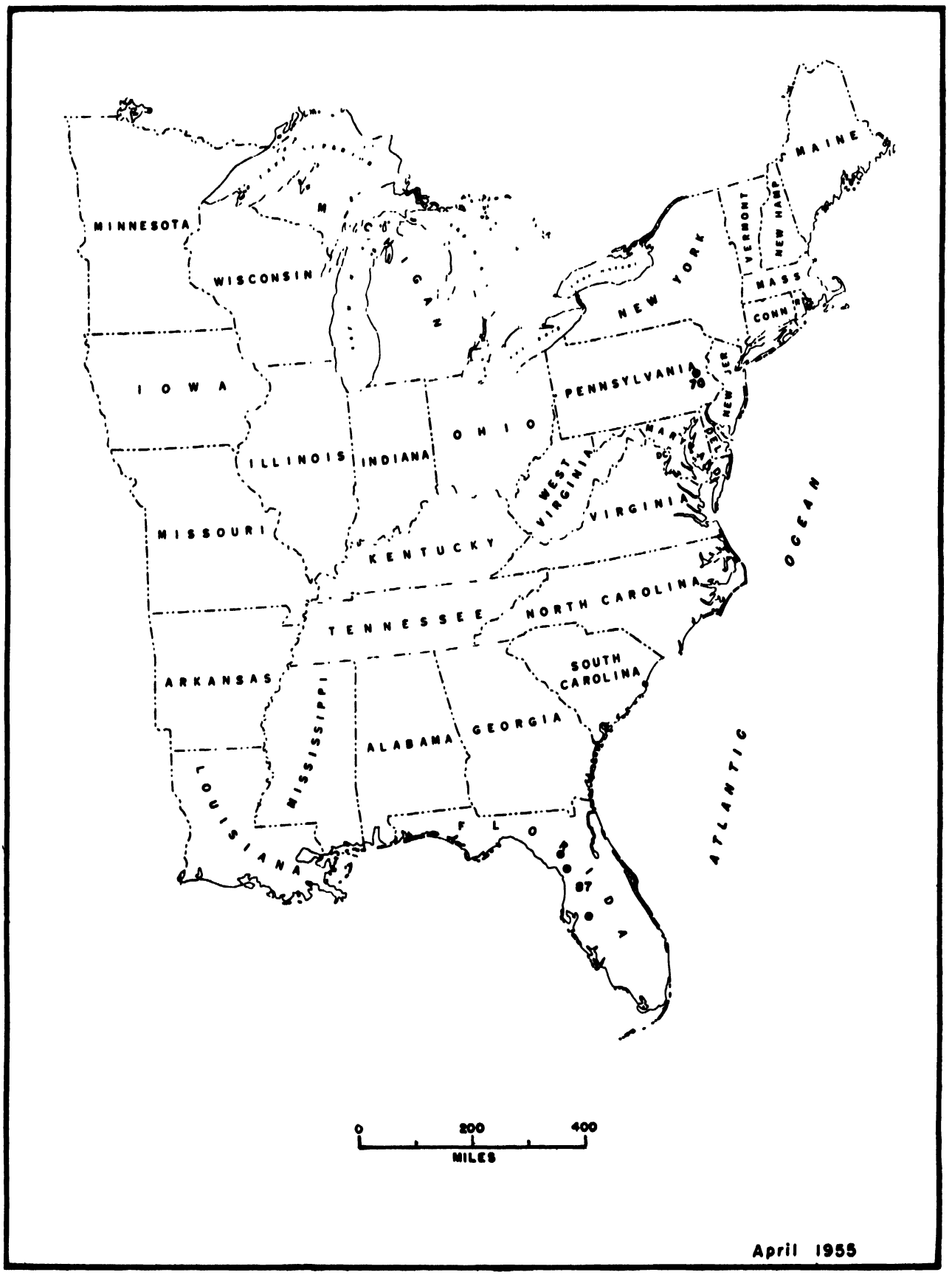


Figure 3. Eastern United States

Table IV. Age, Environment and Production of Host Rocks East of the Continental Divide

Map No. (See Fig. 3)	Age	Uranium host rocks: Unit	Uranium host rocks: Depositional environment	Uranium ore mineralogy	Approximate location	Production category*
65	Pre-Cambrian	Idaho Springs formation	Metamorphics; along parallel breccia veins cutting schists and gneisses	Uraninite, metatorbernite	Schwartzwalder Mine, 7 miles NW Golden, Jefferson Co., Colorado	2
66	Pre-Cambrian	Undifferentiated granite and metamorphics	Igneous; veins in pink coarse-grained granite, with quartz, pyrite and pyrrhotite	Uraninite	Esterbrook area; 35 mi. S of Douglas, Converse Co., Wyoming	1
67	Pre-Cambrian	Undifferentiated metasediments	Metamorphosed sediments; in quartz veinlets	Autunite, uraninite (?)	Bald Mt. mining area, Lead, Lawrence Co., So. Dakota	1
68	Cambrian	Gros Ventre formation	Metamorphosed marine shales; along fractures in dense gray-green phyllite	Autunite	Crooks Gap, Green Mtns.; Fremont Co., Wyoming	1
69	Cambrian	Gallatin limestone	Marine; along fractures in gray to brown, silicified dolomite	Carnotite	8 miles SW of Dubois, Fremont Co., Wyoming	1
70	Pennsylvanian	Pottsville formation	Fluvial – littoral; graywacke conglomerate	Uraninite	½ mile NW of Jim Thorpe (Mauch Chuck), Carbon Co., Pennsylvania	2
71	Permian	Maroon formation	Marine; sandstones	Carnotite, volborthite	9 miles S of Fairplay, Park Co., Colorado	2
72	Upper Jurassic	Sundance formation	Marine; interstitial in buff to gray, thin to massive-bedded oolitic limestone	Uranophane, metatyuyamunite	J. D. Masek No. 1, 3 miles SE of Mayaworth, Johnson Co., Wyoming	1
73	Upper Jurassic	Morrison formation	Fluvial; fine to medium-grained silty gray, cross-bedded sandstone	Meta-autunite	Lucky Mac, Gas Hills, 35 mi. S of Moneta, Fremont Co., Wyoming	2
74	Lower Cretaceous	Inya Kara group (Lakota sandstone)	Fluvial disseminated fine to medium-grained cross-laminated, gray sandstone with cargon trash	Carnotite	Belle Fourche River Area, 18 mi. N of Moorcroft, Crook Co., Wyoming	3
75	Lower Cretaceous	Inya Kara group (Fall River sandstone)	Fluvial; disseminated in fine- to very fine-grained quartz sandstone, with shaly laminations and carbon flecks	Carnotite, corvusite, rauvite	Virginia C Mine, 8 mi. N of Edgemont, Fall River Co., South Dakota	3
76	Upper Cretaceous	Dakota sandstone	Littoral-fluvial; argillaceous sandstone, with fluorite, near monzonite plug	Carnotite, fluorite	15 miles N of Walsenburg, Huerfano Co., Colorado	1
77	Upper Cretaceous	Thermopolis shale	Marine; along seams and partings in black fissile shale	Unknown	Gas Hills, 35 mi. S of Moneta, Fremont Co., Wyoming	1
78	Upper Cretaceous	Mesa Verde formation	Fluvial-littoral; in lenses of carbonaceous shale in fine-grained, brown sandstone	Carnotite	9 mi. N of Casper, Natrona Co., Wyoming	1
79	Upper Cretaceous	Lance formation	Fluvial-littoral; gray-brown, fine-grained, massive sandstone with coaly matter	Unknown	Near Linch, Campbell Co., Wyoming	1
80	Tertiary	Boulder Batholith	Veinlets filling silicified shear zones in quartz monzonite	Pitchblende	Butte, Jefferson Co., Montana	2
81	Eocene	Undifferentiated igneous	Veinlets in monzonite stock	Pitchblende	4 miles NW of Nederland, Boulder Co., Colorado	1

(*Continued on next page*)

Table IV. Age, Environment and Production of Host Rocks East of the Continental Divide (*continued*)

Map No. (See Fig. 2)	*Age*	*Uranium host rocks*		*Uranium ore mineralogy*	*Approximate location*	*Production category**
		Unit	*Depositional environment*			
82	Paleocene	Fort Union formation	Fluvial-paludal; in thin, lignite beds	Meta-autunite, metatorbernite, metazeunerite	Cave Hills area, Harding Co., South Dakota	2
83	Eocene	Wasatch formation	Fluvial; disseminated in coarse-grained, cross-bedded, bluff, arkosic sandstone with Mn-Fe concretions	Carnotite, tyuyamunite uranophane, uraninite	Anomaly No. 119, 45 miles SW Gillette, Campbell Co., Wyoming	3
84	Eocene	Wind River formation	Fluvial; disseminated in coarse-grained, cgl, cross-bedded, gray sandstone with inter-bedded shale	Uraninite and coffinite, with uranium phosphates arsenates and carbonates	Lucky Mac Mine, 35 mi. S of Moneta, Fremont Co., Wyoming	3
85	Oligocene	White River formation	Fluvial; disseminated in coarse-grained, cgl. and arkosic sandstone	Metazippeite, metatyuyamunite	Lance Creek area, Niobrara Co., Wyoming	2
86	Miocene	Browns Park formation	Fluvial; disseminated in brown, silty cross-bedded sandstone, interbedded with shale	Uranophane, meta-autunite	6 miles E of Baggs, Sweetwater Co., Wyoming	2
87	Pliocene (?)	Bone Valley formation	Residual phosphatic clays, sands, gravels, and reworked hard uraniferous Miocene phosphates	U is present in apatite and fluorapatite	Hillsborough and Polk Cos., Florida	3
88	Recent	Hueco Alluvium	Residual soil mantle and alluvium; U costs Hueco limestone (Permian) fragments	Yellow secondary U-minerals	20 mi. E of El Paso, El Paso and Hudspeth Counties, Texas	1

* 1. Production less than 25 tons; 2. Production 25 to 1000 tons; 3. Production over 1000 tons

egional Transmissivity of the Exposed Sediments of the olorado Plateau as Related to Distribution of ranium Deposits

y D. A. Jobin,* USA

Uranium deposits, which also contain vanadium id copper, are widely distributed in sedimentary rata of the Colorado Plateau. Although the deposits cur in many formations, most of them are found a few favorable strata. The deposits are typically d or blanket shaped, generally conformable to dding and other sedimentary structures, and generly located in or adjacent to the thick portions of fluvial sandstone or conglomerate stratum. In indidual pods the transition from ore to barren rock generally abrupt, but some ore bodies have fingerce extensions along individual laminae or an alteran of lean and rich bands, similar to diffusion bands, ripheral to the ore pod. With few exceptions the e deposits are not obviously localized by fractures faults.

The habits of typical Colorado Plateau uranium posits suggest that the ore minerals were carried fluid to their present position. This writer believes at the host rocks were saturated or partially satated and that precipitation took place at a fluid terface, which was controlled in varying degrees the contrasting chemical character of the mineraling fluid and the pore fluid, as well as the transissive ability of the host rock.

This paper summarizes part of a more inclusive udy of the history of fluid movement in the sedients of the Colorado Plateau and attempts to late the distribution of known uranium deposits Permian and Mesozoic rocks to the transmissive aracter of these rocks.

The Colorado Plateau covers an area of about 0,000 square miles. Rocks exposed, predominantly rmian and Mesozoic sedimentary rocks, consist rgely of fine clastics, eolian sandstones, and interdded fluvial sandstones, conglomerates, and mudones. Limestones, evaporites, and marine sandstone e also exposed.

Rocks composed largely of shale, mudstone, limeone, and evaporites were assumed, on the basis of preliminary set of samples and theoretical conlerations, to have no appreciable intrinsic transissive capacity. Sampling was therefore restricted sedimentary rocks with measurable permeability and of regional extent such as sandy siltstones, sandstones, and conglomerates.

The intrinsic ability of sediments to transmit fluids, when unfractured and with identical recharge potential and structural attitudes, is a function of their permeability and geometrical configuration and continuity. In this study the intrinsic transmissive capacity or the coefficient of transmissivity of a sedimentary unit at any point over its extent is equal to the product of arithmetic-mean permeability in darcys and thickness in feet. (Theis,[1] defined an analogous term, transmissability, for use in treating the discharge of a well mathematically. This term has not been used, as the assumptions Theis made for its use are not fulfilled in this study).

The permeability of each lithologic assemblage treated as a unit was outlined by computing the mean permeability of a suite of samples from each of many widely spaced exposures and contouring the resulting values. Permeability determinations were made by two methods; a direct measurement using standard techniques as outlined by Muskat,[2] and an indirect measurement utilizing standard parameters of grain-size analysis.† The data on thickness, continuity, and regional extent were obtained largely from published[3] and unpublished work of members[4] of the US Geological Survey.

LITHOLOGIC UNITS AND TRANSMISSIVITY

The rocks of the Colorado Plateau with appreciable intrinsic transmissive capacity may be grouped into two main categories: (1) eolian and marine sandstones and siltstones that have a relatively uniform thickness and permeability over wide areas, and (2) fluvial sandstones and conglomerates that locally are lenticular and exhibit a relatively great range in thickness and permeability. The intrinsic transmissivity of eolian and marine sediments is relatively high and fluid movement through them relatively uniform. Generally, higher mean permeability, greater thickness, and more uniform gradient in both permeability and thickness give the eolian and

* US Geological Survey.

† R. A. Cadigan of the US Geological Survey furnished over a thousand grain-size analyses made for sedimentologic studies and worked jointly with the author on a formula for computing permeability from these measurements.

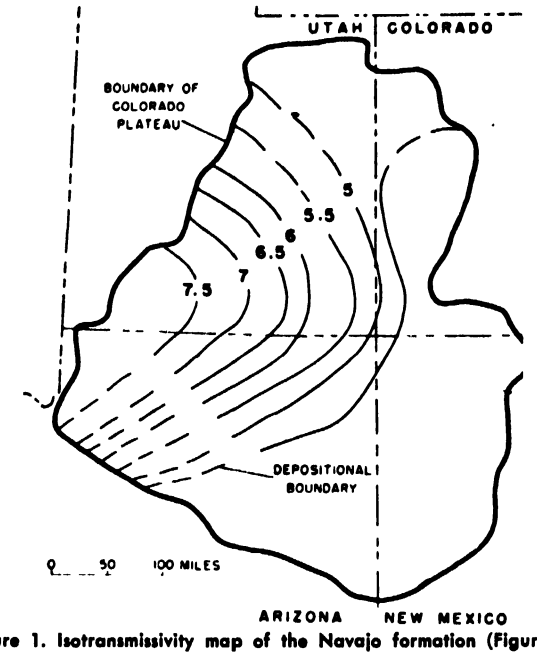


Figure 1. Isotransmissivity map of the Navajo formation (Figures in diagrams indicate isopleth of transmissivity in Darcy-feet expressed in natural logarithms)

marine sandstones a higher transmissive capacity than the fluvial sediments (compare Figs. 1 and 2). The regional intrinsic transmissivity of fluvial sediments is not only less, but its ground-water circulation is much more complex than that of eolian and marine sandstones. In contrast to the simple geometry and uniform permeability of eolian and marine strata, these fluvial sediments consist of one or more strata of sandstone or conglomerate which have a large range in permeability and which are separated by relatively impermeable mudstones. Considered individually, each stratum composed of from one to several lenticular beds thickens and thins in a highly erratic manner. The permeability gradient within a fluvial stratum varies erratically both vertically and horizontally, but, in general, high mean permeabilities correspond with its thick parts and low mean permeabilities correspond with its thin parts. Transmissivity maps of representative fluvial sandstones and conglomerates are shown in Figs. 2 and 3.

Fluids moving through fluvial sandstones and conglomerates will have greatly varying rates of movement depending in part on the route they take. The bulk of the movement will be along the thickest and most permeable segments. Many slow moving and even semistagnant fluids will be present in circuitous routes of low permeability and constricted cross section. Though the over-all transmissivity of fluvial sediments of the Colorado Plateau is generally low, numerous examples of their ability to transmit ground water today leave no doubt of their efficacy in the past to transmit fluids many miles.

INFLUENCE OF TRANSMISSIVITY ON THE DISTRIBUTION OF URANIUM DEPOSITS

The gross lithologic sequence, transmissivity, and distribution of uranium in the exposed Permian and Mesozoic sedimentary rocks of the Colorado Plateau are shown in Table I. Although few strata are entirely devoid of uranium deposits, most of the deposits are confined to essentially two strata, the sandstones of the Morrison formation and the Shinarump conglomerate and lower sandstones and conglomerate of the Chinle. These two groups have many characteristics in common. The habit of deposits within both groups is essentially similar. Pods of ore are mainly conformable to the bedding and are most commonly found in or adjacent to the thick, more permeable, and therefore, more transmissive parts of a favored stratum. The regional distribution of deposits in both groups appears unrelated to any particular intrinsic transmissivity range (Figs. 1 and 2). Both groups are chiefly composed of fluvial sandstones and conglomerates, are overlaid by thick, relatively nontransmissive units, vary greatly in local transmissivity, and have a low to moderate regional transmissive capacity.

The differences in transmissive characteristics between strata of the Morrison and strata of the Shinarump and Chinle seem to correlate with the greater frequency of occurrence and smaller range in size of uranium deposits in the Morrison strata. The bulk of the mined ore and known reserves in the Morrison strata is found in many widely scattered moderate-sized deposits. The bulk of the mined ore and known reserves of the Shinarump and Chinle strata is found in a few, widely scattered, large deposits.

Other lithologic assemblages that contain significant amounts of uranium are the Mesaverde, Dakota, Burro Canyon, Buckhorn,[7] Cutler, Entrada, Todilto, and Pony Express units. The first three of these units are fluvial sandstones and conglomerates; they have transmissive characteristics essentially similar to the Morrison and Shinarump strata, and they

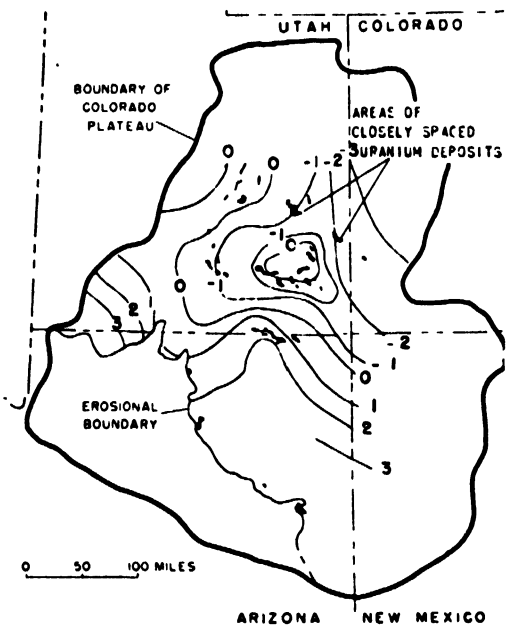


Figure 2. Isotransmissivity map of the Shinarump conglomerate and lower Chinle sandstones showing distribution of uranium deposits

Table I. Summary of Lithologic Sequence, Transmissivity, and Uranium Distribution of the Colorado Plateau

System	Formations or lithologic assemblage treated as a unit[a]	Intrinsic transmissivity		Distribution of uranium deposits[c]	
		Type	Mean[b]	Relative frequency	Mode
Cretaceous	Mesaverde	moderately variable	5.5	moderate	small, widely scattered
	Mancos	uniform	0	infrequent	one occurrence, small
	Dakota, Burro Canyon, and Buckhorn conglomerate (of Stokes,7)	highly variable	3.3	moderate	small, widely scattered
Jurassic	Morrison (mudstones)	uniform	<0	infrequent	associated with sandstone deposits
	Morrison (sandstones)	highly variable	3.8	very high	wide distribution, large and small
	Bluff and Junction Creek	uniform	4.0	infrequent	one occurrence
	Cow Springs	uniform	4.4	none	none
	Summerville	uniform	0	infrequent	small, widely scattered
	Todilto and Pony Express	uniform	0	moderate	medium, to large, most in one district, fracture control
	Curtis	uniform	2.0	infrequent	two small deposits
	Entrada	uniform	3.2	moderate	small widely scattered, large deposits in three districts
	Carmel	uniform	0	infrequent	small, ore district
Jurassic and Jurassic(?)	Navajo	uniform	6.1	infrequent	two occurrences, fracture control
Jurassic(?)	Kayenta	moderately variable	2.1	infrequent	small, widely scattered
Triassic	Wingate	uniform	3.6	infrequent	small, widely scattered one large deposit at Temple Mountain, Utah
	Chinle (excluding basal sandstones)	uniform	0	infrequent	small, two localities
	Shinarump conglomerate (including basal sandstones of the Chinle)	highly variable	0	high	small, wide distribution with few widely scattered very large
	Moenkopi	uniform	0	infrequent	small, widely scattered
Permian	Kaibab	uniform	0	infrequent	small, one district, fracture control
	Cutler (individual)	highly variable	1.0	moderate	small, one district
	Coconino and San Andreas (and sandstone members of Cutler)	uniform	4.0	infrequent	one occurrence in Coconino, fracture control
	Hermit shale	uniform	0	infrequent	one occurrence
	Supai	uniform	0	infrequent	one occurrence, vein type

a) Lithologic sequence is in chronological order except where equivalents are treated as individual units.

b) Natural logarithm of product of arithmetic mean thickness in feet and arithmetic mean permeability in darcys.

c) Finch,(5); Isachsen, Mitcham, and Wood,(6).

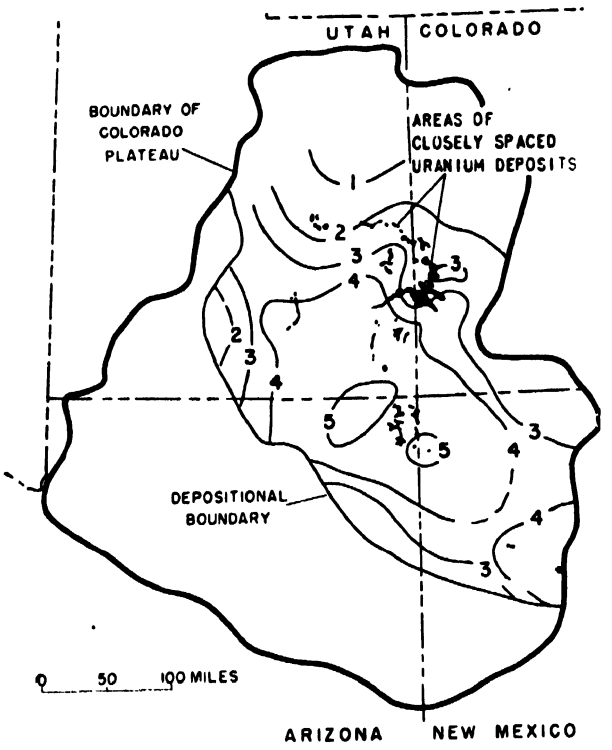


Figure 3. Isotransmissivity map of the Morrison sandstones showing distribution of uranium deposits

are also overlain by relatively nontransmissive units. Although uranium deposits are wide spaced in these strata, they do not approach the deposits in the Morrison or Shinarump strata in frequency or size.

The Entrada sandstone and Todilto limestones constitute opposite extremes in intrinsic transmissive capacity; and the habit and distribution of uranium deposits seem to be controlled to some degree by these differences. The Entrada deposits are the only known sizeable uranium deposits found in eolian or marine sandstones of the Colorado Plateau. Most of these deposits are located in three districts and in each district the ore bodies represent locally thickened portions of an essentially continuous layer.[8] Individual ore bodies are large, relative to those deposited in the Morrison and Shinarump strata, and exhibit most of the same habits, but on a larger scale and with less distinct boundaries. The Todilto and Pony Express strata, with no intrinsic transmissive capacity, are also unique in that they contain nearly all the sizeable deposits of uranium found in limestone on the Colorado Plateau, and these are localized by fractures.

In summary, the contrast in total quantity of uranium, and the contrast in frequency and mode of distribution of uranium deposits between major intrinsic transmissivity types is striking. Those strata, which vary greatly in local transmissivity, which have a moderate to low regional intrinsic transmissive capacity, and which are overlain by a thick nontransmissive unit, contain most of the mined ore and known reserves. Strata that fall into this category have a moderate to high frequency of uranium occurrence with the distribution of deposits showing no preferred transmissivity range. With the exception of the Entrada sandstone, units with a uniform intrinsic transmissive capacity, either high or low, contain only a few small uranium deposits.

The mode of uranium distribution correlates well with intrinsic transmissive capacity in all uranium-bearing units. Generally, as the transmissive capacity increases and the range in local transmissivity decreases the range in size of deposits decreases.

REFERENCES

1. Theis, C. V., *The Significance and Nature of the Cone of Depression in Ground-Water Bodies,* Economic Geology 33: 889–902 (1938).
2. Muskat, Morris, *The Flow of Homogeneous Fluids through Porous Media,* J. W. Edwards, Inc., Ann Arbor, Michigan (1946).
3. Craig, L. C., Holmes, C. N., Cadigan, R. A., Freeman, V. I., *et al., Preliminary Report on the Stratigraphy of the Morrison and Related Formations of the Colorado Plateau Region,* US Atomic Energy Commission, TEI-180, Technical Information Service, Oak Ridge, Tennessee (1951).
4. Mullens, T. E. and Freeman, V. L. (US Geological Survey), unpublished data.
   Williams, G. A. *et al.* (US Geological Survey), unpublished data.
5. Finch, W. I., *Preliminary Geologic Map Showing the Distribution of Uranium Deposits and Principal Ore-Bearing Formations of the Colorado Plateau Region,* US Geological Survey Mineral Investigation Field Studies Map MF 16 (1955).
6. Isachsen, Y. W., Mitcham, T. W. and Wood, H. B., *Age and Sedimentary Environments of Uranium Host Rocks, Colorado Plateau, Economic Geology* 50: 127–134 (1955).
7. Stokes, W. L., *Morrison Formation and Related Deposits in and Adjacent to the Colorado Plateau,* Geologic Society of America Bulletin 55: No. 8, 951–992 (1944).
8. Fischer, R. P., Haff, J. C. and Rominger, J. F., *Vanadium Deposits near Placerville, San Miguel County, Colorado,* Colorado Scientific Society Proceedings 15: 117–134 (1947).

Relation of Carnotite Deposits to Permeable Rocks in the Morrison Formation, Mesa County, Colorado

By David A. Phoenix,* USA

The habits of the carnotite deposits in the Salt Wash member of the Morrison formation of Late Jurassic age suggest the deposits were formed from solutions that moved laterally through the sediments.

This report reviews the physical character of the Salt Wash member, particularly of the sandstone strata near the top of the member that contain most of the carnotite deposits in the Morrison formation. The capacity of these sediments to transmit solutions is described and the possible relationship of this capacity to the control of deposition of carnotite deposits is discussed.

MORRISON FORMATION

In most of the Colorado Plateau the Morrison formation is divided into two members, an upper member, the Brushy Basin, and a lower member, the Salt Wash.

The Salt Wash member is of fluvial origin and is divided into three prominent facies, a conglomeratic sandstone facies, a mudstone and lenticular sandstone facies, and a claystone and discontinuous sandstone facies.[1] Carnotite deposits are almost restricted to the mudstone and lenticular sandstone facies. Lenticular sandstone strata near the top of the Salt Wash member are the most productive.

ORE-BEARING STRATA

In areas that are favorable to ore deposits the thick parts of individual light-colored sandstone strata near the top of the Salt Wash member are superimposed and form a layer that frequently crops out continuously for several miles. In areas unfavorable for ore deposits the rock in this same stratigraphic interval is mostly mudstone with only thin, sometimes disconnected strata of dark-colored sandstone.

A single sandstone stratum is not over 30 feet thick, but where the thick portions of several strata are superimposed the strata frequently reach an aggregate thickness of 100 feet. Individual sandstone strata may be narrow, elongate, and somewhat sinuous in plan, but commonly they are tabular and cover broad areas. In most places a single stratum contains tabular units of sand several feet thick, and within each tabular unit the bedding is either horizontal, troughlike or inclined, or a single type of sedimentary structure may prevail in a stratum even though it is composed of several distinct tabular units of sand. Commonly the tabular units of sandstone are separated by a local disconformity.

Linear aggregates of sand grains on bedding surfaces, called current lineation, are abundant in the sandstone strata, particularly where the beds are horizontal or nearly so. Trough cross-stratification[2] is common in the thick central parts of the strata. These beds often contain clay galls, mudstone seams, and fossil wood. Asymmetric ripple marks are present in mudstone and other fine-grained sediments that separate the sandstone strata. These structures indicate the direction of sediment transport and suggest deposition from streams.

Sedimentary structures in a single stratum trend in a common direction. In west-central Colorado this direction is usually northeast or east. Locally, however, strata are found with sedimentary structures that show departures from the prevailing orientation. Detailed mapping in small areas has shown that sandstone strata are elongate lenses that may extend about 3 miles parallel to the trend of their contained sedimentary structures, but at right angles to this trend the lenses are usually between 500 and 3000 feet wide. In the area of detailed study, in Mesa County, Colorado, these relations are well exposed; they are illustrated on Fig. 1.

POSITION AND SHAPE OF THE CARNOTITE DEPOSITS

Carnotite deposits are usually found in the thick portions of a sandstone stratum. The ore is associated with trough-shaped bedding, accumulations of organic debris, and seams and pellets of mudstone. Some deposits occur where a single stratum changes thickness. Many deposits have also been found above or below places where the thick parts of individual sandstone strata are in contact (Fig. 1). The descriptive field term "puncture point" has been applied to these places. In at least one area, lenticular sandstone strata near the top of the Salt Wash member connect with other strata lower in the member. Here the lower sandstone strata also contain ore deposits.

The ore deposits are tabular masses generally parallel to bedding, but they cross-cut bedding in detail. Ore rolls are peculiar, concretionary-like structures in the ore. They are conspicuously elongate

* US Geological Survey.

in one direction, ranging from 10 to 100 feet or more in length. Locally the long axes of the rolls have a common trend, which is parallel to the dominant orientation of fossil logs. Ore bodies are also elongate in the same direction.[3]

Although the controls for localization of the deposits are somewhat variable, precipitation of the metals in most places appears to have responded to the size as well as the chemical composition and transmissivity of the ore-bearing strata.

PERMEABILITY CHARACTERISTICS OF THE ORE-BEARING STRATA

The permeability of a rock is its capacity to transmit a gas or liquid under pressure. The permeability of sediments is measured with nitrogen and calculated in millidarcy units.

Nitrogen instead of water is used as the flow medium because the laboratory procedure for determining the gas permeability of a consolidated sediment is quick and easy. The results are therefore not an accurate measure of the water-bearing properties of the rocks because nitrogen has a much lower coefficient of viscosity than water and because gas does not react with the sediments. The water permeability of the sediments, particularly those containing clay, is probably less than is indicated by the data presented here.

The permeability of about 900 specimens was determined in the laboratory. Each specimen was cylindrical, 0.75 inch long and 0.05 inch in diameter. About 50 specimens were taken from the outcrop and the rest from diamond-drill core. All specimens were collected from one area where details of the geology are well known (Fig. 1).

The permeability of some specimens was measured across the bedding, whereas the permeability of other specimens was measured in the plane of bedding parallel to the trend of sedimentary structures. The permeability of rock specimens from drill cores was determined parallel to the bedding. Specimens selected for permeability measurements were free of all joints or fractures that could be detected with the naked eye or with the aid of a hand lens. Sediments with differing permeability were studied in thin section to determine the effects of diagenesis on the porosity of the rocks.

The permeability characteristics of drill cores from the upper part of the Salt Wash member are shown on Fig. 2. Although the permeability logs are complex in detail, they show a systematic rise and fall in permeability. Each complete fluctuation corresponds to a unit of sediment that has nearly constant lithologic characteristics throughout. These lithologic units are between 3 and 6 feet thick. The permeability of each unit, particularly the most permeable ones, is lowest near the bottom and top and usually rises to a maximum near the middle of the unit. For some units the maximum permeability is between 100 and 300 millidarcies; in others it is much less. The units with the highest permeability are composed of light-colored, fine- to medium-grained sandstone; the least permeable are the units composed of laminated, fine-grained, dark-colored sandstone or siltstone.

Drill core CA-269 (Fig. 2) represents ground unfavorable to ore deposits. The permeability log of this core illustrates permeable units of sandstone, but they are thin. Most of the core is composed of nearly impermeable units of dark-colored, fine-

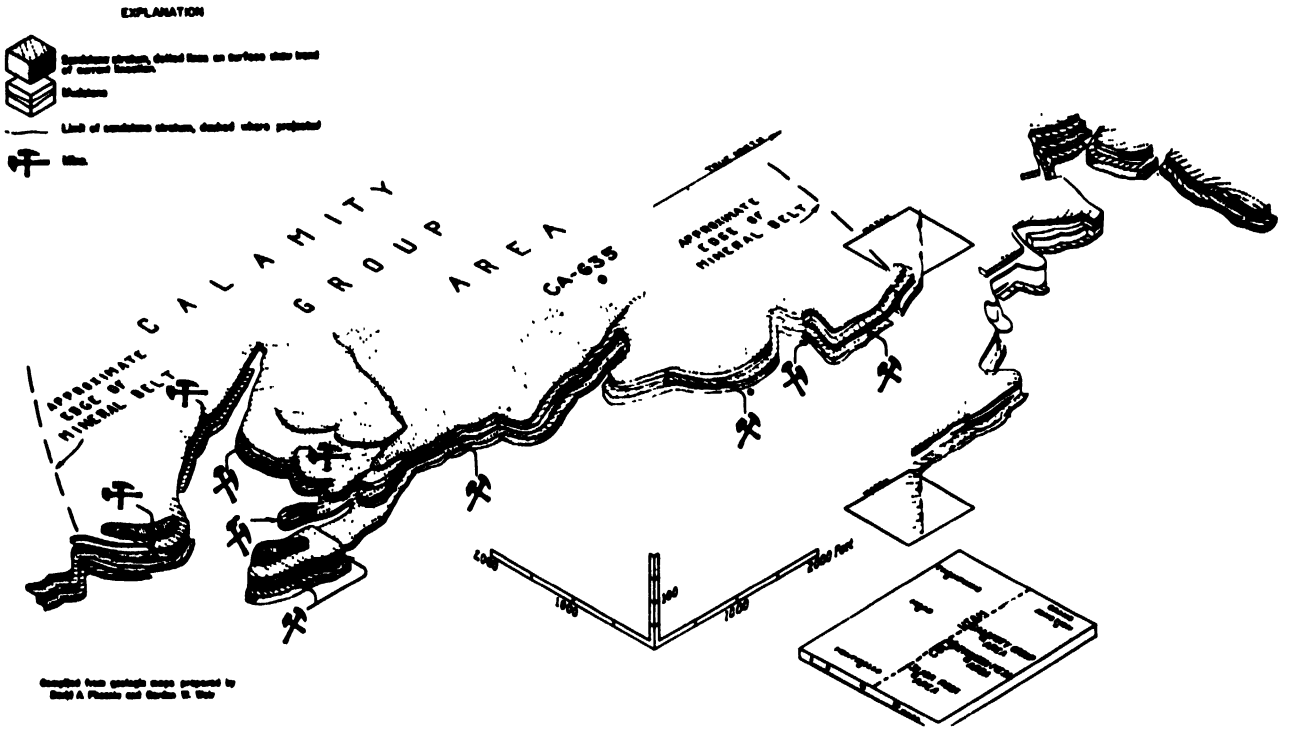


Figure 1. Isometric map of the area of detailed studies, Mesa County, Colorado

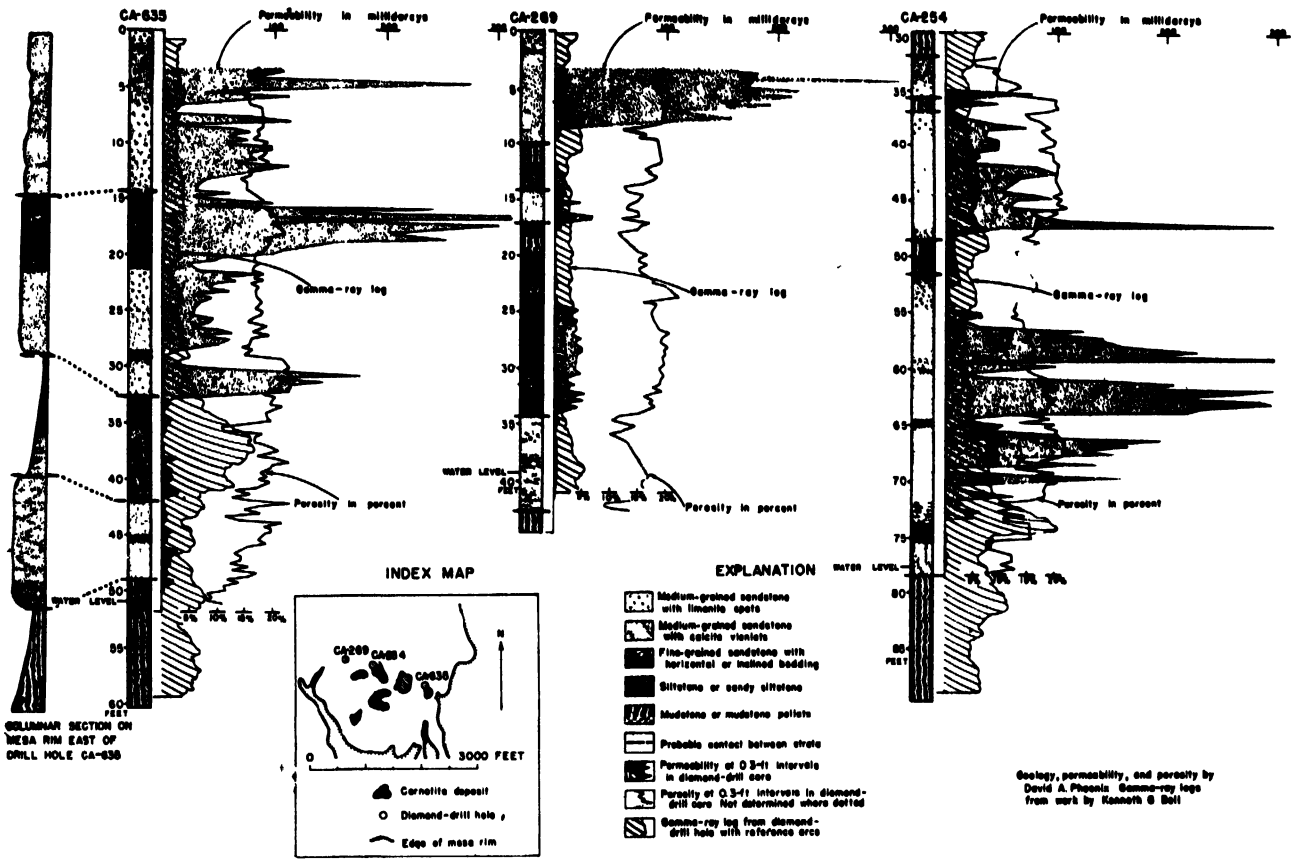


Figure 2. Geologic logs of three drill cores showing the relations between lithology, porosity, permeability, and gamma-ray activity

grained laminated sediments. The average permeability of this core is about 30 millidarcies. The permeability logs of cores CA-254, and CA-635 represent ground favorable to ore deposits. These logs both illustrate at least 5 permeable units of light-colored sandstone, and the nearly impermeable units are thin. The average permeability of each of these cores is about 60 millidarcies.

Core CA-635 was obtained from near the outcrop, and the permeable units within it were related to details of the outcrop. On the nearby outcrop, the upper part of the Salt Wash member is composed of three strata of sandstone. The tabular units in the strata crop out as ledges several feet thick that in profile have a rounded appearance similar to roll structures in the ore deposits. These units of sandstone within the strata correspond to the units in the geologic log that have permeability characteristics usually greater than 100 millidarcies. Between sandstone strata are fine-grained, laminated sediments or mudstone, which correspond to units in the geologic log that have permeabilities of less than 30 millidarcies.

The zig-zag detail in the larger units of permeability may be due to local differences in the amount of cementing minerals, to original depositional features, or to fractures induced while collecting the specimens.

The permeability of rocks oriented in the plane of bedding and parallel to current lineation is 5 to 15 millidarcies greater than that in specimens oriented at right angles to the trend of current lineation. In laminated sediments the permeability is always less across laminae than in the plane of laminae. In the plane of laminae the permeability is usually between 10 and 30 millidarcies, but normal to laminae the permeability is never greater than 5 millidarcies. Where slight changes in color show the bedding, the drop in permeability across bedding is usually less than 15 millidarcies. Where bedding is emphasized by films of mudstone, the drop in permeability is sometimes as great as 100 millidarcies. The influence of postdiagenetic openings on the determination of permeability could not be measured in the laboratory, but judging from the thin sections of these sediments, it is believed to be small.

ALTERATION IN ORE-BEARING STRATA

The degree of alteration in the sediments is related to the permeability of the sediments. Thin sections of nearly impermeable, fine-grained, dark-colored sediments that occupy the stratigraphic interval where sandstone strata are thin and discontinuous, contain somewhat corroded quartz grains usually embedded in a matrix of red-brown clay. Overgrowths on the quartz grains are generally lacking in these rocks, and interstitial clay appears as ragged closely packed flakes. Rounded grains of magnetite and ilmenite are also present. In thin strata of dark-colored but permeable sandstone, a clay, similar to

that in associated but less permeable sediments, is partly altered to illite (?), ilmenite is sometimes altered to leucoxene, and magnetite is partly oxidized.

The light-colored sandstone—permeable rock that is contained in the layer-forming sandstone strata—is usually an interlocking mosaic of sand grains with porosity reduced by the interpenetration of quartz grains with quartz overgrowths. The amount of quartz removed by solution and the amount deposited as overgrowths is approximately equal. Illite(?) occupies many of the interstices, leucoxene is a common minor constituent, and magnetite is absent.

At the base of the lowest layer-forming sandstone stratum in the upper part of the Salt Wash member and at the base and top of permeable units in the sandstone strata, silica overgrowths and calcite are abundant and fill most of the pore spaces. A minutely crystalline mineral, possible tyuyamunite [$Ca(UO_2)_2(VO_4)_2 \cdot 7\text{–}10\ 1/2H_20$], was observed in some thin sections of rock collected from the base of permeable units in the sandstone strata.

TRANSMISSIVITY OF ORE-BEARING STRATA

In the area of detailed study, geologic logs of almost 2,000 cores describe the upper part of the Salt Wash member in as many places. Where sandstone strata are thin, at least 40 feet of dark-colored, fine-grained sedimentary rocks were penetrated in the stratigraphic interval elsewhere occupied by sandstone strata. In places where sandstone strata are thick the drills encountered a maximum of 90 feet of sediments before all the sandstone strata were fully penetrated. The transmissivity of this stratigraphic interval was determined at points spaced 300 to 400 feet apart throughout an area of about 4.5 square miles.

The coefficient of transmissivity is the average coefficient of permeability (per unit thickness) times the total thickness (in the same units). Because measurements in the field are in feet, the millidarcy coefficient of permeability is multiplied by a factor of 0.021 to convert it to the Meinzer coefficient of permeability. Thus, transmissivity is shown in Meinzer-feet.

Average permeability values were assigned to each rock type described in the written logs. The thickness in feet of each rock type in the log is multiplied by its representative average permeability and the sum of the "thickness times permeability" values of the various lithologic units in each geologic log is the transmissivity of the upper part of the Salt Wash member at the point drilled. In the region studied the transmissivity of the uppermost Salt Wash member ranges from a low of about 5 to a high of about 275 Meinzer-feet (Fig. 3).

In the area studies most of the productive deposits are found where the upper part of the Salt Wash member has a transmissivity greater than 100 Meinzer-feet. Where the layer has a transmissivity between 50 and 100 Meinzer-feet it contains isolated or sometimes clusters of small deposits, but these are apparently randomly distributed. Where the upper part of the Salt Wash member has a transmissivity less than 50 Meinzer-feet it is essentially barren.

Figure 4 compares the area underlain by each transmissivity class with the total area of ore deposits and the tonnage of ore in each class. This summary shows that, although the most highly transmissive parts (greater than 150 Meinzer-feet) of the uppermost Salt Wash member constitute only 2 per cent of the total area studied, the most transmissive places are most likely to contain ore deposits. However, a larger target for the drill, as well as the greatest amount of ore-grade rock is obtained where the transmissivity is between 100 and 150 Meinzer-feet. About 21 per cent of the area is underlain by sediments with these characteristics. Only 18 per cent of the total reserves is found where the transmissivity of the sediments is between 50 and 100

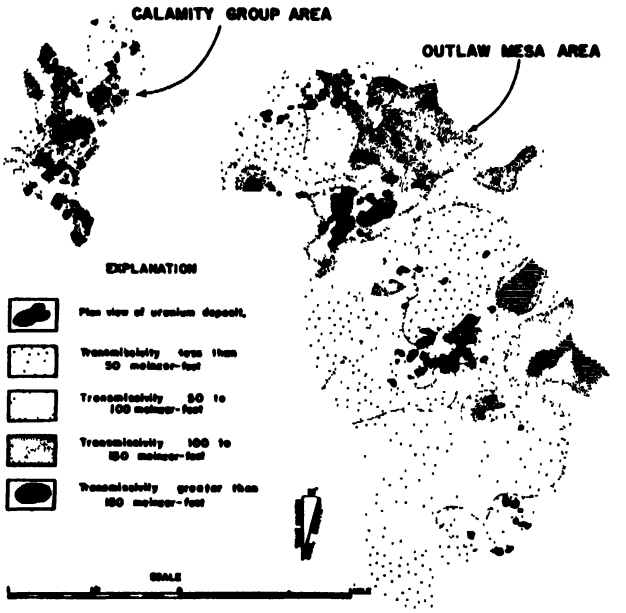


Figure 3. Transmissivity of the uppermost sandstone layer, in two adjoining areas, Mesa County, Colorado

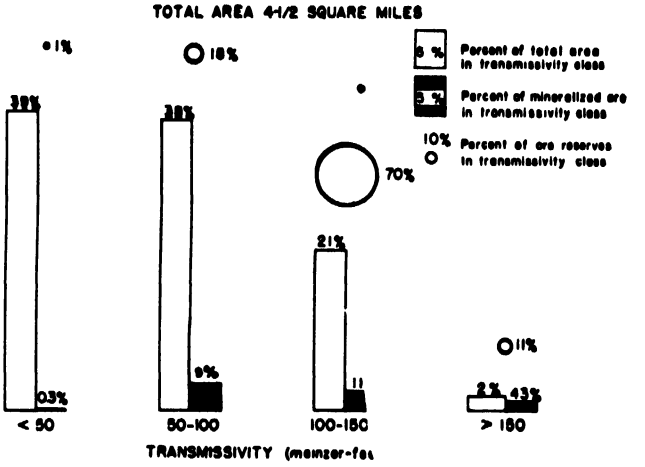


Figure 4. Graphic summary of the relations between transmissivity and the carnotite deposits, area of detailed studies, Mesa County, Colorado

Meinzer-feet, and a sharp drop in total reserves is indicated where the sediments are least transmissive. Seventy-seven per cent of the area is underlain by rocks with negligible total reserves of ore.

CONCLUSIONS

Sandstone strata of the Salt Wash member of the Morrison formation that are favorable to ore form a complex, nearly horizontal "plumbing system". The conduits in this system have a prevailing easterly or northeasterly orientation. Ore deposits are localized in this system at connections between conduits, where the conduits change in size, and where the conduits are largest. Internally the conduits contain many "baffles" in the form of local disconformities, bedding, laminae, mudstone lenses and sedimentary structures. These "baffles" affect the rate and direction of solution movement, and ore deposits are localized where the "baffles" are numerous.

The transmissivity of the upper part of the Salt Wash member is a measure of the capacity of this stratigraphic interval to transmit solutions laterally. In the area of study this capacity varies from a high of about 275 Meinzer-feet to a low of 5 Meinzer-feet or less; the ore deposits are localized in the most transmissive parts of the layer.

If the mineralizing solutions have been in a static environment since shortly after Salt Wash time, then the areas of high transmissivity can be regarded as places where the metals could accumulate but not readily escape. On the other hand, if the mineralizing solutions moved laterally through the permeable sediments after Salt Wash time, then mineral deposition probably responded to changes in the velocity of solution movement and to changes in the hydrostatic pressure as well; other factors such as changes in temperature of the solutions may have influenced mineral deposition but to a degree which has not yet been defined.

REFERENCES

1. Craig, L. C., Holmes, C. N., Cadigan, R. A., Freeman, V. L. and others, *Preliminary Report on the Stratigraphy of the Morrison and Related Formations of the Colorado Plateau Region,* US Geological Survey Bulletin 1009-E (in press).

2. McKee, E. D. and Weir, G. W., *Terminology for Stratification and Cross-stratification in Sedimentary Rocks,* Geological Society of America Bulletin 64 (1953).

3. Fischer, R. P. and Hilpert, L. S., *Geology of the Uravan Mineral Belt,* US Geological Survey Bulletin 988-A (see p. 5) (1952).

Direction of Transportation of the Sediment Constituting the Triassic and Associated Formations of the Colorado Plateau

By Forrest G. Poole and George A. Williams,* USA

Studies of primary sedimentary structures are being made as part of a detailed stratigraphic study of Permian through Jurassic formations of the Colorado Plateau region (Table I) in order to better interpret the geologic history of the Colorado Plateau as related to the localization and distribution of uranium and vanadium ore deposits.

The many geologists who helped accumulate the vast amount of field data pertinent to this paper are not listed here; however, special thanks are extended to G. W. Weir and O. B. Raup who collected and assembled much of the information.

PRIMARY DIRECTIONAL SEDIMENTARY STRUCTURES

Continental and marginal marine sediments commonly possess primary sedimentary structures that reflect the direction in which the transporting medium was moving. The most useful sedimentary structures that possess directional characteristics are channels, current lineation, ripple marks, and cross-strata (Fig. 1). From these sedimentary structures the direction of the transport can be determined and the location of the source area can be inferred.

Sedimentary structures can be divided into two types (Fig. 1): unidirectional structures that can be used to determine a specific direction of transportation, and bidirectional structures that indicate two alternative but opposing directions.

Channels are symmetrical or asymmetrical troughs cut into the underlying beds or within the same bed and subsequently filled by sediment. Channels are elongate and parallel to stream flow. Figure 1A shows a cross-sectional view of a typical channel cut into the underlying unit and subsequently filled with sediment. Channels are bidirectional and, where exposures are sufficiently good, may be used to determine the trend of the ancient stream; however, in some places the orientation of the sedimentary structures of the channel fill may not coincide with the orientation of the channel because the channel may have received sediment from tributary streams.

In some stratigraphic units, current lineation is a common sedimentary structure on bedding planes.[1] Lineation is a bidirectional structure consisting of linear aggregations of sand grains arranged parallel with the direction of current movement (Fig. 1B).

Ripple marks are of two major types: symmetrical and asymmetrical. Symmetrical or oscillation ripples are bidirectional (Fig. 1C) and must be supplemented by unidirectional sedimentary structure data. The direction of transportation is perpendicular to the linear ridges.

Asymmetrical or current ripple marks are unidirectional with the short steep slope on the down current side (Fig. 1D). The asymmetrical type is the most useful ripple mark in determining direction of current movement.

Cross-strata are the most useful of the primary structures in determining direction of transport because they are the most common structure encountered. Cross-stratification terminology used in this paper is that of McKee and Weir.[2]

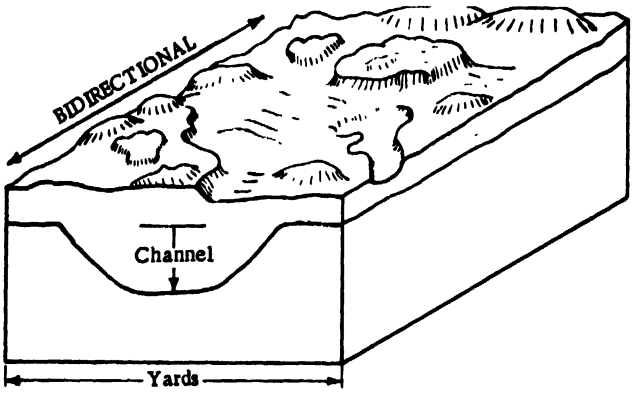
Trough cross-stratification is probably the most common type encountered in the sandstone studies on the Colorado Plateau (Fig. 1E). The trough pattern is the result of the repetition of two steps: erosion that produces plunging troughs, and filling of the troughs by thin concave layers conforming, in general, to the shape of the trough floors. The closed end is interpreted to be in the up-current direction and the open end in the down-current direction. The trough cross-stratification of the Plateau rocks is essentially the same as the festoon cross-lamination in the Casper formation of Wyoming described in detail by Knight.[3] Knight attributes a marine origin to the festoon cross-stratification in the Casper formation; however, the term "festoon" is widely used by Plateau geologists to describe trough cross-stratification in fluvial sediments.

Planar cross-stratification is the result of erosion that produces a planar surface and subsequent deposition (Fig. 1F).

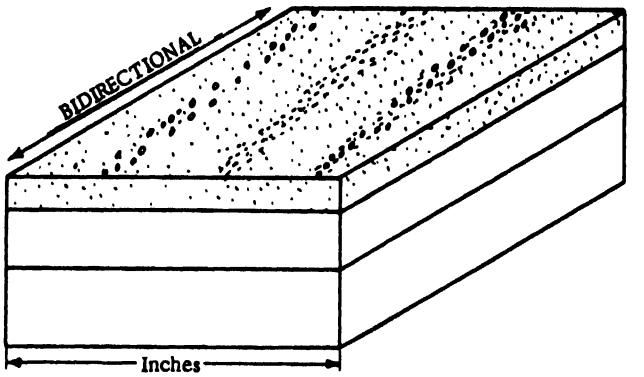
METHOD USED IN CROSS-STRATIFICATION STUDIES

In making a sedimentary structure study on cross-strata a basic assumption is made that one component of the dip direction is in the down-current direction. Studies of the direction of dip of cross-strata involve taking a number of measurements on the surfaces of the cross-strata with a Brunton compass and then determining the resultant dip bearing from all measurements. Care is taken to make only one measurement in each set of cross-strata. In studying trough cross-stratification the direction of maximum

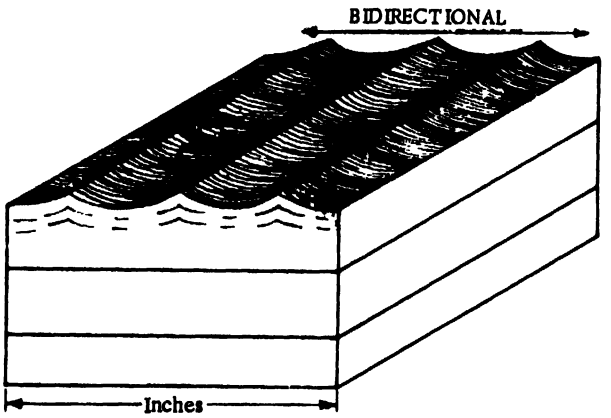
* US Geological Survey.



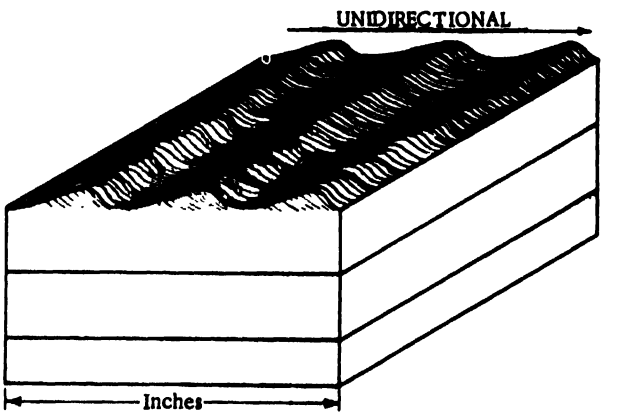
A. BURIED CHANNEL



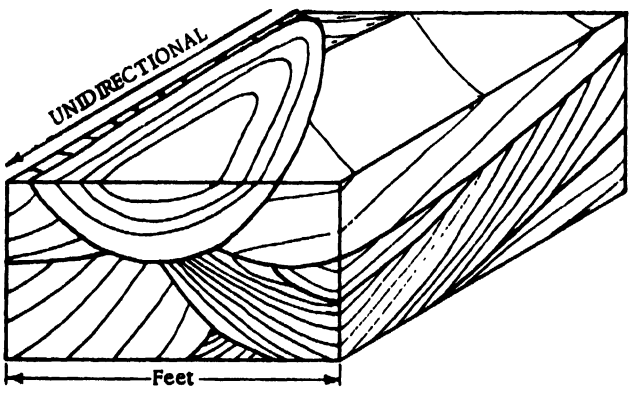
B. CURRENT LINEATION



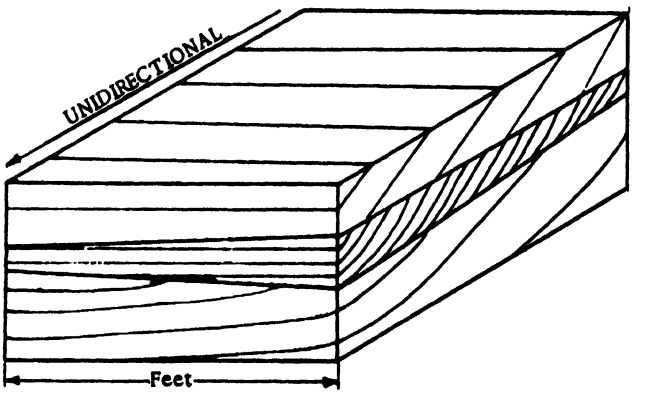
C. SYMMETRICAL RIPPLE MARKS



D. ASYMMETRICAL RIPPLE MARKS



E. TROUGH CROSS - STRATIFICATION



F. PLANAR CROSS - STRATIFICATION

Figure 1. Primary sedimentary structures showing directional characteristics. Scales given to show comparative size of individual blocks

Table I. Generalized Section of Upper Paleozoic and Mesozoic Strata in Southeastern Utah and Adjoining Parts of Colorado, Arizona and New Mexico

System or Series	Group	Formation	Member or tongue	Thickness (feet)	Character	Transport direction
Upper and Lower(?) Cretaceous		Dakota		0-200	Gray and brown sandstone and shale; forms cliff, widespread	
Lower Cretaceous		Burro Canyon		0-250	Light-colored conglomeratic sandstone and green and maroon mudstone; mesa-capping, absent in western part of region	
Upper Jurassic		Morrison	Brushy Basin	300-500	Varicolored shale (or mudstone), some sandstone lenses; forms slopes, widespread	NE
			Westwater Canyon	0-350	Light-colored sandstone; forms cliffs and benches, absent in northern part of region	NE
			Recapture	0-680	Red shales and sandstones; forms cliffs and benches, absent in northern part of region	NE
			Salt Wash	0-400	Light-colored sandstone and red mudstone; forms cliffs and benches, widespread	NE
	San Rafael	Bluff		0-55	Red massive sandstone; forms cliff, absent in northern part of region	
		Summerville		0-400	Red and gray shale, thin sandstone; forms slopes, thickens westward, widespread	
		Curtis		0-100	Light-colored sandstone; absent in southern Utah	
		Entrada		50-1000	Light-colored massive sandstone; forms cliff, thickens westward to red earthy sandstone	
Upper and Middle Jurassic		Carmel		0-600	Red earthy sandstone; thickens westward to gray and red shale; limestone, and gypsum, widespread	
Jurassic and Jurassic(?)	Glen Canyon	Navajo		0-2000	Red sandstone; irregularly bedded; forms bench; absent in eastern part of region	SE
Jurassic(?)		Kayenta		0-300	Light-colored, massive sandstone; cliff-forming, absent in western Colorado	
Upper Triassic		Wingate		0-400	Red massive sandstone; forms cliff absent in eastern part of region	SE
		Chinle	"A" unit of Gregory	0-350	Red siltstone and sandstone; forms ledges and slopes, widespread	
			Owl Rock	0-450	Gray limestone and red siltstone; forms ledges and slopes, widespread	
			Petrified Forest	0-700	Variegated claystone; forms slopes, widespread, absent in northern Utah	
			Moss Back	0-150	Light-colored conglomeratic sandstone; forms cliff, fills channels, widespread	NW
			Monitor Butte	0-250	Gray claystone and sandstone; forms slopes, widespread	
		Shinarump		0-250	Light-colored conglomeratic sandstone; fills channels, forms cliff, widespread	NW
Middle(?) and Lower Triassic		Moenkopi		0-700	Red siltstone and sandstone; ripple marks, forms slopes and ledges, widespread	
			Sinbad	0-200	Limestone; absent in eastern part of region	NW
				0-200	Red siltstone; ripple marks, forms slopes and ledges, thins eastward	
Permian		Kaibab	Hoskinnini	0-120	Red siltstone; absent in northwestern part of area, forms steep slopes and cliffs	
			White Rim	0-230	White sandstone; absent in eastern part of region, forms cliffs	
		Cutler	DeChelly	0-850	Light-colored sandstone; absent in northern part of area, forms cliffs	SW
			Organ Rock	250-800	Red siltstone; absent in northern part of region, forms steep slopes	
			Cedar Mesa	0-1250	Light-colored sandstone; thickens to the north, forms cliffs and benches	SE
		Coconino	Halgaito	0-500	Red siltstone and sandstone; absent in north part of region	
Permian(?) and Pennsylvanian		Rico		300-500	Red sandstone and siltstone; light-gray limestone, forms cliffs and ledges, widespread	

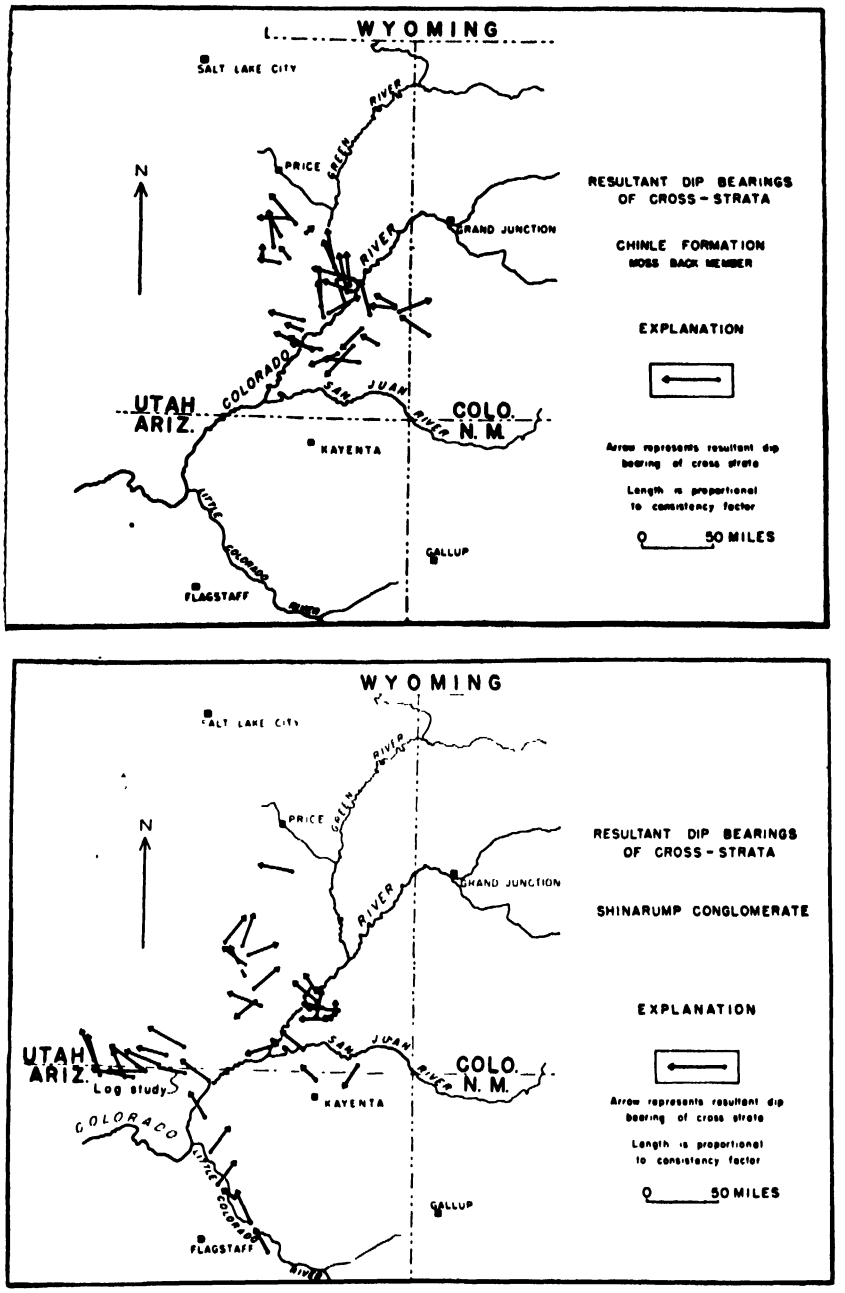


Figure 2. Maps of the Colorado Plateau area showing direction of sediment transport in the Shinarump conglomerate and Moss Back member of the Chinle formation: A. Shinarump conglomerate; B. Moss Back member of the Chinle formation. (Tails of arrows mark location of cross-stratification study)

dip is recorded where possible, but in many places most of the trough is covered and a reading is taken on a small part of a trough. These readings on part of a trough should compensate one another, if enough measurements are taken, so that an average of these readings should indicate the general trend of the current. The number of measurements required at any one locality depends on the amount of variation in the dip direction of cross-strata. The amount of variation in dip direction is represented by a consistency ratio[4] or factor, expressed numerically from 0.00 to 1.00. If all measurements are in the same direction the consistency factor would be 1.00, whereas if the readings are evenly distributed through 360° the consistency factor would be zero. In an area where the regional dip is in excess of 4°, each measurement is corrected to its original attitude with a Wulff stereographic polar net. Measurements are then plotted graphically or calculated mathematically to determine the dip direction.

The method used by the authors in making sedimentary structure studies is after Reiche[4] and Raup.[5]

DIRECTION OF SEDIMENT TRANSPORTATION

Sedimentary structure studies have been made on continental sediments of the Colorado Plateau that

range in age from Permian through Jurassic (Table I). Structure studies made in rocks of Permian age indicate that the Coconino sandstone had a southerly direction of transport,[4] the Cedar Mesa sandstone member of the Cutler formation had a southeasterly direction of transport, and the DeChelly sandstone member of the Cutler formation was transported southwesterly.[4] The Moenkopi formation, Shinarump conglomerate (Fig. 2A), and Moss Back member of the Chinle formation (Fig. 2B), all of Triassic age, were transported in a northwesterly direction. The Chinle formation, in general, shows a northwesterly direction in Utah and a northerly direction in northern Arizona. The Wingate sandstone of Triassic age and Navajo sandstone of Jurassic and Jurassic(?) age were transported southeasterly. The Salt Wash, Recapture, Westwater Canyon, and Brushy Basin members of the Morrison formation of Jurassic age, in general, were transported northeasterly.[6]

APPLICATION

Sedimentary structures are most useful in determining the direction of sediment transportation and in reconstructing depositional environments. Of the sedimentary structures, cross-strata are particularly useful because they may develop in all environments in which sand is deposited; whether or not cross-strata are present depends upon the velocities of currents and supplies of sand. Cross-strata are made by water and wind, and, in many instances, it is impossible to distinguish the two types of bedding; however, in general, the angle of inclination in a stream deposit is less than that in a wind deposit.

Ripple marks are important in paleogeographic interpretations.[7,8] Ripples formed by wind generally have a higher ripple index—the number obtained by dividing the wave length by the amplitude—than those formed in shallow water.

Sedimentary structures can also be used as a tool in stratigraphic correlation. Similar types of sedimentary structures indicating like directions of transportation are evidences of a similar environment of deposition and can be used, in conjunction with lithologic characteristics and stratigraphic position, to support the correlation of a unit across wide gaps in outcrop.[4]

Sedimentary structures are useful in the exploration for uranium and vanadium ore deposits of the Colorado Plateau. Many ore bodies are localized in channel-filling sandstones of the Shinarump conglomerate, Chinle formation, and the Morrison formation and have a tendency to be elongate in the direction of paleostream flow.[9] Where exposures and sedimentary structures permit, a direction of transportation for the sediment in the channel can be determined that may reduce the amount of drilling required to outline the channel or the ore body, as shown by Stokes[10] and Lowell.[9] Cross-strata are the most abundant and therefore the most useful; however, a combination of cross-strata, current lineation, and ripple marks can be used to determine the direction of transportation. Sufficient measurements should be made to assure adequate sampling.

REFERENCES

1. Stokes, W. L., *Primary Lineation in Fluvial Sandstones: A Criterion of Current Direction,* Journal of Geology 60: 52–54 (1947).
2. McKee, E. D. and Weir, G. W., *Terminology for Stratification and Cross-Stratification in Sedimentary Rocks,* Geological Society of America Bulletin 64: 381–390 (1953).
3. Knight, S. H., *The Fountain and Casper Formations of the Laramie Basin,* Wyoming University Publications in Science, Geology 1: 1–82 (1929).
4. Reiche, Parry, *An Analysis of Cross-Lamination, the Coconino Sandstone,* Journal of Geology 46: 905–932 (1938).
5. Raup, O. B., written communication.
6. Craig, L. C., Holmes, C. N., Cadigan, R. A., Freeman V. L. *et al., Preliminary Report on the Stratigraphy of the Morrison and Related Formations of the Colorado Plateau Region,* US Atomic Energy Commission TEI–180. Technical Information Service, Oak Ridge, Tennessee (1951).
7. Bucher, W. H., *On Ripples and Related Sedimentary Surface Forms and Their Paleogeographic Interpretation,* American Journal of Science 47: 149–210, 241–269 (1919).
8. Pettijohn, F. J., *Sedimentary Rocks,* Harper and Brothers, New York (1949).
9. Lowell, J. D., *Applications of Cross-Stratification Studies to Problems of Uranium Exploration, Chuska Mountains, Arizona,* Economic Geology 50: 177–185 (1955).
10. Stokes, W. L., *Primary Sedimentary Trend Indicators as Applied to Ore Finding in the Carrizo Mountains, Arizona and New Mexico,* US Atomic Energy Commission RME–3043, Technical Information Service, Oak Ridge, Tennessee (1953).

Sedimentary Features of Upper Sandstone Lenses of the Salt Wash Sandstone Member and Their Relation to Uranium-Vanadium Deposits in the Uravan District, Montrose County, Colorado

By R. L. Boardman, E. B. Ekren and H. E. Bowers,* USA

The Uravan district is in the northwest part of Montrose County in southwestern Colorado. The principal uranium-vanadium deposits occur in the western part of the district (Fig. 1). Natural boundaries of the district are Paradox Valley to the southwest, the Dolores River to the west, the Mesa Creek drainage to the north, and the Uncompahgre Plateau to the northeast. Altitudes in the western part of the district range from about 4900 to 7000 feet above sea level; locally in the Uncompahgre Plateau altitudes reach 8000 feet. The climate is semiarid.

The oldest rocks exposed are Precambrian granitic and metamorphic rocks which crop out along the southwestern flank of the Uncompahgre Plateau. Overlying these basement rocks are gently dipping formations of marine and terrestrial sedimentary rocks ranging in age from late Paleozoic to late Mesozoic. Quaternary alluvium, gravel, and landslide material obscure older rocks in many places. A general description of the sedimentary beds exposed in the Uravan district has been given by Fischer.[2]

The Uravan district lies between two major northwest-trending structures, the Uncompahgre Plateau uplift to the northeast, and the salt anticline that underlies Paradox Valley to the southwest. Along the flanks of these structures high-angle strike faults and zones of intensely jointed sandstone strata are common. Between these structures is the San Miguel syncline, which strikes northwest through the central part of the district (Fig. 1). The sedimentary beds dip about 5° or less toward this synclinal axis in most of the district; however, high on the flanks of the major folds the dip steepens sharply to 15° or more.

Except for one very small prospect in the Burro Canyon formation of Early Cretaceous age, all the known uranium-vanadium deposits in the Uravan district are in the underlying Morrison formation of Late Jurassic age. The Morrison formation in the district is divided into two members; the Brushy Basin shale member, which averages about 400 feet in thickness, and the underlying Salt Wash sandstone member, which averages about 300 feet in thickness. Only two uranium-vanadium deposits of 1000 tons or more have been found in the Brushy Basin member in the district; all other deposits of 1000 tons or more, as well as most of the minable ore bodies, are in sandstone lenses in the upper part of the Salt Wash member. As much or more uranium-vanadium ore has been produced from the Uravan district as has been produced from any other mining district in the Colorado Plateau province.

A detailed study of the rim of the upper sandstone lenses of the Salt Wash member in the western part of the Uravan district was completed in 1954. The horizontal extent and geologic character of the sandstone lenses were recorded, as were the sedimentary trends determined from festoon cross-laminations, ripple and current lineation marks, and crossbedding.[3,4] The data compiled during this study

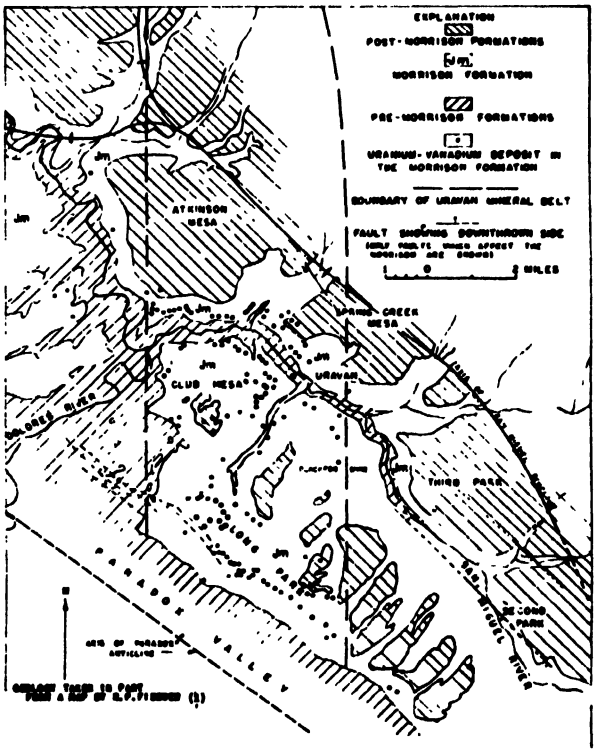


Figure 1. Simplified geologic map of the western part of the Uravan district, Montrose County, Colorado

* US Geological Survey.

have been used to determine the approximate limits of ground that is believed to be geologically favorable for the occurrence of ore. These data have also been used to aid in planning drilling in unexplored ground at a distance of several hundred feet or more behind the rim. The information from the rim study has been integrated with information derived from detailed mine mapping, from cursory mine examinations, and from partial compilation of the more than 3000 US Geological Survey drill holes in the district. Together, these data give a general picture of the deposition, extent, and structure of the upper sandstone lenses of the Salt Wash member and provide a basis for relating sedimentary features to ore features throughout the area studied.

UPPER SANDSTONE LENSES OF THE SALT WASH

The Salt Wash member in the Uravan district is composed of a series of terrestrial sandstone, siltstone, and mudstone lenses. A sandstone lens is defined here as a mappable unit that is generally a single layer of sandstone but in many places may split into two or more layers of sandstone separated by thin beds of mudstone and siltstone. The lenses range from a few hundred feet to several miles in length and are as much as several thousand feet wide. The sandstone lenses constitute about 50 per cent of the Salt Wash member throughout the district, although the ratio of sandstone to mudstone and siltstone varies considerably in short distances. In many places the sandstone is quartzitic and grades to quartzite. Commonly, 3 to 5 sandstone lenses, each 20 feet or more thick, are prominent along the outcrop of the Salt Wash member. The sandstone lenses generally exhibit scour-and-fill-type bedding in the vicinity of ore deposits. The prominent sandstone lens or lenses in approximately the upper 100 feet of the Salt Wash member contain the largest uranium-vanadium deposits in that member. The detailed rim study was made of only this part of the Salt Wash section in the productive western part of the district. Similarly, the US Geological Survey's drilling projects in the district have been planned almost exclusively to test the upper sandstone lens or lenses of the Salt Wash member.

Preliminary analysis of the data obtained from the rim study and drilling programs suggests that the upper sandstone lenses of the Salt Wash may not be extensive regional aquifers. In some places they appear to be enclosed by relatively impermeable mudstone beds. Pinchouts of the principal ore-bearing sandstone lenses between the richly mineralized Club Mesa and Long Park areas (Fig. 2) make it improbable that these lenses were continuous or connected at this locality. The principal ore-bearing sandstone lens along the southwestern part of the bench around Atkinson Mesa (Fig. 2) pinches out northward on the rim. Information from drill cores shows, in general, the upper sandstone lenses of the Salt Wash member to be thin and discontinuous northward and eastward under the Atkinson Mesa,

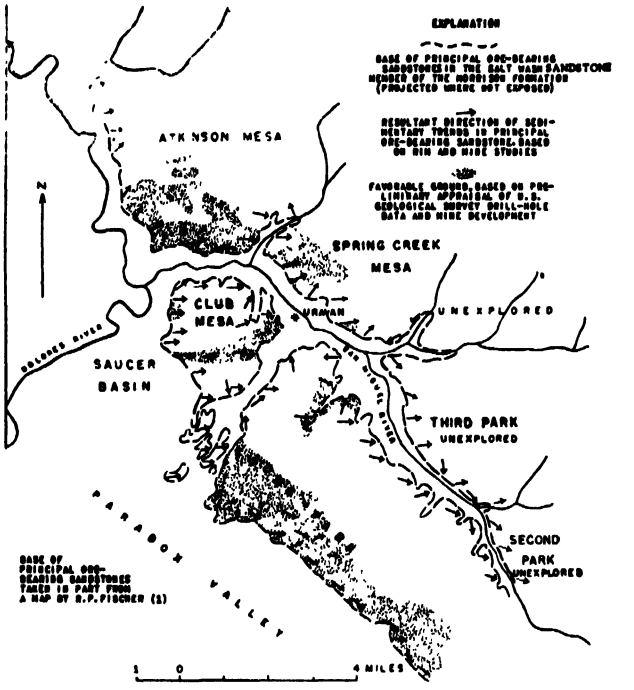


Figure 2. Map showing relation of resultant direction of sedimentary trends and favorable ground in the western part of the Uravan district, Montrose County, Colorado

Spring Creek Mesa, and Long Park areas. The upper sandstone lenses along the flank of Paradox Valley northwest of Long Park thin and split into several beds at the eastern margin of Saucer Basin (Fig. 2). It is possible that the lack of thick continuous sandstone lenses in the upper part of the Salt Wash member in the Saucer Basin area facilitated removal of sediments by erosion and resulted in the topographic basin present today.

In the western part of the Uravan district, the sedimentary trends in upper sandstone lenses of the Salt Wash member are, in general, easterly. An average northeast trend was observed in the northern part of the area studied, and an average southeast trend in the southern part. Figure 2 shows the resultant direction of several hundred trends of primary sedimentary structures that were observed on the outcrop and in mines. No consistency ratio is indicated for the directions plotted, but, as shown in Fig. 3 of the Club Mesa area, the consistency ratio is generally high.

The strike of the sedimentary features is nearly parallel to the long axes of ground that by preliminary appraisal of US Geological Survey drill-hole data[5] and of mine development is believed to be geologically favorable for ore (Fig. 3).

Fischer and Hilpert[6] noted the parallelism of the orientation of fossil logs and long axes of ore rolls and ore bodies. They also noted an *en echelon* arrangement of the ore bodies within deposits in the Club Mesa and Long Park areas. The long axes of the ore bodies are, in addition, nearly parallel to the strike of the sedimentary features and favorable ground, as shown in the Club Mesa area (Fig. 3).

it is believed that the parallelism of ore body axes and trends of sedimentary structures is a strict relationship, and that an *en echelon* arrangement of the ore bodies is a reflection of an *en echelon* arrangement of sedimentary structures. This arrangement of sedimentary structures is likely the result of shifting channels of upper Salt Wash streams.

The parallelism of ore bodies (mineralized logs and rolls) and primary sedimentary structures is clearly shown in the Blackfoot mine (Fig. 4), located about 2½ miles northeast of Long Park (Fig. 1). Figure 4 also shows a point diagram of the joints mapped in the Blackfoot mine. A conjugate joint system related to the regional structure is apparent, but there is no evidence of any correlation between fractures and ore trends. Based on the rim and mine mapping completed to date, the writers concur with Fischer's observation[2] that ". . . all joints related to regional structures are believed to have been formed later than the early ore minerals." All known faults in the district that cross ore bodies displace the ore. Many of these faults contain ore gouge and breccia derived from the displaced ore.

APPLICATION OF SEDIMENTARY AND STRUCTURE DATA

It is appropriate to apply in a preliminary manner some of the foregoing observations to the concept of the Uravan mineral belt and to hypotheses of the origin and localization of the ore. The Uravan mineral belt, described by Fischer and Hilpert,[6] is about 4½ miles wide and strikes about north through the west-central part of the district (Fig. 1). The concept of such a belt in the district cannot be seriously

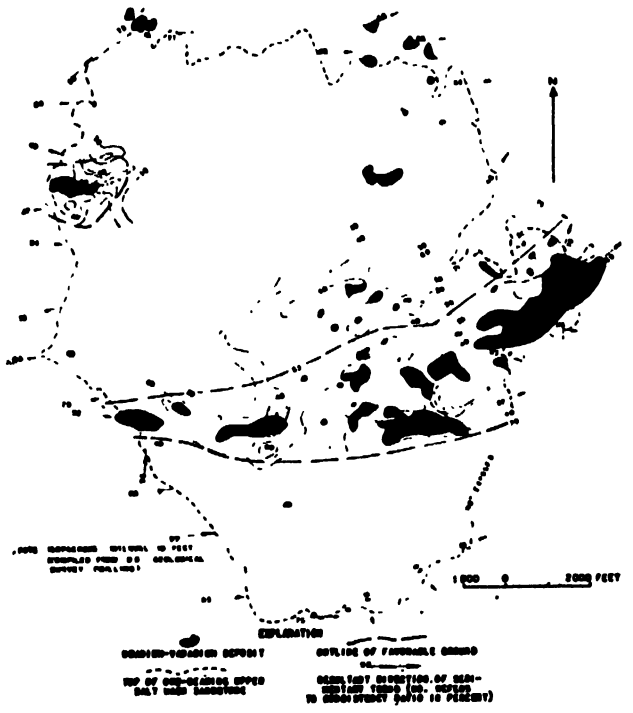


Figure 3. Club Mesa area showing the relations of the deposits and favorable ground to sedimentary trends and thickness of the ore-bearing upper Salt Wash sandstone

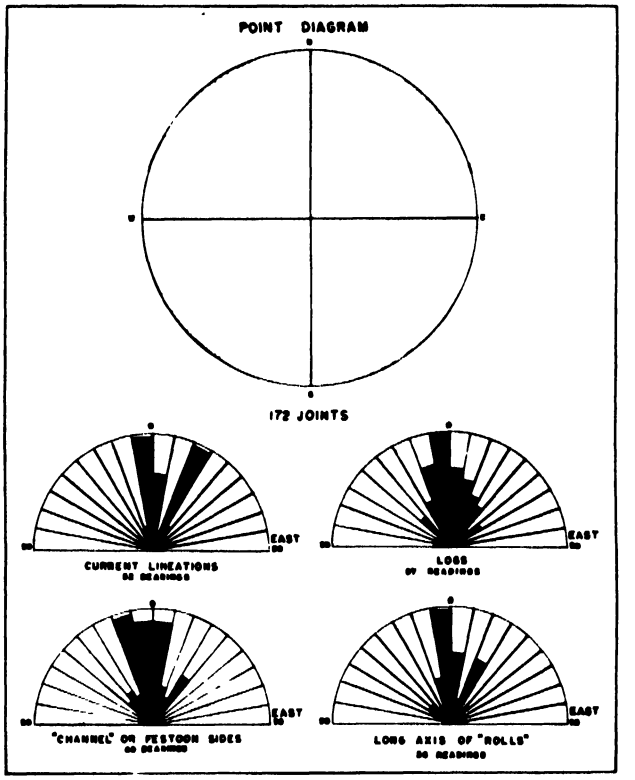


Figure 4. Point diagram of joints and string diagrams of primary sedimentary structures, mineralized logs and rolls in the Blackfoot mine, Uravan district, Montrose County, Colorado

questioned on the basis of present knowledge. Except for three large deposits east of the belt and southeast of Long Park, there are no known deposits of significant size outside of the belt in the district. The belt tends to become wider in the vicinity of Paradox Valley than it is to the north. The common orientation of ore rolls and fossil logs normal to the trend of the belt is believed to be directly related to the average easterly sedimentary trends. Where the sedimentary trends parallel the mineral belt, the orientation of ore rolls and fossil logs is likewise parallel, as in the Blackfoot mine (Fig. 4). The present application of the mineral belt concept in the Uravan district might best be summarized as follows: where upper sandstone lenses of the Salt Wash member are appraised as geologically favorable for ore, it is expected that a much greater concentration of large ore bodies will be present within the Uravan mineral belt than outside of the belt. This application is being further tested by US Geological Survey drilling in ground that is appraised as geologically favorable for ore east of the mineral belt in the Uravan district.

The source of the uranium and vanadium and the factors that controlled the emplacement of the ore bodies remain imperfectly understood. Although such features as primary sedimentary structures, carbonaceous material, and "altered" mudstone apparently have a direct relationship to the localization of most of the ore bodies in the Uravan district, these sedimentary and lithologic features are abundant in

adjacent barren sandstone. It is improbable that the origin and localization of uranium-vanadium deposits in the district were in any manner controlled by known faults or fractures. If the sedimentary data and the fracture relationships described above are valid, as we believe, one must appeal to unproven conduitive fractures for a hypogene source of the ore-bearing solutions. Many such conduits may be needed to explain deposits in relatively isolated sandstone lenses. The deposits are more easily explained, perhaps, if it is assumed that the ore elements were originally contained in some part of the sediments at the time of deposition and were subsequently concentrated by solution and precipitation in approximately the present positions of the ore bodies.

REFERENCES

1. Fischer, R. P., *Simplified Geologic Map of the Vanadium Region of Southwestern Colorado and Southeastern Utah,* US Geological Survey Strategic Minerals Investigations Preliminary Map (1944).
2. Fischer, R. P., *Vanadium Deposits of Colorado and Utah,* US Geological Survey Bulletin 936-P (1942).
3. McKee, E. D., *Classification and Interpretation of Cross-Lamination,* Geological Society of America Bulletin 59: 1378 (1948).
4. Stokes, W. L., *Primary Lineation in Fluvial Sandstones, A Criterion of Current Directions,* Journal of Geology 55: 52–54 (1947).
5. Weir, D. B., *Geologic Guides to Prospecting for Carnotite Deposits on Colorado Plateau,* US Geological Survey Bulletin 988-B (1952).
6. Fischer, R. P. and Hilpert, L. S., *Geology of the Uravan Mineral Belt,* US Geological Survey Bulletin 988-A (1952).

Significance of Roll Ore Bodies in Genesis of Uranium-Vanadium Deposits on the Colorado Plateau

By Daniel R. Shawe,* USA

Similarities between roll ore bodies and the more prevalent tabular ore bodies in sedimentary rocks of the Colorado Plateau suggest a common origin for the two types. Similarities include internal structure, mineralogy, and associated altered zones. Moreover, the types in many places intergrade. Thus, close study and interpretation of details of roll ore bodies may help clarify the genesis of the uranium-vanadium ore deposits of the Colorado Plateau.

Roll ore bodies are generally layered deposits that cut across sandstone bedding in sharply curving forms.[1] In cross section, rolls commonly show "C," "S" and "socket" shapes (Figs. 1A, B, and C), but in plan are linear; many elongate rolls curve sharply at their extremities into "noses" or "prows." Roll surfaces are fractures that separate mineralized rock from barren rock. The fractures are best developed in roscoelite- and carnotite-bearing oxidized rolls but are also present in uraninite- and montroseite-bearing unoxidized rolls of similar form and distribution.

Most rolls are found in sandstone lenses and layers in the upper part of the Salt Wash sandstone member of the Morrison formation of Jurassic age; however, they are less common than tabular deposits. Rolls are also less common than tabular deposits in other ore-bearing formations of the Colorado Plateau.

Most roll ore deposits are near the base of thick sandstone units where numerous, thin, well-defined mudstone layers are interbedded with thin sandstone layers. Where mudstone splits or partings are less well defined, tabular ore bodies predominate. Although rolls commonly terminate against an upper and lower mudstone layer, in places they are split into two distinct rolls by a third thin mudstone layer along their axes (Fig. 1D). Rolls may bulge above places where thick parts of sandstone strata are in contact—termed "puncture points"—, and noses of rolls may be situated under these places.[2]

The long axes of rolls may be continuous for many hundreds of feet in the plane of thin sandstone layers. Essentially, roll ore bodies in any particular sandstone layer are all segments of a continuous "roll front", which in places appear to be lacking as a result of flattening of rolls into tabular form. These axes are characteristically sinuous in plan and commonly double back on themselves so that cross sections through loops in the roll fronts show mirror images of the roll shapes on either side of the loops (Fig. 1E and F). Individual roll fronts in different sandstone layers show little similarity in local distribution. In many places rolls grade into tabular ore bodies which are essentially parallel to bedding planes (Fig. 1A and C).

Detailed mapping of sedimentary structures underground has shown the general coincidence of the long axes of rolls with the trend of such structures as current lineation, trough cross-stratification, and local channels in the thin sandstone layers in which ore is found. The relationship between position of ore and sand-filled local channels or thicker parts of sandstone layers remains to be demonstrated. However, the consistent relationship between trends of the long axes of ore bodies and sedimentary structures probably reflects the orientation of the most permeable units in the sandstone layers.[3]

Rolls commonly lie against mineralized carbonized logs or are indented where such logs lie across the general trend of the roll. Logs typically lie in or just under thin mudstone layers which contain abundant carbonized plant debris, so, the upper edges of roll ore bodies are commonly adjacent to logs.

Many rolls of uranium-vanadium ore show concentric layering parallel to ore surfaces (Fig. 2A). Commonly, the concave surface of rolls show sharp transitions into barren rock, whereas the convex side of rolls commonly show more gradual transitions into barren rock, or may even be continuous laterally into tabular ore bodies.

The distribution of minor elements across roll ore bodies is asymmetric. For example, in a deposit in Navajo (?) sandstone near Rifle, Colorado, layers rich in galena and chromium minerals are parallel and adjacent to ore layers in both roll and tabular bodies (Fig. 2B).[5] In ore deposits in the Salt Wash member hematite- or limonite-, calcite-, and selenide-rich layers commonly lie concentrically on the concave side of roll ore bodies (Fig. 2C).

Hematite and magnetite comprise more than half the heavy detrital minerals in unaltered Salt Wash sandstone members, but they are sparse in altered rock on the convex side and absent in altered rock on the concave side of some rolls where normal

* US Geological Survey.

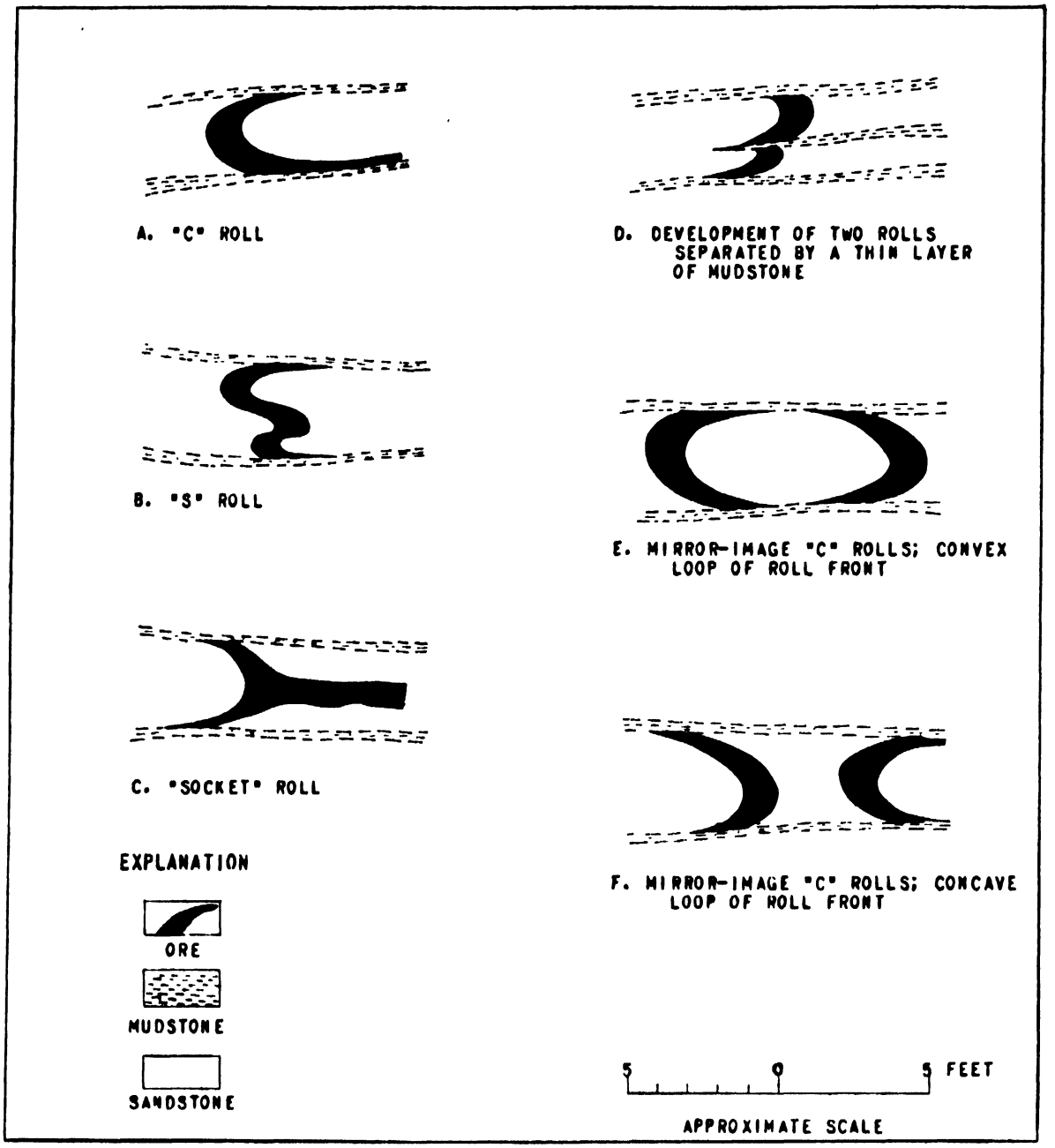


Figure 1. Cross-sectional forms of roll ore deposits

amounts of other heavy detrital minerals occur. These rolls contain an abundant, unidentified black opaque mineral probably altered from detrital magnetite or hematite, or both.

In summary, rolls are layered ore bodies that cut sharply across sandstone bedding. In plan the long axes of rolls may be several hundred feet in length, in many places sinuous, and locally oriented parallel to sedimentary structures. In cross section, minor elements in ore bodies are distributed asymmetrically and alteration seems more extensive on the concave side of the deposits.

One possible explanation for all these features is that roll ore bodies were formed by precipitation of minerals at an interface between solutions of different composition and density, and that flow of the active or ore-bearing solution as it passed through connate waters in the sediments was influenced strongly by local sedimentary structures.

It is postulated that at the time of ore deposition warm water solutions moved freely through many of the formations of the Colorado Plateau. The solutions moved through more permeable channels, altering and strongly leaching the sediments. Possibly uranium and vanadium as well as other elements were leached from the sedimentary rocks by solutions passing through them. As warm water moved through cooler connate water, well-defined solution pathways became established and interfaces between warm and cool water became fixed. It is further postulated that

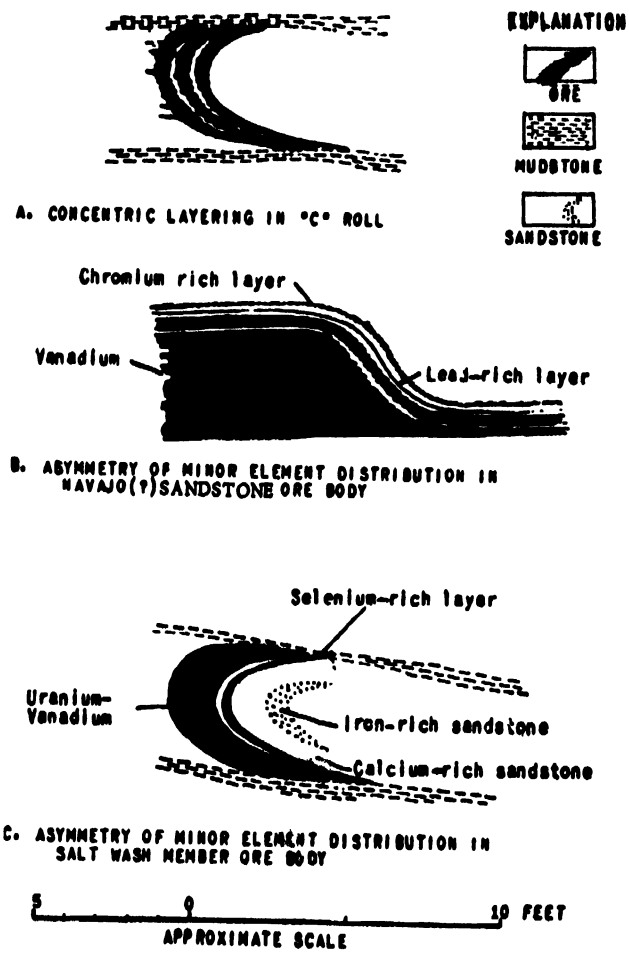


Figure 2. Details of roll ore bodies

along these interfaces elements or ions in solution in the moving warm water were precipitated in the cooler surrounding water. Under this hypothesis, slight oscillation of the essentially static interfaces would account for the concentric layering in the deposits, and different response of various elements or ions to temperature and concentration differences across the interfaces would account for the asymmetric layering of minor elements in ore bodies. Active leaching continued within the areas of warm water movement while ore deposition took place.

Roll ore bodies are thought to be localized where numerous thin mudstone layers divided a moving sheet of warm water and funneled it into many fingers with resultant sinuous roll fronts, and the development of mirror-image rolls on the sides of the fingers of moving warm water. Permeability blocks such as carbonized logs have modified the configuration of roll fronts. Puncture points in thin mudstones permitted the ore-bearing solutions to move into overlying sandstone, thereby accounting for the absence of roll ore beyond, and for roll bulges above, such puncture points. It is further postulated that tabular ore bodies were deposited at an interface between connate water and an overlying sheet of warm water essentially parallel to the bedding.

REFERENCES

1. Fischer, R. P., *Vanadium Deposits of Colorado and Utah,* US Geological Survey Bulletin 936-P (1942).
2. Phoenix, D. A., oral communication.
3. Lowell, J. D., *Application of Cross-statification Studies to Problems of Uranium Exploration, Chuska Mountains, Arizona,* Economic Geology 50: 177–185 (1955).
4. Flint, A. E. and Boardman, R. L., oral communication.
5. Fischer, R. P., oral communication.

Uranium Deposits in Limestone

By John W. Gabelman,* USA

Although uranium occurrences are known in limestones of six different ages in ten isolated areas (Fig. 1) in New Mexico, Arizona, Colorado, and Wyoming, only the Grants and Laguna districts of New Mexico have been productive. However, the mineralized formations comprise virtually all the limestone units on the Colorado Plateau.

DEPOSITS IN LACUSTRINE LIMESTONE

Todilto Limestone

The Todilto limestone of upper Jurassic age is limited to northwest New Mexico and southwest Colorado where its extent roughly coincides with that of the San Juan basin (Fig. 2), except for extensions into central Colorado and across the northern Rio Grande valley. The formation is exposed in a nearly complete ring around the margins of the basin (Fig. 3).

Stratigraphy and Sedimentation

The Todilto unconformably overlies the Entrada sandstone, and locally interfingers with the overlying Summerville silty shale. In the eastern part of the area, the Summerville and Bluff formations are missing and the Todilto is unconformably overlain by the Morrison. In the southwest, the formation is entirely limestone up to 20 feet thick. In the northeast, 5 to 10 feet of limestone are overlain by up to 40 feet of gypsum formed from anhydrite with attendant swelling. Generally, the limestone is slightly petroliferous.

The Todilto limestone is here considered lacustrine principally because of the fresh water fossils found near the western pinch-out[1] though Smith[2] considers both the limestone and gypsum facies marine.

The Todilto limestone in the Grants district attains thicknesses up to 30 feet and contains three recognizable units with irregular boundaries: a basal platy almost lithographic limestone, a middle finely wrinkled extremely thin-bedded limestone, and an upper massive recrystallized limestone. The contact with overlying Summerville is reported to be both intertonguing[3] and erosional.[4] Thin siltstone partings are common in the platy unit, and locally in the higher units.

Pre-Consolidation Deformation

The lower part of the Todilto limestone is usually very thin-bedded and the bedding displays preconsolidation deformation wherever it is exposed. Deformation is in the form of small folds which range from upright to recumbent in the same or different folds over remarkably short distances. Folds or similar widths, which range from several inches to over thirty feet, occur in groups. Locally, thrust faults break fold flanks. Deformation generally is confined to the limestone, or in the smaller folds to zones within the limestone. The fold axes (in the few areas measured) coincide with directions of joint pattern components, or larger faults; and veinlets and slickensides indicate post-lithification movement in directions and on surfaces controlled by diagenetic folding. Proper interpretation of deformation is important because the folds control the distribution of uranium ore. Because some folding is present wherever the Todilto is exposed on the margins of the basin regardless of type, direction, or intensity of tectonic deformation, folding probably began during diagenesis, and later tectonic movement, where mild, followed these predetermined directions. Where the tectonic stresses were more intense the limestone probably flowed by recrystallization and the larger fold axes are compatible with tectonic strain directions. Folds of greater than 10 feet in width are usually reflected in the overlying Summerville formation.

Tertiary Outlining of the San Juan Basin

The present shape of the San Juan basin was essentially established during the Laramide revolution by the formation of bounding ranges. Marginal deformation resulted in three major tectonic directions which occur in diametrically opposed pairs on the edges of the basin (Fig. 2). The margins were further complicated by Miocene intrusion and volcanism on all sides and by late Tertiary block faulting on the east side of the basin where Colorado Plateau bounds the Great Basin.

Mineralized Areas

The Todilto limestone contains uranium deposits in four districts on the margins of the basin. The major area is near Grants; minor production comes from the Laguna area. Unexplored prospects occur in the Sanastee and Rio Cebolla areas (Fig. 3).

Grants District

The Grants district is at the southeast end of the Thoreau monocline (northeast flank of the Zuni Mountains) physiographically expressed by northeast-dipping cuestas. The uranium mines and the general geology are shown in Fig. 4.

* US Atomic Energy Commission.

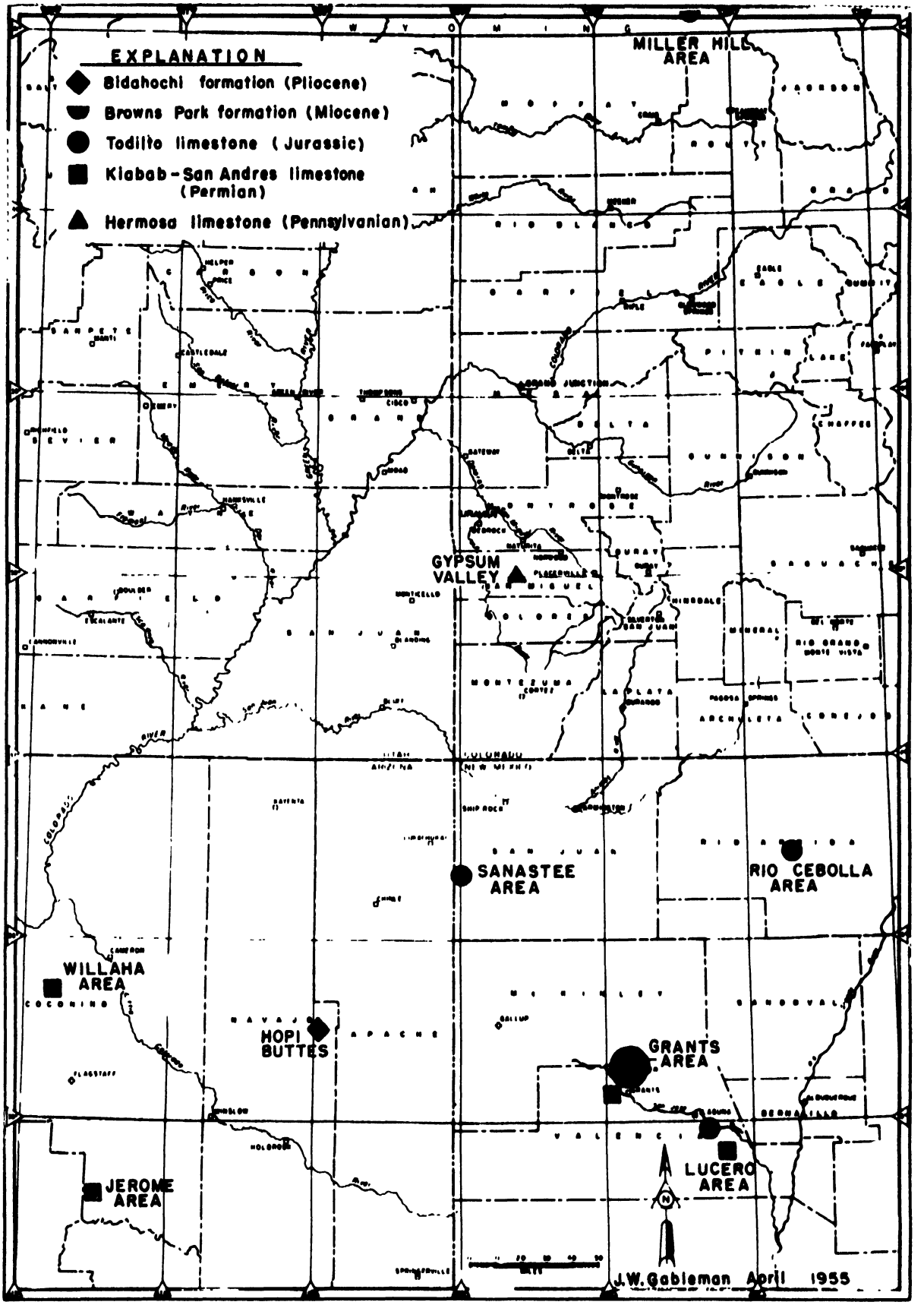


Figure 1. Index map of uranium deposits in limestone

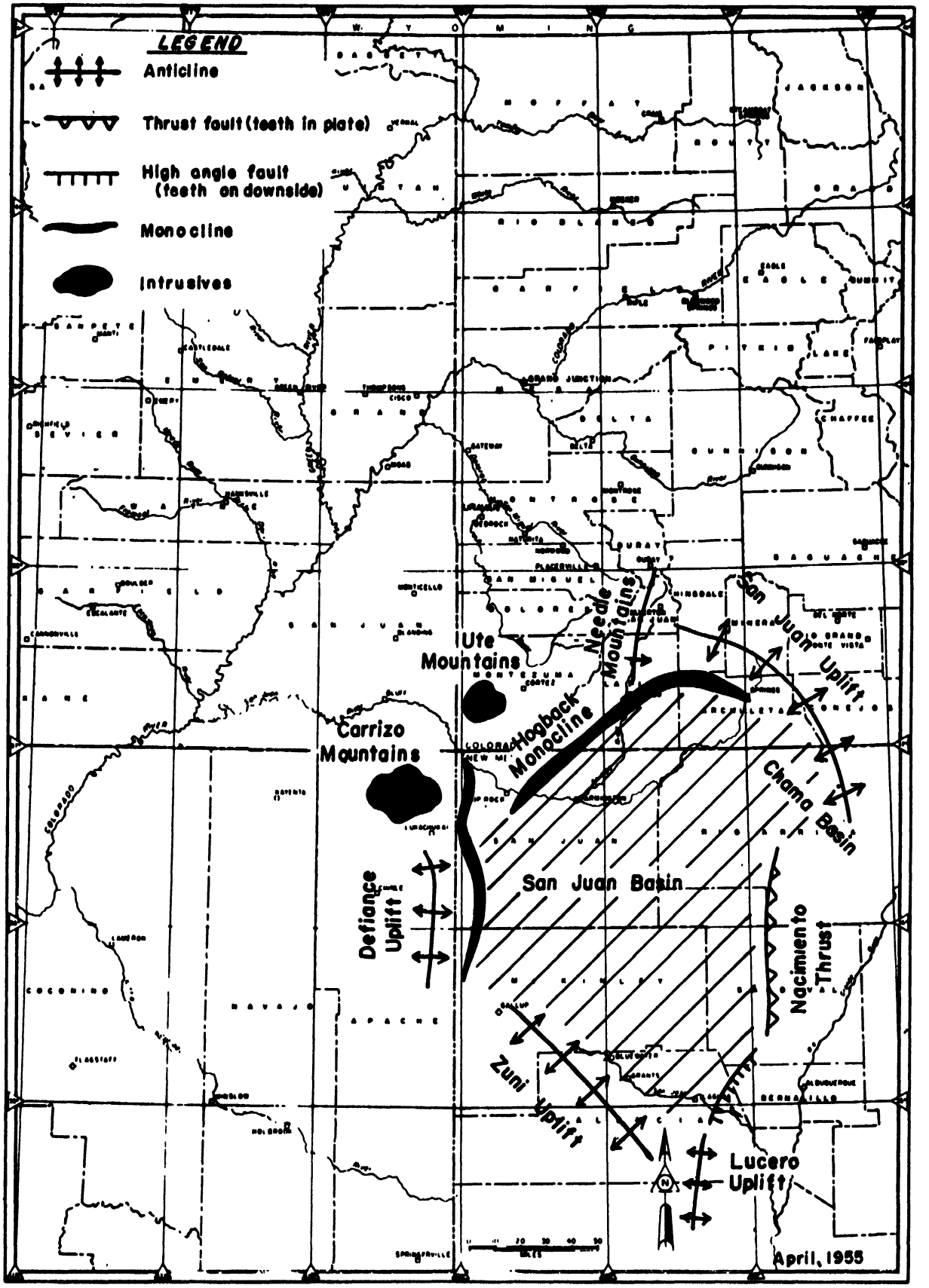


Figure 2. Index map San Juan Basin, New Mexico

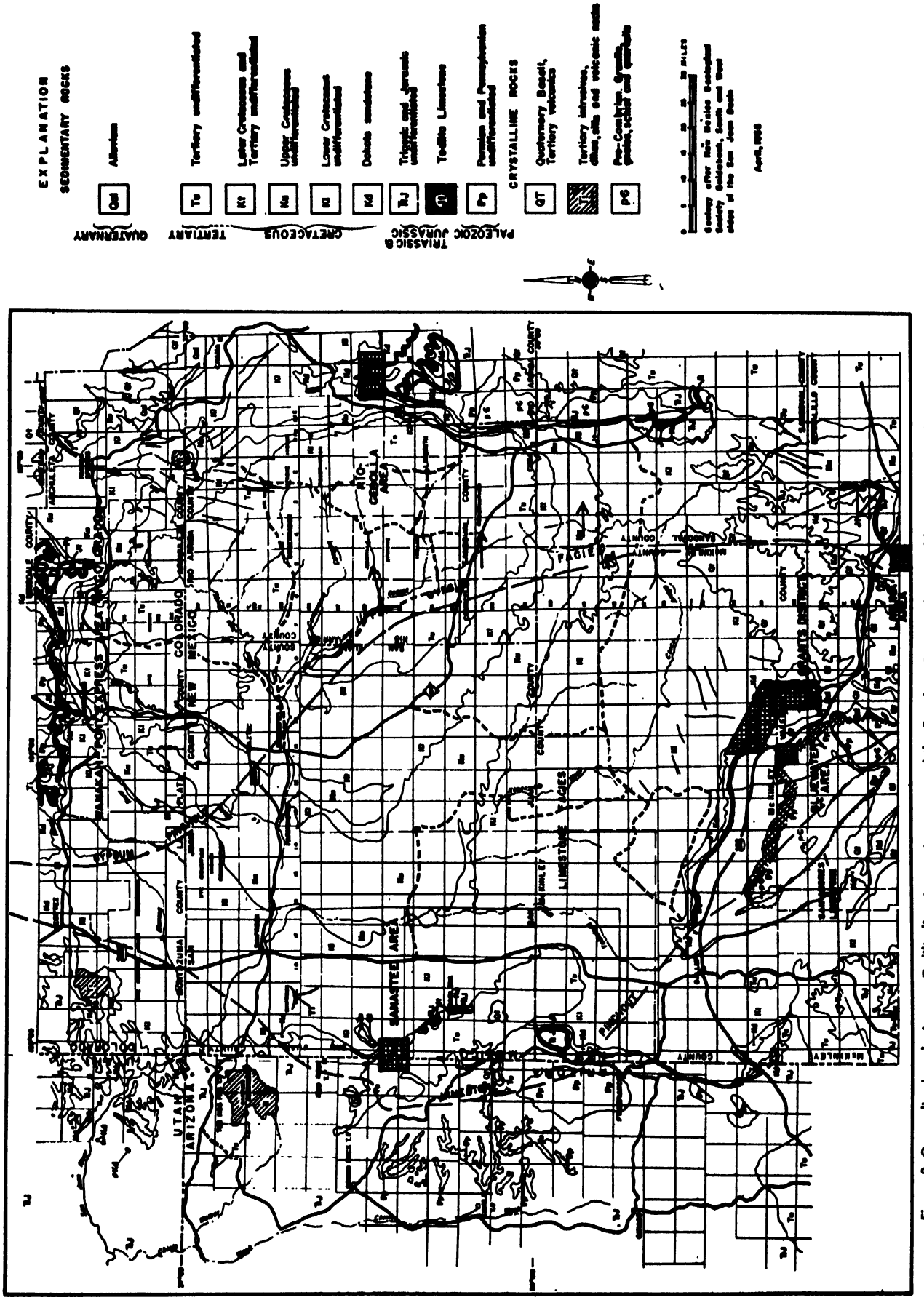


Figure 3. Generalized geologic map; Todilto limestone outcrops around the San Juan Basin and areas of limestone mineralization

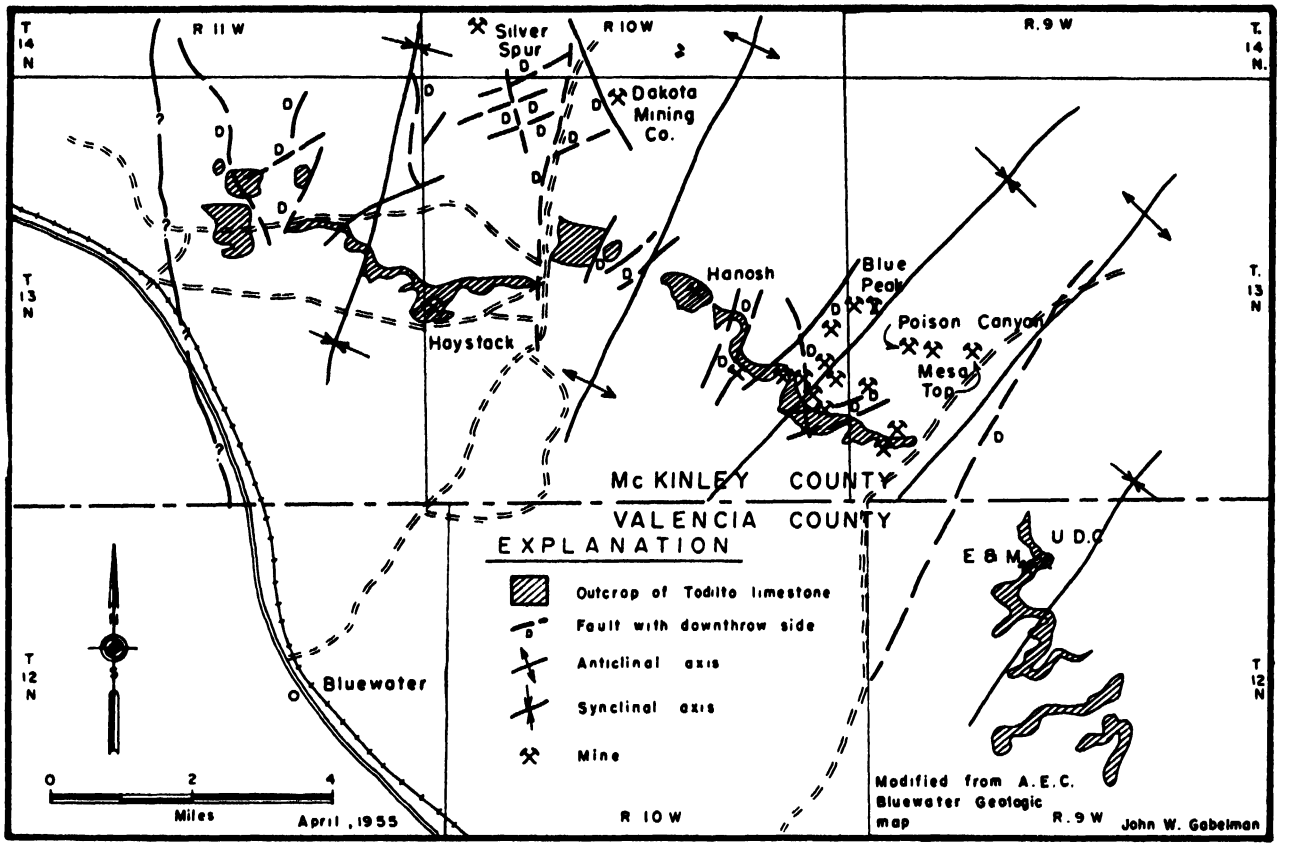


Figure 4. Structures and Todilto outcrops, Grants area, McKinley County, New Mexico

The monocline contains broad gentle northeasterly plunging cross folds, 3 to 5 miles wide, as well as high angle faults (Fig. 4), generally perpendicular to the axis of the Zuni uplift. The faults rudely coincide with the fold axes. In the larger mineralized area, are fault zones of two types. One is represented by long faults of relatively large displacement and usually concealed by broad valleys. Examples are the Bluewater and San Mateo faults which bound the west and east sides of the most strongly mineralized areas. The San Mateo fault coincides with an anticlinal axis. The Bluewater fault trends N-S as it cuts the monocline, and is diagonal to an anticlinal axis. Uranium deposits are present but not well developed near these faults. The other type of fault zone consists of many short faults of minor displacement which have a variety of trends and are commonly en echelon. Trends represented are ENE, N-S, and NNW in order of decreasing prominence.

The two areas of greatest uranium production are localized along two fault zones, up to 3 miles wide. The eastern zone, which localizes the 2½ mile wide Poison Canyon uranium area, coincides with a synclinal axis and is about 1½ miles wide (Fig. 4). The western zone, which localizes the Haystack Butte area, is 2½ to 3 miles wide and seems to coincide with the southeast flank of a syncline rather than its axis. The syncline itself is 3 to 4 miles wide; the belt of uranium deposits is only about one mile wide. The two fault zones and uranium belts are separated by a parallel barren zone 2½ to 3 miles wide. It is noteworthy that the uranium belts extend northeast off the limestone bench and into the Morrison formation where lenticular sands in the Brushy Basin mudstone member contain ore. However, no mineralization occurs in the intervening Summerville and Bluff formations and the Recapture and Westwater members of the Morrison formation.

A narrow northeast uranium belt, the Gay Eagle area, less than ½ mile wide, occurs about 1½ miles southeast of the San Mateo fault and is parallel to it. It coincides approximately with the axis of a very shallow syncline but contains no fault zone. This area is of less commercial significance than the Poison Canyon or Haystack Butte areas. Another, very small uranium area is localized where the Bluewater fault intersects the Todilto limestone on the western side of the district.

Within the uranium belts, deposits occur as irregular rounded lenses more than 200 feet in maximum diameter, and as stringer-like bodies of great length. Ore bodies are elongated in the north, east, or northeast structural directions and coincide with axes of anticlines, suggesting emplacement of uranium from solutions trapped in anticlinal crests beneath Summerville shaly siltstone. The width of mineralized anticline ranges from five to over 30 feet. Lengths range to a maximum of 5000 feet. However, bodies of such great length are usually discontinuous and not all of ore grade. Most mineralized anticlines are

not straight but sinuous. The main structure is a compound group of shorter echelon folds connected by diagonal folds. A reticulate system of smaller folds and joints accompanies the structure. Joints locally carry mineralization beyond the limits of the main fold.

Mineralization is confined to the platy limestone unit at the base of the Todilto except where joints carry secondary minerals throughout the formation. In several areas, particularly the Gay Eagle area, mineralization is in the upper massive unit rather than the basal wrinkled unit. In such areas mineralization is locally controlled by the interfingering siltstone beds and lenses in the transition zone from Todilto to Summerville.

Pitchblende, pyrite, fluorite, barite, and calcite replace limestone along anticlinal crests. Much of the massive character of the limestone results from recrystallization which selectively accompanied mineralization regardless of position in the formation and destroyed bedding and joints. Bleaching of the normally reddish Summerville in haloes over ore bodies commonly accompanies primary mineralization. In some areas original limestone bedding is preserved in banded ore. Replacement is strongly selective, and may occupy one thin bed to the exclusion of others, or may terminate abruptly against a fracture.

Oxidation of primary ore produces the secondary yellow minerals carnotite, tyuyamunite, meta-tyuyamunite, uranophane, beta-uranotile, sklodowskite, and gummite along with hematite, limonite, and vagrant manganese oxide. Many ore bodies consist entirely of secondary ore in networks of fractures. The fracture-ridden wrinkled zone of the Todilto is most favorable for secondary ore.

The control of uranium orebodies by Tertiary structural features sets the approximate age of mineralization (no radiometric age determinations have been made), and the intimate intergrowth of pitchblende with fluorite suggests a hydrothermal origin for the limestone deposits. The termination of ore against underlying Entrada sandstone implies lateral feeding to individual deposits. However, the obvious clustering of orebodies near fault zones cutting the Thoreau monocline indicates the faults may have been vertical feeders, although no primary ore has been found in the faults. Fluorite-quartz-calcite-barite veins in the pre-Cambrian crystalline core of the Zuni Mountains, about 10 miles distant up dip also could have fed uranium-fluorite solutions into the Todilto and Morrison formations for down-dip migration, although Morrison sandstone deposits contain no fluorite. Rapaport[5] interprets the limitation of orebodies to large synclines as indicating the accumulation of uraniferous solutions in physiographic sumps under the action of gravity.

Laguna District

The Laguna district is in the northwest part of the Lucero uplift (Fig. 2), a large NNE-trending, strongly faulted fold in the southeastern corner of the San Juan basin. Todilto here is 10 to 22 feet thick and is exposed in a northeast trending monocline which dips about 5 degrees northwest. It is underlain by about 100 feet of Entrada sandstone and overlain by about 100 feet of Summerville mudstone. The limestone consists of a basal very thin-bedded wrinkled limestone, a thin middle medium-bedded undeformed limestone and an upper massive recrystallized limestone. The wrinkled and middle units contain siltstone partings.

Several uranium deposits in limestone are known, but only one, in Section 8, T. 8 N., R. 5 W., has produced ore. This deposit occurs in an isolated dome of about 150 feet diameter on an otherwise uniform portion of the monocline flanking the northwest portion of the Lucero uplift.

Mineralization is confined to the crest of the dome. Pitchblende, pyrite and calcite have replaced limestone in small irregular areas and spots which are disseminated through the formation and seem controlled by a similar distribution of finely disseminated carbonaceous material. Oxidation products consist of yellow and green secondary uranium minerals and limonite, which occur principally in the basal wrinkled zone on bedding planes, in irregular fractures on fold flanks, and uncommonly as minute disseminations. Yellow minerals have oxidized in place where disseminated; elsewhere they have migrated to open fractures. However, two prominent joint systems in the dome are unmineralized.

Sanastee Area

The Sanastee area (Figs. 1, 3) in the Chuska Mountains is situated on the Defiance monocline which forms the east side of the broad flat Defiance uplift and the west side of the San Juan Basin. In this area the monocline trends northwest and dips as much as 15 degrees northeast.

The Todilto limestone at Sanastee is underlain by the Entrada sandstone and overlain by the Summerville formation and Bluff sandstone. The area is near the western strand line, and the formation thins from 10 feet in the south to 6 feet in the north. No gypsum is present. The formation consists of a lower thin-bedded unit and an upper thicker-bedded unit which has been selectively recrystallized. There is a 6-inch oolitic limestone bed immediately beneath the Summerville.[6] Pre-consolidation folding is confined essentially to the upper unit. Recrystallization is prominent along anticlinal axes. Most folds have a common northeast orientation.

The limestone contains secondary uranium minerals near Roy Mesa over an area about 3 miles long in a northerly direction and one to two miles wide. Tyuyamunite with calcite and small amounts of barite occur in joints, bedding, and vugs in the upper 5 feet of the Todilto. Mineralization occurs principally in the crests and flanks of anticlines.

Rio Cebolla Area

The Rio Cebolla area (Fig. 3) is near the center of the Chama basin, a shallow depression perched

shelf-like on the east side of the San Juan basin between the off-set ends of the San Juan and Nacimiento uplifts. Sediments in the area are flat and undeformed, although the area is just east of the faulted northern end of the Nacimiento hogback.

The Todilto formation is underlain by the Entrada sandstone and overlain by the Saltwash sandstone member of the Morrison formation. It is about 50 feet thick and consists of a lower limestone unit, the Pony Express, and an upper gypsum unit, the Wanakah. The limestone is thin-bedded and wrinkled by small pre-consolidation.

Uranium prospects occur in an area several miles long and about 2 miles wide, as sporadic secondary uranium mineralization along bedding and joints in the wrinkled limestone. Secondary minerals are associated with veinlets of radioactive red chert which fill joints.

Brown's Park Formation

The Brown's Park formation of southwest Wyoming and northwest Colorado is fluvial and lacustrine and was deposited in one of the intermontane Miocene basins isolated by the Wyoming Rockies during the latest Cretaceous, and in Eocene.

Secondary uranium deposits occur in a thin algal limestone in the Brown's Park formation at Miller Hill on the Continental Divide, 20 miles south of Rawlins, Wyoming. Uranophane, minor amounts of meta-autunite, and uraniferous opal fill small fractures and cavities in association with lenses and nodules of dark chalcedony which are erratically distributed.[7] Locally uranophane impregnates thin lenticular sandstones. Sporadic mineralization is present in the host limestone for several square miles.

Bidahochi Formation

The Pliocene Bidahochi formation is confined to the Black Mesa basin of northeastern Arizona which lies to the west of the Fort Defiance uplift. In late Miocene and Pliocene time the basin was filled with fluvial and lacustrine Bidahochi sediments. On the southern edge of the basin where the Bidahochi truncates underlying Jurassic and Cretaceous beds, the Hopi Buttes volcanics[8] were erupted from numerous vents in Bidahochi time and constitute the middle member of the formation.

In the Hopi Buttes volcanic field the Bidahochi formation rests unconformably on gently dipping Triassic Wingate sandstone. The Bidahochi consists of 3 members. The lower member contains banded gray, brown, and pink mudstone and argillaceous sandstone, interbedded with white rhyolitic ash. These beds accumulated in a large lake. The middle member rests unconformably on the lake beds and contains basaltic volcanics up to 200 feet thick, which were extruded on a land surface.

Of the scores of collapsed vents, 4 widely separated ones contain uranium. The Horseshoe vent, over 2 miles in diameter, contains anomalous radioactivity, but no uranium minerals, at two localities in water-laid pyroclastics on the outer rim.

At one locality mineralization is in a filled channel scoured into underlying lake beds and extends over 1700 feet laterally. Another occurrence is in tuff immediately adjacent to a small subsidiary vent on the rim of the larger vent.

The Seth-la-Kai vent contains anomalous radioactivity, but no visible uranium minerals, in travertine and marl at several closely spaced similar localities on the rim of the collapsed basin. Travertine at the orifice of a dead feeder spring in the center of the basin is also mineralized. Calcite, jarosite, limonite, and carbonaceous material are prevalent in the marl at the rim localities. which have produced several shipments of uranium ore.

At the Hoskietso property, in a small collapsed vent marginal to an imposing plug-filled vent near Indian wells, schroeckingerite is present coating fracture surfaces in mudstone between marl interbeds in the interior of the collapsed basin.

Anomalous radioactivity without visible uranium minerals occurs in travertine on the rim of the small "Donut" vent at the road junction east of Na-ah-tee Trading Post.

DEPOSITS IN MARINE LIMESTONE

Uranium deposits in marine limestone are insignificant at present. In all known occurrences replacement is unimportant, and secondary uranium minerals fill available cavities as in any other rock type.

Kaibab-San Andres Limestone

The Permian Kaibab limestone and its New Mexican correlative, the San Andres formation, contain secondary uranium deposits in 4 areas.

Willaha Area, Coconino County, Arizona

Anomalous radioactivity associated with chalcopyrite. bornite, covellite, chrysocolla, malachite, azurite, chalcocite, jarosite, geothite, and quartz occurs in lenses of cherty arenaceous limestone and in small associated fractures. The horizon is in the uppermost part of the Kaibab formation.

Jerome Area, Yavapai County, Arizona

Yellow secondary uranium minerals locally fill vugs in white chalky Kaibab limestone about 5 miles northeast of Jerome. There are no other minerals.

Bluewater Area, Valencia County, New Mexico

Anomalous radioactivity, associated with marcasite, limonite, and calcite, occurs in silty limestone at the top of the San Andres formation where the limestone is cut by the Bluewater fault. The minerals fill minute vugs and small fractures.

Correo Area, Valencia County, New Mexico

Secondary uranium minerals fill vugs and fractures in massive limestone near the top of the San Andres formation 8 miles southwest of Correo in the Lucero uplift. An intrusive sill overlies the San Andres formation.

Hermosa Limestone

The limestone facies of the Pennsylvanian Hermosa formation contains uranium at one locality on

the northeast flank of the Gypsum Valley anticline, 13 miles southwest of Naturita, Colorado. Here the Hermosa is composed of thin-bedded limestone with shale partings. The beds are overturned to the southwest and form a steep hogback. Carnotite occurs in the Bald Eagle mine in closely spaced irregular fractures which give the rock a high permeability.

REFERENCES

1. Williams, G. A., oral communication.
2. Smith, Clay T., *Problems of Jurassic Stratigraphy of the Colorado Plateau and adjoining regions,* N. Mex, Geol. Soc., Guidebook of S. and W. sides of San Juan Basin, New Mex. and Ariz.; 99–102 (1951).
3. Dane, C. H., *Geologic map of part of eastern San Juan basin, Rio Arriba County, New Mexico* (descriptive text), US Geol. Survey Oil and Gas Invest. Map 78 (1948).
4. Rapaport, Irving, *An interim report on the ore deposits of the Grants area,* US Atomic Energy Commission RMO-840, Part II (1952).
5. Rapaport, I., personal communication.
6. Blagbrough, J. W., written communication.
7. Grutt, E. W., personal communication.
8. Shoemaker, E. M., P/48 *Occurrence of Uranium in Diatreme,* Vol. 6, Session 6B, these Proceedings.

Guides to Uranium Deposits in the Gallup-Laguna Area, New Mexico

By L. S. Hilpert and V. L. Freeman,* USA

In the Gallup-Laguna area (Fig. 1) of New Mexico, productive uranium deposits are in the Todilto limestone, Summerville formation, Morrison formation, and Dakota sandstone. During the past two years the Morrison formation has increased greatly in significance because of new discoveries.

Recent field work by the writers indicates that the larger known uranium deposits in the Morrison formation in the Gallup-Laguna area are in distinctive sandstone units in the Brushy Basin member. This paper presents a preliminary description of the general characteristics of two of these sandstone units and points out how these characteristics can be used as guides to ore.

Much of the data presented is based on information provided by mining men in New Mexico and US Atomic Energy Commission personnel. Special acknowledgments and thanks for assistance are due personnel of the Lea Exploration Co., Anaconda Copper Mining Co., Haystack Mountain Development Co., and the St. Anthony Uranium Co.

GENERAL GEOLOGY

Productive uranium deposits in the Gallup-Laguna area (Fig. 1) are in sedimentary rocks of Jurassic and Cretaceous ages. These rocks generally dip northward at a low angle and form an almost continuous outcrop for about 80 miles, extending from Gallup to the west side of the Rio Grande Valley. Locally the rocks are folded broadly and broken by faults, and north of US Highway 66, between the towns of Grants and Laguna, they are intruded and largely buried by the Mount Taylor volcanic field.

The sequence of sedimentary rocks containing the productive deposits are, in ascending order, the Todilto limestone, Summerville formation, Bluff sandstone, and Morrison formation, all of Jurassic age, the sequence is unconformably overlain by the Dakota sandstone of Cretaceous age. All these rocks except the Bluff sandstone, contain uranium deposits. In September 1954, the Todilto, Morrison, and Dakota were the only formations in the Gallup-Laguna area that were known to contain significant deposits.

The Morrison formation in this area is subdivided, from base to top, into the Recapture shale member, Westwater Canyon sandstone member, and Brushy Basin shale member. The Recapture is a fine- to medium-grained friable sandstone that contains some beds of silty claystone. It ranges from about 20 to 185 feet in thickness and has distinctive alternating light-gray and reddish-brown units.

The Westwater Canyon is predominantly a medium- to coarse-grained pebbly sandstone that contains some thin units of claystone. The Westwater Canyon ranges from a knife edge to about 200 feet in thickness, and from yellowish gray to reddish brown. It locally interfingers with the underlying Recapture and overlying Brushy Basin members. In the eastern part of the area it is locally absent, and there the Brushy Basin rests directly on the Recapture member.

The Brushy Basin member is predominantly a grayish-green claystone with subordinate lenses of hard, medium-grained, locally calcareous green sandstone. These lenses, generally ranging from a few inches to a few feet in thickness, are chiefly quartz grains and abundant interstitial clay. Locally, however, the Brushy Basin contains relatively thick lenses or units of coarser grained sandstone that generally range from a knife edge near Gallup to a thickness of about 375 feet north of Laguna. These differences in thickness are mainly the result of pre-Dakota erosion after broad folding.

In the Gallup-Laguna area nearly all the known uranium deposits in the Morrison formation are in the relatively thick, rather coarse-grained sandstone units of the Brushy Basin member, which can be distinguished from the thinner lenses of hard, medium-grained green sandstone.

The ore-bearing units range from white to moderate brown but are generally yellowish orange. Near deposits they are yellowish gray. The units are composed mostly of quartz, some pink feldspar, and a few other minor accessory minerals; white specks, probably kaolin, are common. These sandstone units are locally conglomeratic, crossbedded, show scour-and-fill features, and are quite friable. Carbonaceous debris—such as small silicified logs, tree limbs, and reeds—and claystone lenses and galls, are present at certain places, and are most abundant near deposits. The general features of these sandstone units indicate a fluvial origin, and channeling in the underlying claystone is common.

* US Geological Survey.

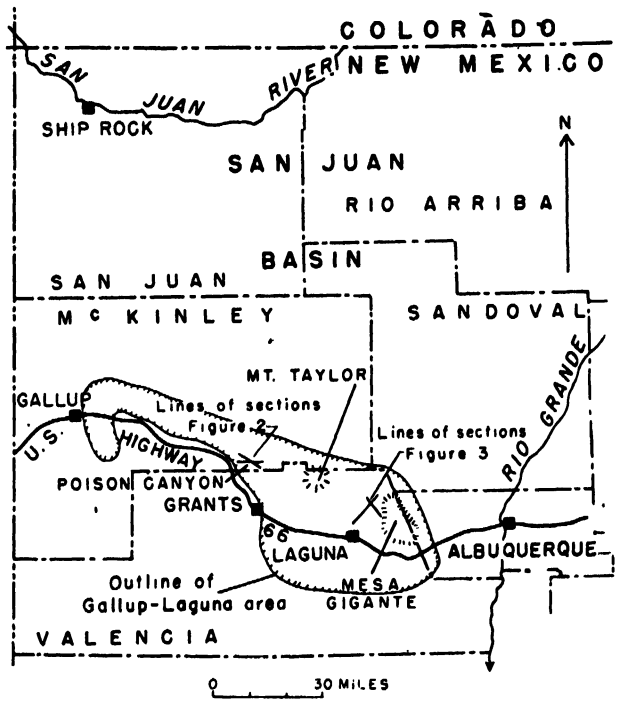


Figure 1. Index map of northwest New Mexico showing Gallup-Laguna area and location of Figs. 2 and 3

Two of these sandstone units in the Brushy Basin contain all the larger deposits. The unit in the vicinity of Poison Canyon (Fig. 1) northwest of Grants is referred to as the so-called Poison Canyon sandstone. The second unit, which contains the Jackpile mine, is referred to as the so-called Jackpile sandstone.

The so-called Poison Canyon sandstone crops out at the head of Poison Canyon and is exposed for about 2 miles eastward and westward from Poison Canyon. From drill-hole information it is known to extend northward from the outcrop for at least half a mile. This unit is a tongue of the underlying Westwater Canyon, which merges with the Westwater Canyon about 2 miles northwest of Poison Canyon. Eastward from the point where it merges with the Westwater Canyon it rests upon a 15- to 25-foot thick unit of the Brushy Basin shale member, and is assigned by the writers to the Brushy Basin. The thickness of the so-called Poison Canyon sandstone ranges from 35 to 90 feet, but most of the deposits occur where this sandstone is more than 50 feet thick. The relatively thick parts of the sandstone generally range from about 500 to 1000 feet wide and from 1000 to 2500 feet long; they have a dominant eastward trend. Two generalized cross sections (Fig. 2), compiled from drill-hole information and outcrops, show the relationship of the deposits to the sandstone thickness.

The so-called Jackpile sandstone constitutes the upper part of the Brushy Basin and is unconformably overlain by the Dakota sandstone. The so-called Jackpile sandstone is present throughout an area of at least 200 square miles, but its limits are not known. It is best exposed north of Laguna (Fig. 1) between Mesa Gigante and the eastern edge of the Mount Taylor volcanic field, where it generally ranges from about 60 to 175 feet in thickness. About 7 miles northeasterly from Laguna it thickens to a maximum of about 175 feet. It appears significant that all the known deposits in the area north of Laguna and between Mesa Gigante and the eastern edge of the Mount Taylor volcanic field are in the vicinity of this maximum thickness where the sandstone generally exceeds 150 feet in thickness. Two generalized cross sections (Fig. 3) drawn from outcrops and drill-hole data, show this relationship. Moreover, beneath the thicker part of the so-called Jackpile sandstone the entire Brushy Basin member is largely sandstone which is similar lithologically to the Jackpile sandstone.

The Morrison uranium deposits in the area consist of concentrations of black and yellow uranium minerals in tabular bodies. These bodies generally follow the bedding and range from about a foot to several tens of feet in thickness, and from several feet to hundreds of feet in width and length. The amount of ore in these bodies ranges from a few tons to many hundreds of thousands of tons.

BRUSHY BASIN POTENTIAL FOR URANIUM

The so-called Poison Canyon and Jackpile sandstone units of the Brushy Basin shale member contain all the larger uranium deposits, and these two units and others of similar type in the Brushy Basin contain nearly all of the Morrison deposits in the Gallup-Laguna area. Some measure of the relatively great uranium potential of the Brushy Basin can be determined by comparing mine production and reserves of the Brushy Basin for the Gallup-Laguna area with production and reserves of other formational units in the area, with the production and reserves of New Mexico, and with the production and reserves of the Colorado Plateau. The comparisons are based on figures that are applicable at the end of September 1954.

PRODUCTION AND RESERVES

About 98 per cent of the ore produced from the Morrison formation in the Gallup-Laguna area has come from the Brushy Basin shale member, mostly from the so-called Poison Canyon and Jackpile sandstone units. This production represents 50 per cent of the total ore produced from the area and about 45 per cent of the total uranium ore produced in New Mexico.

The commercial significance of uranium in the Gallup-Laguna area was not realized until after the discoveries made in 1950. Between 1950 and 1952, little ore was produced as this time was spent in prospecting and development. The production from the Brushy Basin member (and other units in the Gallup-Laguna area), thererefore, represents only about 2 years of mining effort. Even so, the Brushy Basin production from this area constitutes a significant part of the total from the Colorado Plateau.

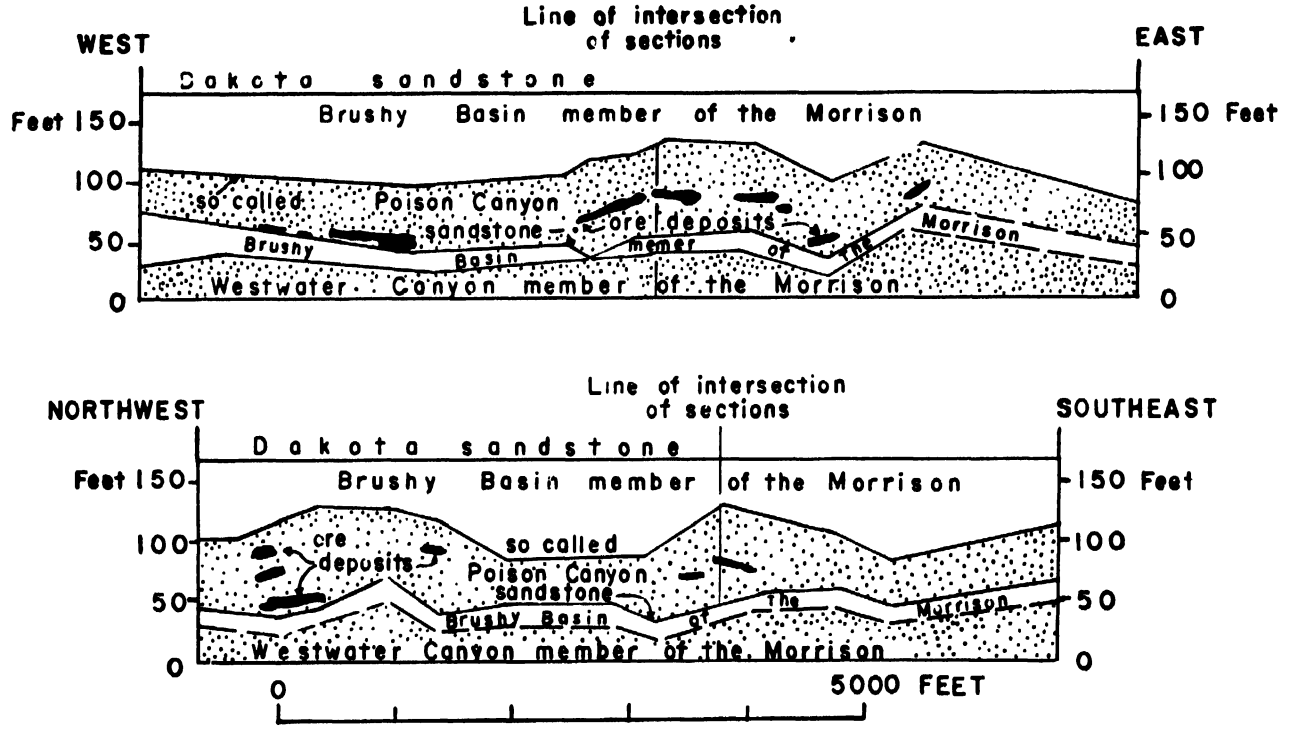


Figure 2. Generalized geologic sections showing the stratigraphic relations of the Morrison uranium deposits northwest of Grants, New Mexico

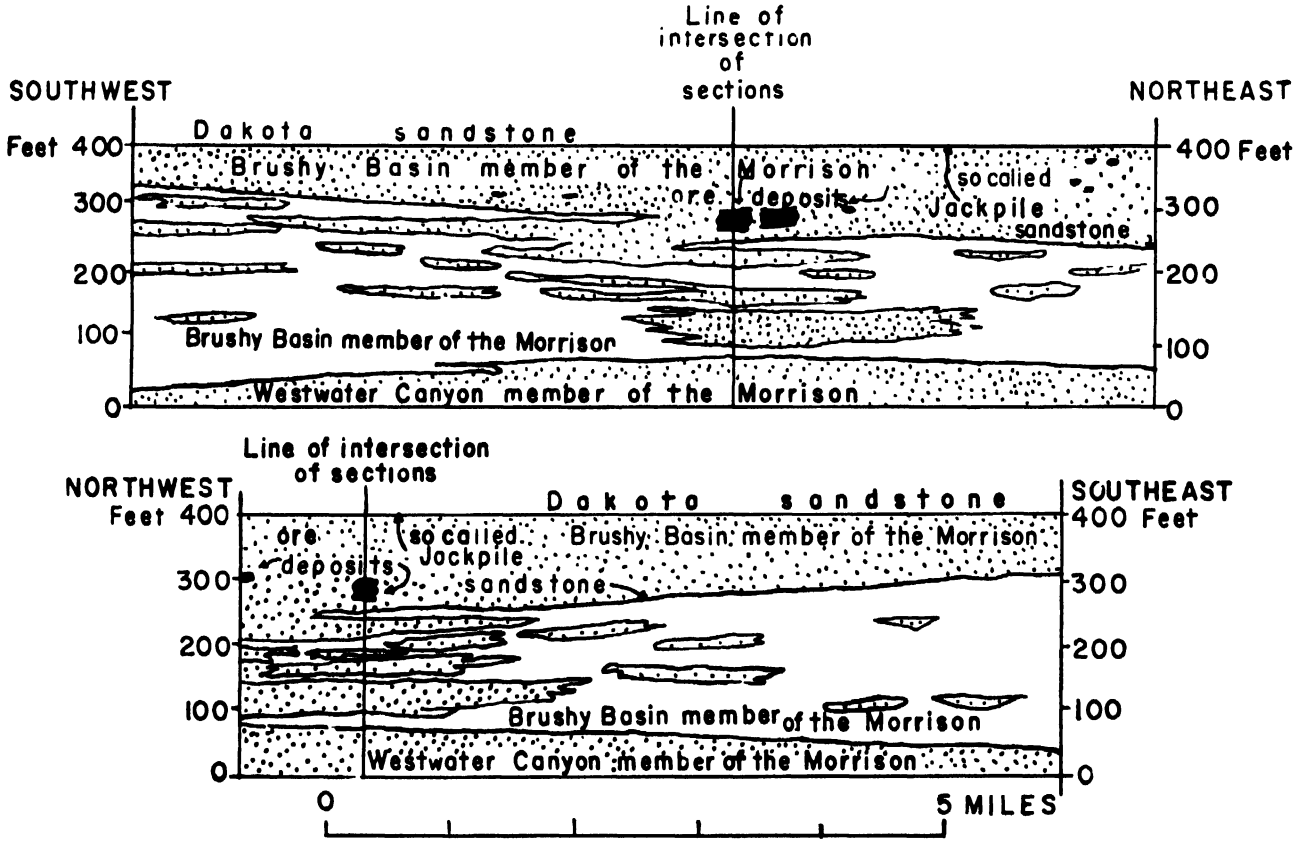


Figure 3. Generalized geologic sections showing the stratigraphic relations of the Morrison uranium deposits north of Laguna, New Mexico

Almost the entire reserves for the Morrison formation in the Gallup-Laguna area are in the Brushy Basin. These reserves represent about 90 per cent of the total reserves in the Gallup-Laguna area and about 85 per cent of the reserves for New Mexico. These Brushy Basin reserves constitute an important part of the reserves in the Colorado Plateau. Almost all Brushy Basin reserves are in the so-called Poison Canyon and so-called Jackpile sandstone units.

As only a small percentage of the Brushy Basin shale member in the Gallup-Laguna area has been explored, the potential reserves of this member are probably many times as great as the known reserves.

GUIDES TO ORE

The general characteristics of the so-called Poison Canyon and so-called Jackpile sandstones make it possible to recognize these units at the outcrop and to extend and define their limits by drilling. Also, these characteristics may have application in searching for and defining other similar units in the Brushy Basin of the Gallup-Laguna area.

In the so-called Poison Canyon and so-called Jackpile sandstones, other features were noted in the vicinity of deposits that should be useful as guides to ore within the units and perhaps in other similar units in the Brushy Basin of the Gallup-Laguna area. These features are summarized as follows: (1) deposits are generally localized in the thicker parts of the units; in the so-called Poison Canyon sandstone they are found mostly in areas where the thickness exceeds 150 feet; (2) yellow-gray sandstone; (3) abundant carbonaceous debris; (4) abundant claystone lenses and galls.

These ore guides for the so-called Poison Canyon and Jackpile sandstone units make it possible to recognize ground, at the outcrop and in wide-spaced drilling, that is most favorable for ore, thereby eliminating unfavorable ground. The color of the sandstone and the relative abundance of carbonaceous debris and claystone, however, are of limited usefulness as it has not been determined how far away from the deposits these features generally are found. These features, however, at least where observed collectively with optimum thickness relations, should indicate ground most favorable for ore. Such ground, or target areas, can be found and defined by drilling. Drilling within these target areas can then be done to search for deposits and the ore bodies contained in them.

Geology of Uranium Deposits of the Shinarump and Chinle Formations on the Colorado Plateau

By Y. William Isachsen,* USA

The diverse geology of uranium in the Upper Triassic Shinarump and Chinle formations on the Colorado Plateau is illustrated by individual descriptions of six mining districts or mines of major economic and geologic importance. Holiday Mesa, Happy Jack mine, Calyx mines, Big Indian Wash-Lisbon Valley mining district, Delta mine, and Huskon mines.

GENERAL GEOLOGY

The Upper Triassic Shinarump formation is exposed over large areas in the southern part of the Colorado Plateau (Fig. 1), where it lies unconformably on the Moenkopi formation of Lower and Middle (?) Triassic age. It is a fluvial deposit composed mainly of light gray sandstone with lenses of grit and conglomerate, and lesser intercalated mudstone. Major ore producing areas in the Shinarump are the Monument Valley and White Canyon areas (Fig. 1), where ore occurs in basal sandstones and conglomerates filling paleostream channels.

The Chinle formation is more widespread on the Colorado Plateau than the Shinarump (Fig. 1). It lies on the Shinarump where this is present, and directly upon the Moenkopi elsewhere. The Chinle formation consists of fluviatile red, purple, gray and variegated mudstone and siltstone, with lesser interbedded sandstone and conglomerate. Major Chinle production comes from the Big Indian Wash-Lisbon Valley area, Utah, with lesser amounts from the southern part of the San Rafael Swell, Utah, and the Cameron area in Arizona. Ore occurs in several stratigraphic units within the Chinle formation but the basal Moss Back member is currently the most productive.

Uranium ore deposits may be classified according to associated metals into uranium, copper-uranium, copper-uranium-vanadium and uranium-vanadium types. All these are represented in the deposits selected for illustration. The uranium-vanadium type accounts for the greatest production.

The age of uranium mineralization on the Colorado Plateau, based on lead-uranium age determinations, is late Cretaceous or early Tertiary.[1] Furthermore, independent field evidence in many deposits indicates that ores are epigenetic.[2] The source of the uranium is unknown.

* US Atomic Energy Commission.

The rapid growth in economic importance of these formations is shown in the fact that their combined production has risen from 15 per cent to over 40 per cent of total Plateau production during the past three years.

HOLIDAY MESA

(Prepared by C. G. Evensen)

Holiday Mesa (Fig. 1) is on the west side of the Monument Valley mining district and one mile northwest of Oljeto Trading Post, San Juan County, Utah. A forthcoming paper discusses Holiday Mesa in relation to the uranium deposits of Monument Valley.[3] Trimble first found mineralization on Holiday Mesa.[4]

General Geology

Structure

Holiday Mesa is on the eastern, steeply dipping limb of the Organ Rock anticline, one of the superimposed asymmetrical folds on the Monument upwarp. The mesa is on the lower inflection of the structure encompassing easterly dips ranging from 8 degrees to 2 degrees. Fracture sets which trend north and northeast are common on the west end of the mesa, but bear no apparent relationship to ore.

Stratigraphy and Sedimentation

The Shinarump formation, the ore horizon of the area, contains a number of paleostream channels up to 275 feet deep and 3000 feet wide cut into the Moenkopi formation and filled with Shinarump clastics. All ore deposits in the area occur in Shinarump scour-fill along these paleochannels and in downward extensions into the underlying Moenkopi formation. Channel sediments characteristically contain greater amounts of mud-pellet and quartzpebble conglomerates than the normal medium- to coarse-grained sandstones which predominate in interchannel portions of the Shinarump.

Economic Geology

Orebodies on Holiday Mesa are, in general, elongated in the direction of channel-trend (Figs. 2*a*, *b*, and *c*,) and lie near the base of the channel. As a result of regional folding, scours shift downdip from their original position (Fig. 2*c*) to their present position (Fig. 2*b*). Several lines of evidence suggest that the Holiday Mesa channel was mineralized after deformation (Fig. 3), namely: the appar-

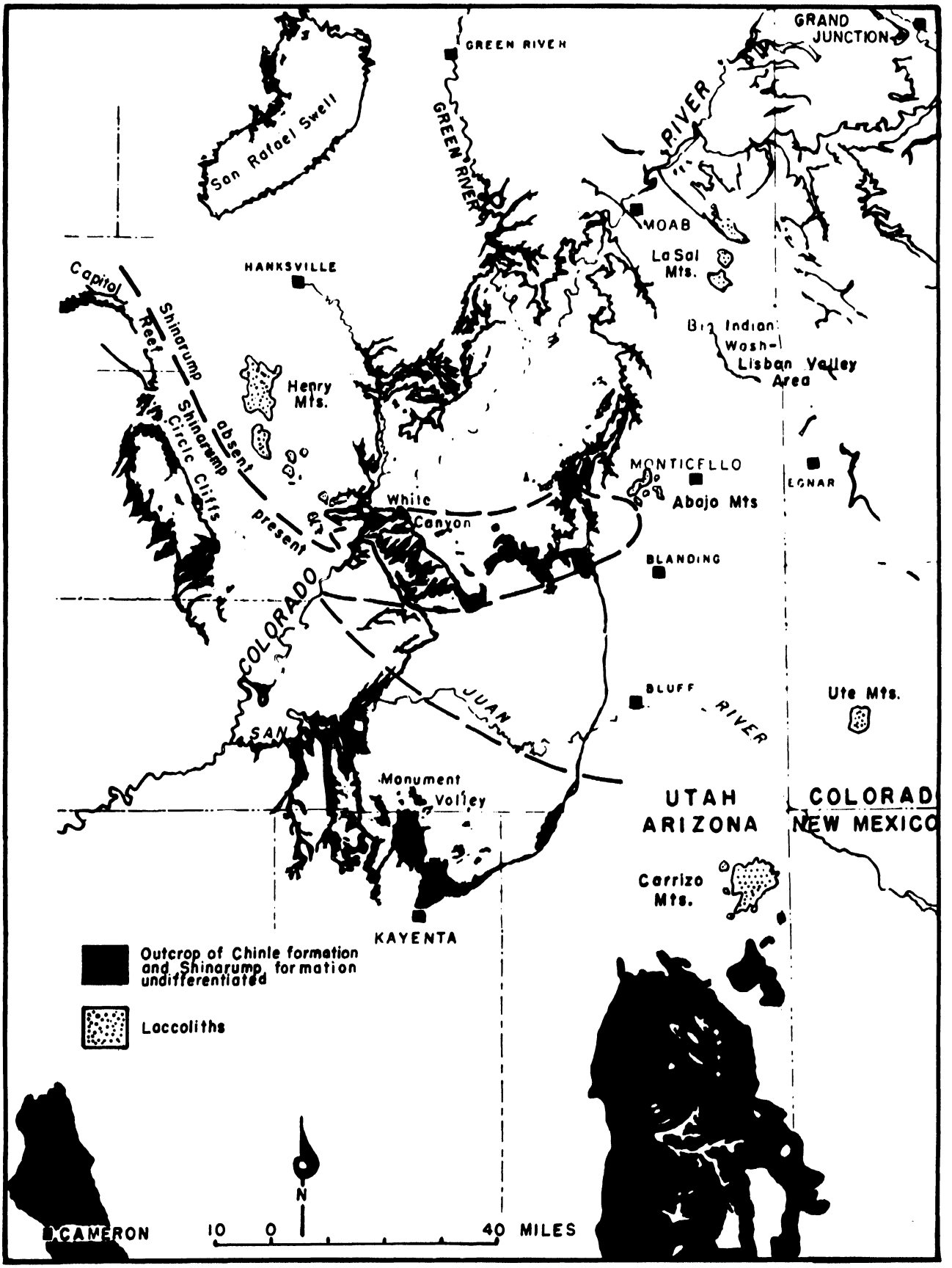


Figure 1. Outcrop of Chinle and Shinarump formations and lacco'iths on the Colorado Plateau

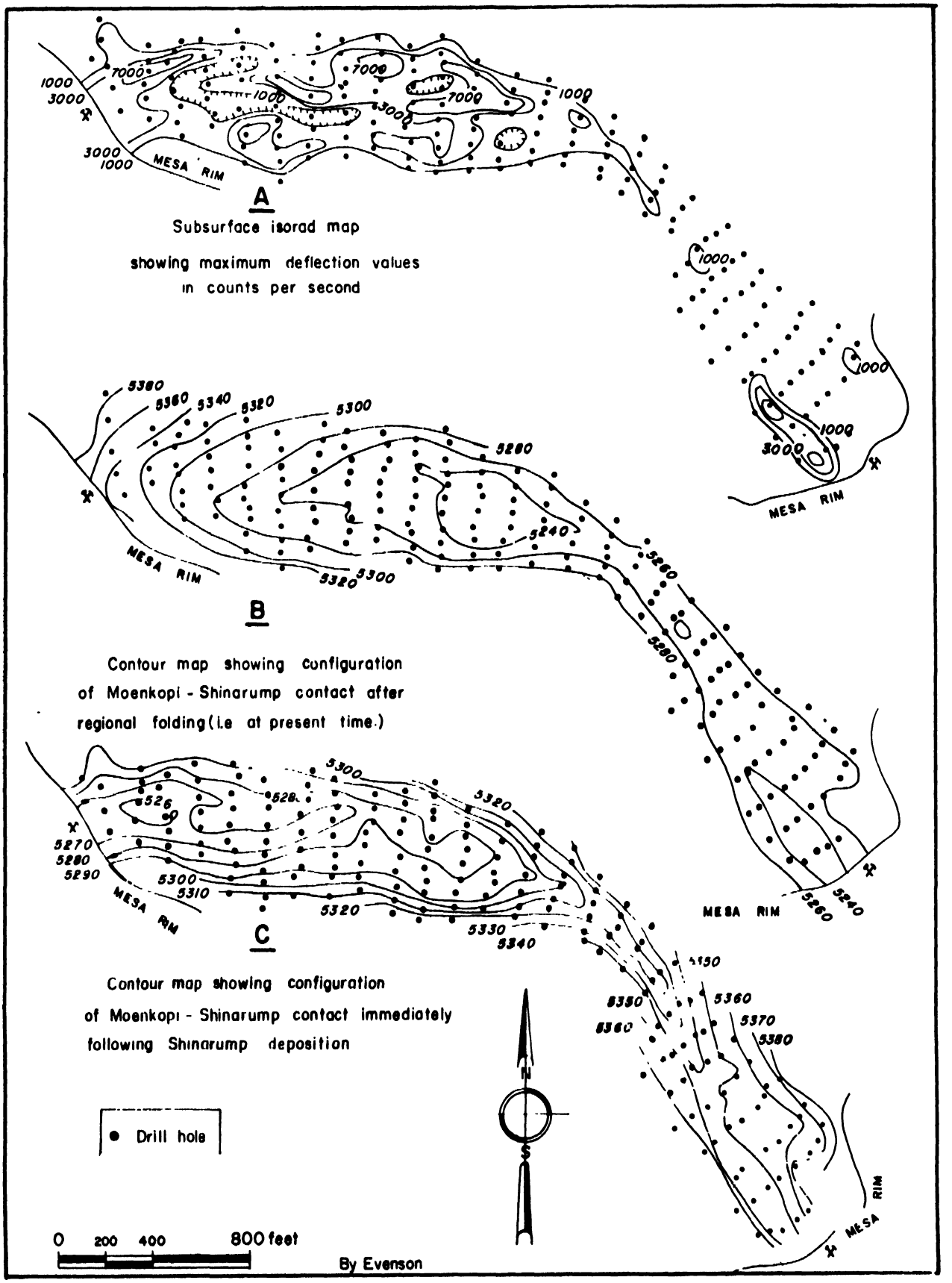


Figure 2. Relationship of mineralization to configuration of channel before and after regional folding, Holiday Mesa, San Juan Count, Utah

ent correspondence of the lowest area of the channel after regional tilting (Fig. 2*b*) with the largest area of high isoradiometric readings (Fig. 3*a*); the largest number of feet in the drill-holes having at least 300 counts per second of gamma radiation (Fig. 3*b*); and the greatest accumulative distance above the contact that the gamma ray reading is 600 counts per second (Fig. 3*c*).

Mineralization gradually diminishes away from ore (Fig. 2*a*) on Holiday Mesa; elsewhere in Monument Valley the cut-off is abrupt. A comparison of the isorad map with the clay content (Figs. 4*a* and *b*) indicates that in the basal portion of the channel, areas with greater than 25 per cent mudstone are in general low in radioactivity, suggesting these areas constituted a permeability barrier during mineralization. This suggests[5] that abrupt changes in mudstone content favor localization of ore.

The Moenkopi formation is altered through varying thicknesses beneath the Shinarump formation as a result of reduction and almost complete removal of ferric iron forming yellowish-brown to chalky white clays. A study of mudstone alteration colors in ore-bearing, mineralized and barren areas of Monument Valley indicates a correlation between intensity of mineralization and intensity of alteration, the favorability increasing from yellowish-brown, through green and gray, to chalky white. Mudstone colors within the ore-bearing Holiday Mesa channel are in the favorable group, as might be expected. A comparison of Moenkopi mudstone core samples with the National Research Council Color Chart indicates that the colors fall into five groups within the broad, relatively well-altered gray to chalky white class. After drilling, alteration colors were designated by relative numerical ranks of favorability, and contoured (Fig. 5*b*). This assigned order of favorability within the well-altered group was then tested in an ore-bearing channel on Oljetoh Mesa (Fig. 1) and, although the broad pattern from yellowish-brown to chalky white was found fairly reliable, the assigned grouping was found to have no recognizable correlation with ore. Thus, it appears that, although broad color patterns due to removal of iron are valid ore guides, minor variations, due perhaps to the addition of trace elements and recent ground water phenomena are not. However, the fairly general correlation between ore and a greater thickness of altered Moenkopi (Fig. 5*c*) is due probably to the greater quantities of mineralizing solutions which passed over a given ore-bearing portion of the Moenkopi-Shinarump contact. Thus, in general, thickness of alteration is a good ore guide. In some places, however, thickness of the altered zone varies with mudstone content of the overlying Shinarump both because Shinarump mudstones were originally Moenkopi and have also been altered, thus lowering the reducing power of the solutions, and because of lack of permeability near the contact in these areas. Concentrations of hydrocarbon could not be correlated directly with ore although its abundance in the Holiday Mesa scour appears to render the scour more favorable.

Mineralogy

Major ore minerals on Holiday Mesa are uraninite, montroseite (?), and corvusite, with tyuyamunite, hewettite, torbernite, and volborthite reported in more oxidized areas near the rim.[6] The ratio of vanadium to uranium averages about 2.5 to 1 on Holiday Mesa. Chalcopyrite is widespread in the ore zone, giving it an average content of one-half per cent copper. Gangue is detrital quartz, kaolinite, and chert, with silica, calcite, and iron oxide cement. Some ore replaces cement.

Supergene Alteration

Migration of copper-bearing acidic solutions away from the uranium-vanadium orebody during oxidation, and precipitation of copper carbonates as a halo surrounding ore is indicated by a graph of assays along a mineralized rim on Holiday Mesa (Fig 6). Vanadium-copper ratios on the oxidized west and east ends of the mesa (Fig. 4*c*) correspond very closely with mineralization. Within the mesa, however, where ore is unoxidized, correlation is somewhat less definite. Because copper content is relatively uniform in unoxidized portions of the deposit, Figure 4*c* indicates vanadium variations to a large extent and shows a close relationship between localization of uranium and vanadium.

Ore Controls and Guides

Ore controls and guides for Holiday Mesa in particular and Monument Valley in general are as follows: (1) ore occurs in and below scour-fill sediments along paleostream channels cut into the Moenkopi formation and filled with Shinarump sediments, with ore apparently introduced after regional folding; (2) areas of increase from sand, to sand with about 25 per cent mudstone are favorable for uranium deposition; (3) alteration in Moenkopi mudstones is generally more intense and the zone is thicker in areas of ore; (4) occurrences of copper may suggest nearby orebodies; (5) isorad values build up gradually toward orebodies in areas having relatively broad, flat-bottomed channels.

HAPPY JACK MINE

The Happy Jack mine in White Canyon, San Juan County, Utah, (Fig. 1) was first located as a copper prospect in 1900, and was mined in 1906 and in 1914. Butler included the property, then called the Blue Dike, in his compilation of Utah ore deposits,[7] and first noted uranium sulfate. Since late 1949 the mine has been worked for uranium and was the first copper-uranium deposit in the Shinarump conglomerate to produce primary uraninite and copper sulfide ore.

General Geology

Regional Structure

The White Canyon mining district is located on the gently dipping west flank of the Monument

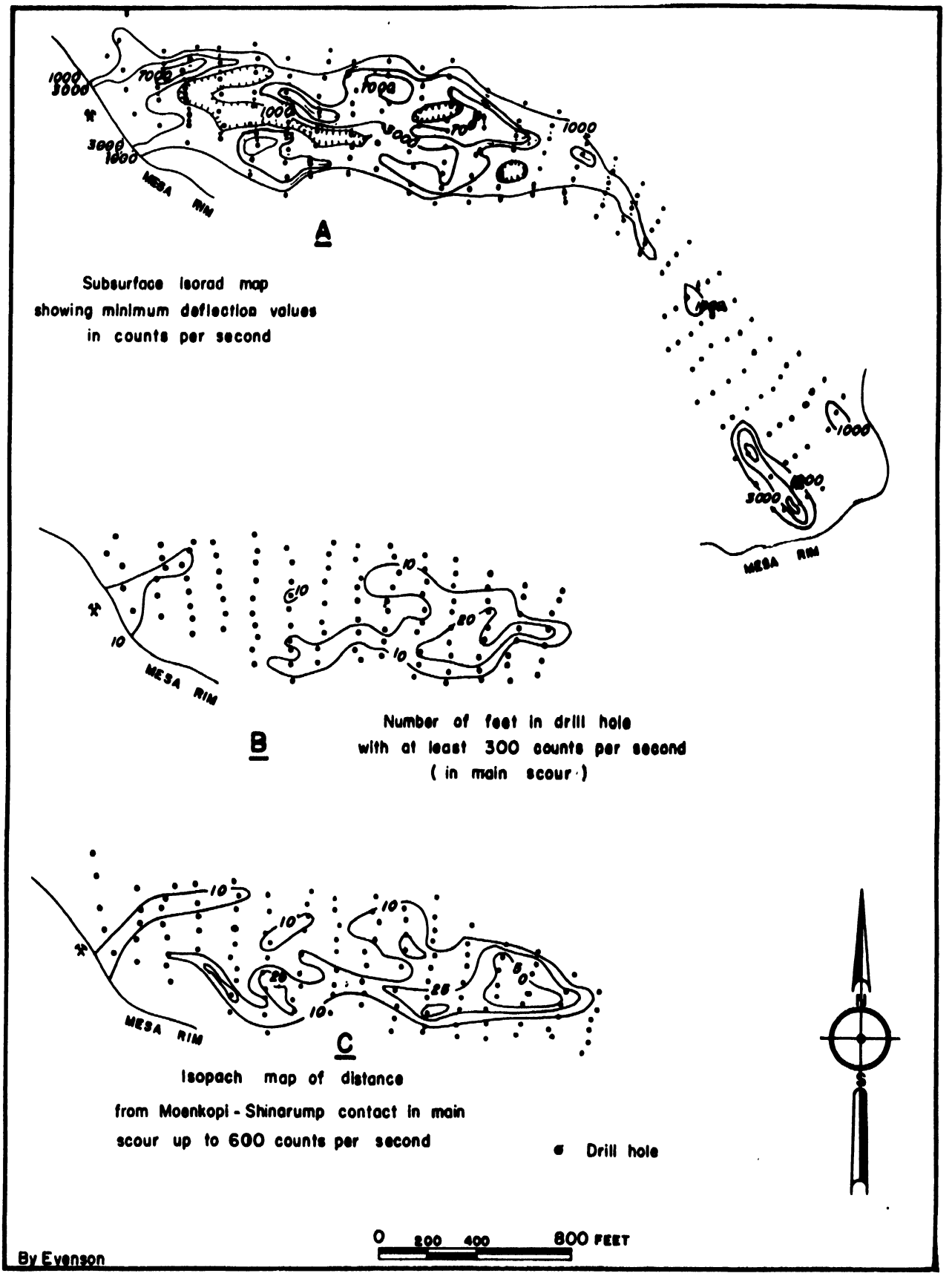


Figure 3. Three methods of showing mineralization on Holiday Mesa, San Juan County, Utah

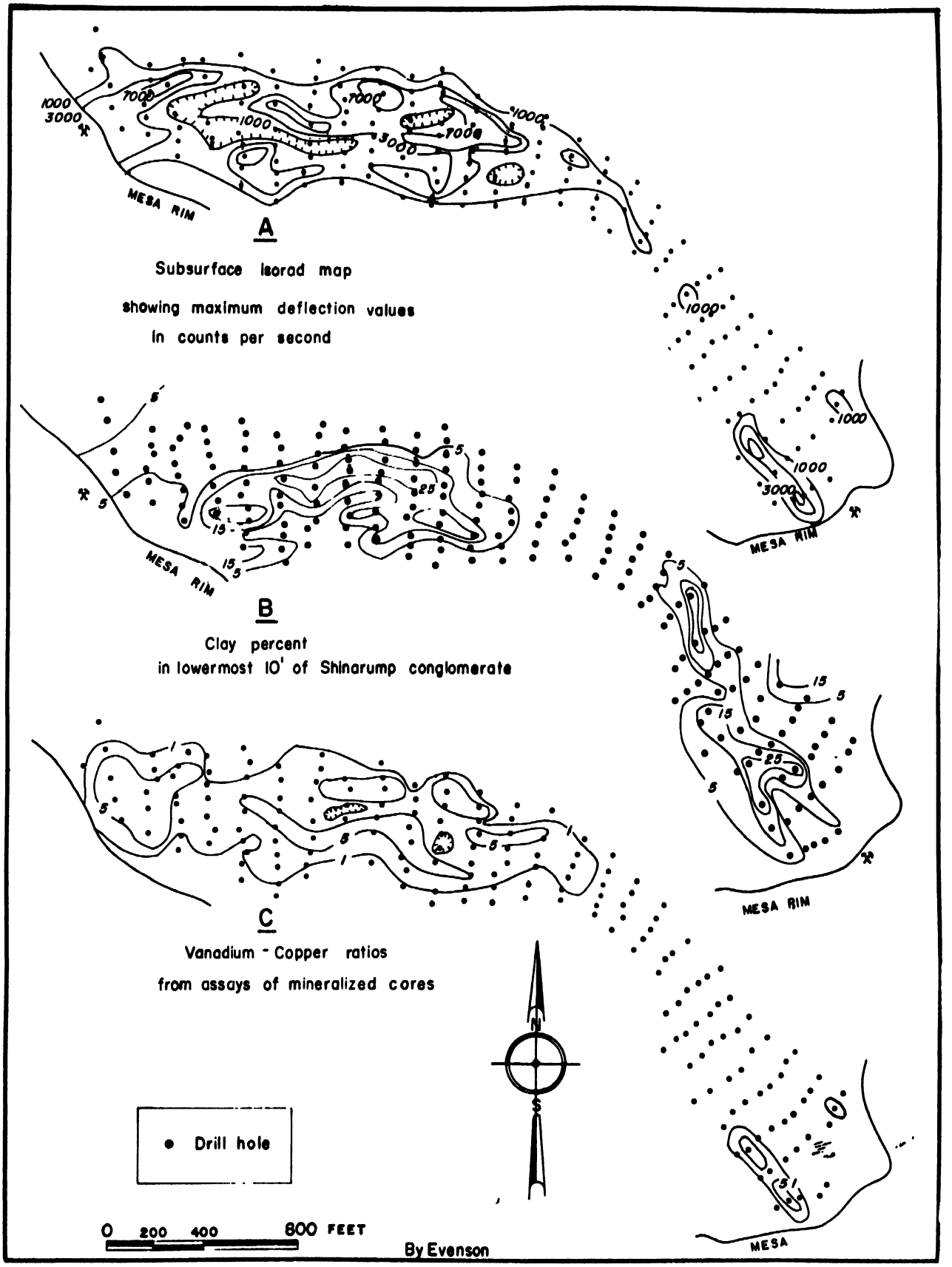


Figure 4. Relationship of mineralization to lithology and Vanadium—Copper ratios on Holiday Mesa, San Juan County, Utah

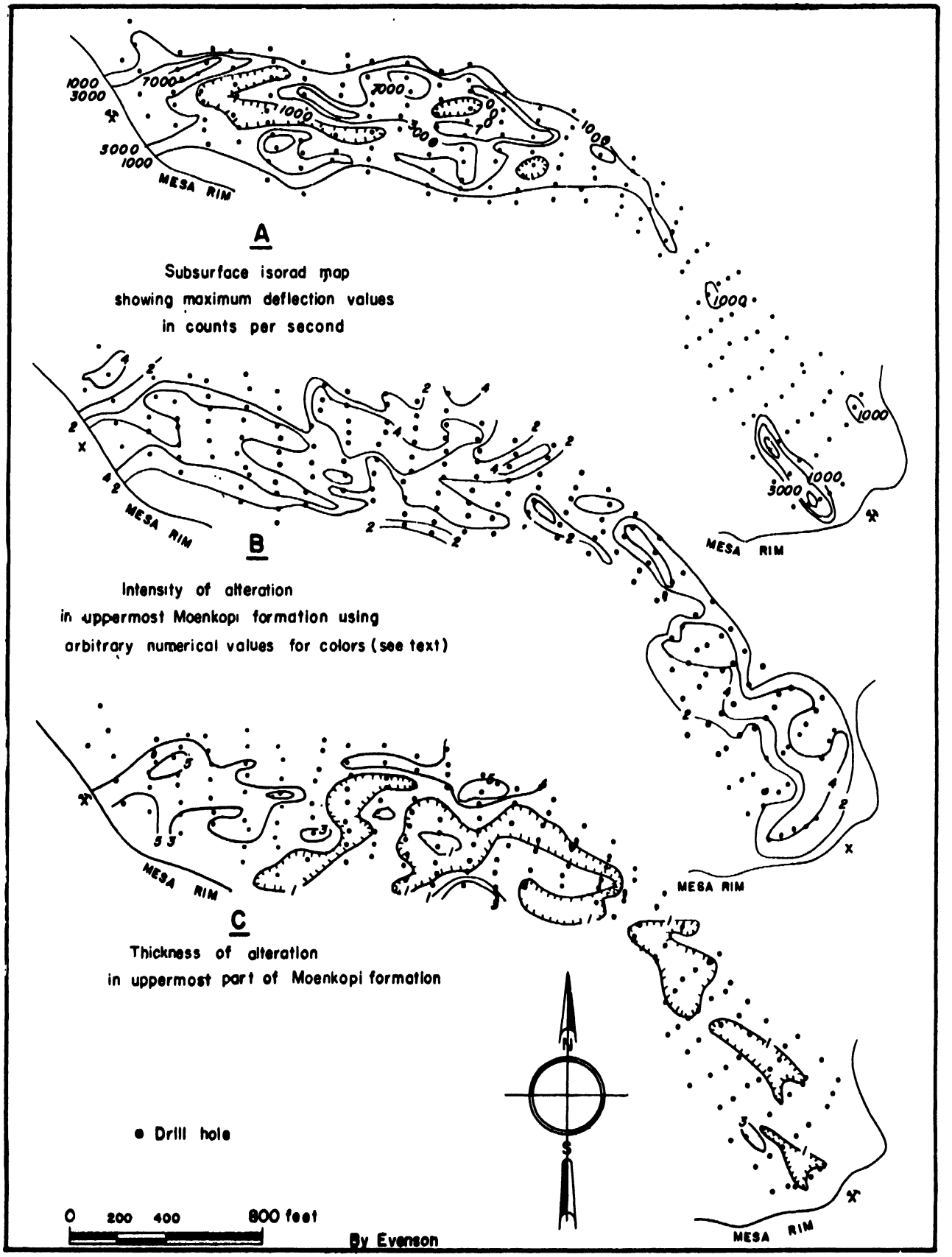


Figure 5. Relationship of mineralization to intensity and thickness of alteration in the Moenkopi formation on Holiday Mesa, Utah

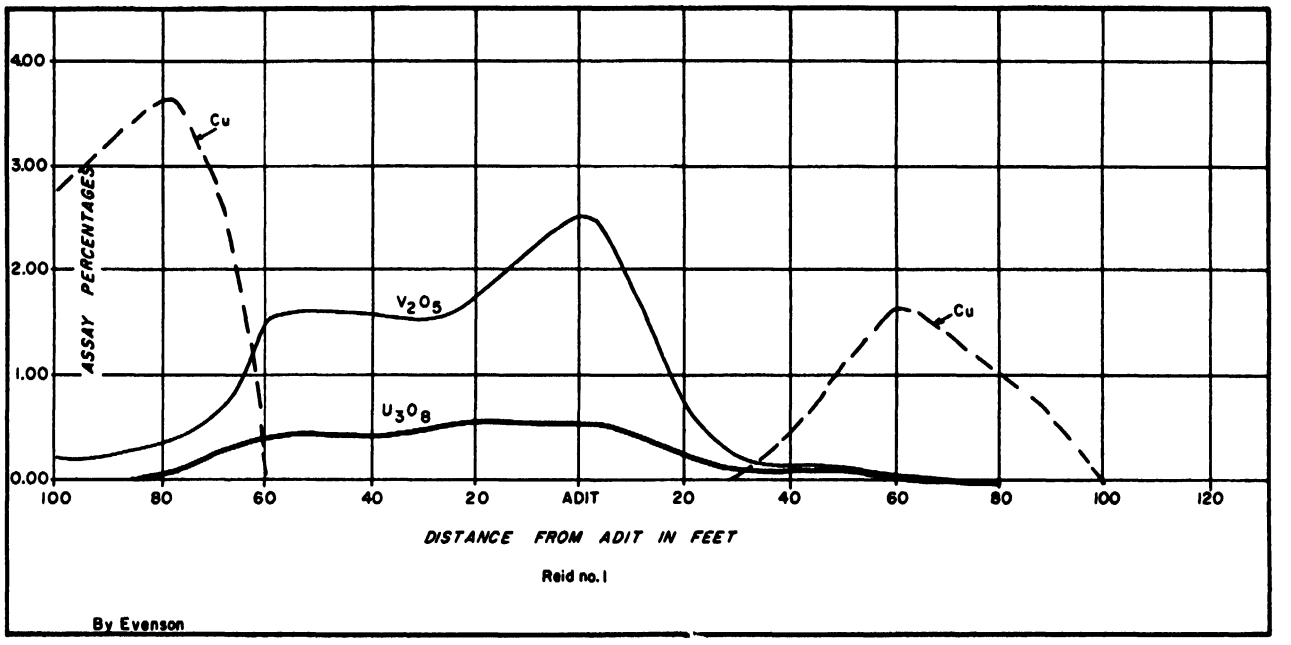


Figure 6. Comparison of assays of one foot intervals along Moenkopi-Shinarump contact, west end, Holiday Mesa channel

upwarp. Beds have a nearly uniform strike of north 15 degrees west and dip southwest 1½ to 2½ degrees. The few minor vertical faults in the district, none near the mine, trend northwest. A conjugate vertical joint system is developed in some beds; the dominant set strikes north 50 degrees east and the minor set strikes north 55 degrees west. The diorite and monzonite intrusive masses of the Henry Mountains,[8] 18–20 miles west of the mine, are the closest known igneous rocks.

Stratigraphy

Sedimentary rocks exposed in the mining district range from the Hermosa formation of Pennsylvanian age to the Jurassic Navajo sandstone. The Happy Jack mine and other deposits of the district are in the Shinarump formation, which was derived from a source to the northeast. The Shinarump is locally divisible into upper and lower units. Ore is restricted to the lower unit which contains coarse- to fine-grained sandstone and siltstone and fills paleostream scours in the underlying Moenkopi formation. Sandstones of the unit are poorly sorted, angular, and contain fragments of microcline. The cement comprises unidentified clay minerals containing shards suggesting a volcanic origin. The upper unit which extends into inter-channel areas, is a light gray fine- to coarse-grained conglomeratic sandstone. Coalified plant fragments, present in both units, are more abundant in the lower, more lenticular part of the formation.

Economic Geology

Occurrence of Ore

Sedimentary structures, rather than tectonic structures, influence ore localization. Miller[9] states that three types of fractures occur in the Happy Jack mine: (1) joints, (2) small faults (displacement 1-foot) caused by regional tension, and (3) minor faults resulting from penecontemporaneous compaction, and that no primary uranium mineralization is associated with any of these.

In the Happy Jack mine, as elsewhere in the White Canyon district, ore deposits are confined to fluviatile channel-fill sediments in paleostream scours.[9,10,11] Broad swales on the Moenkopi surface may have controlled zones of active scouring and deposition of Shinarump streams. In the vicinity of the Happy Jack, the first sediments to fill scour depressions are extremely lenticular and interbedded. The Happy Jack deposit is in a broad shallow U-shaped depression on the Moenkopi surface suggesting a small basin with a restricted channel outlet to the southwest (Fig. 7). Maximum relief from the base of the scour to the divide separating it from the adjacent Sunrise-Gonaway channel to the east, is about 28 feet. The basin containing the Happy Jack deposit is 600 to 700 feet across and has a relief of only 10 feet. The Sunrise-Gonaway channel averages 500 feet wide and has been scoured 10 to 12 feet into the top of the Moenkopi formation. Most ore is in the low scour portions of the channels, only a minor amount extends beyond the scours onto the flank area (Fig. 7).

A positive correlation exists between ore and portions of the channel containing unusual amounts of mudstone interbedded with the sandstone in the lower 10 feet of the Shinarump (Fig. 8).

A map showing distribution of carbonaceous fossil plant material within the ore-bearing basal 10 feet of the Shinarump (not here reproduced), indicates a coincidence of carbonaceous concentrations with areas of high mudstone.

Mineralogy

Gruner[12] has identified the suite of minerals from the Happy Jack orebody as shown on p. 359.

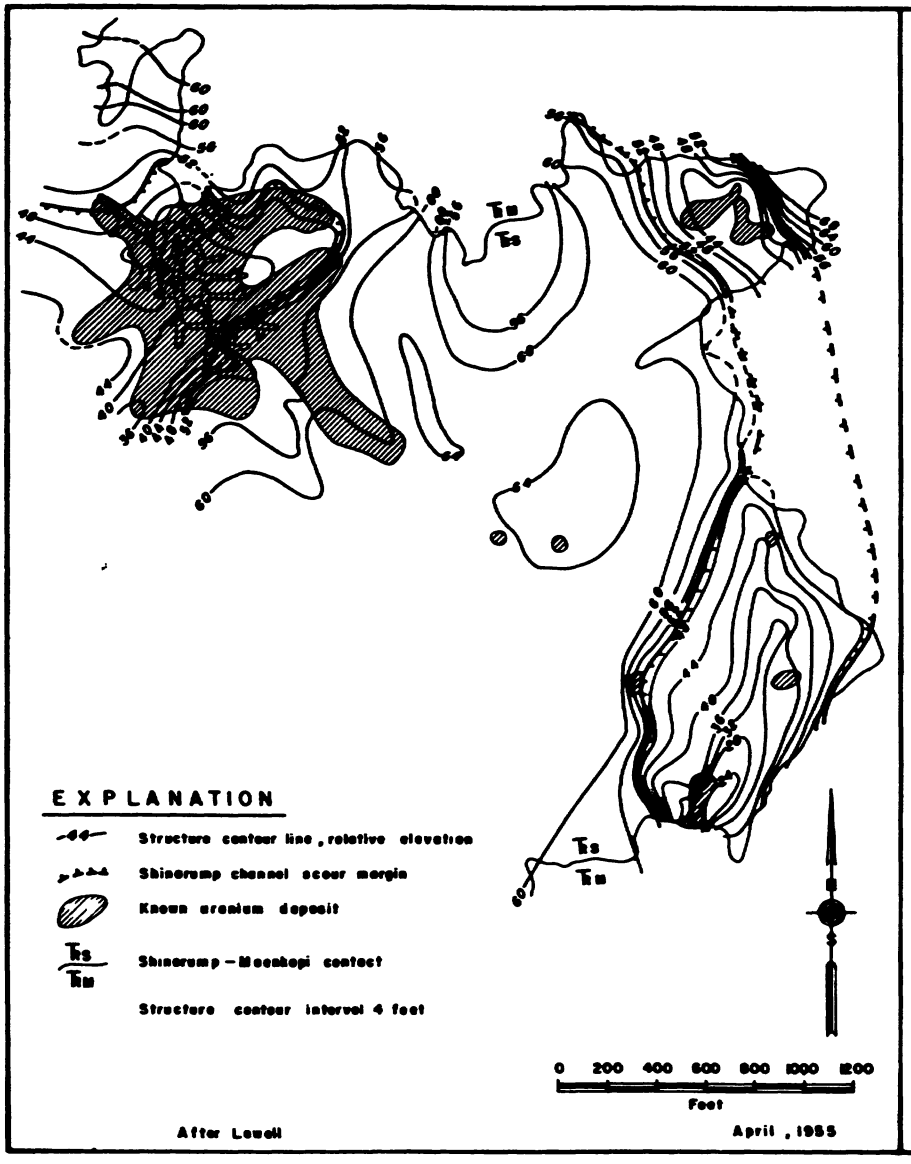


Figure 7. Uranium ore bodies localized in channel scours on the Moenkopi surface, Happy Jack mine and vicinity, White Canyon, San Juan County, Utah

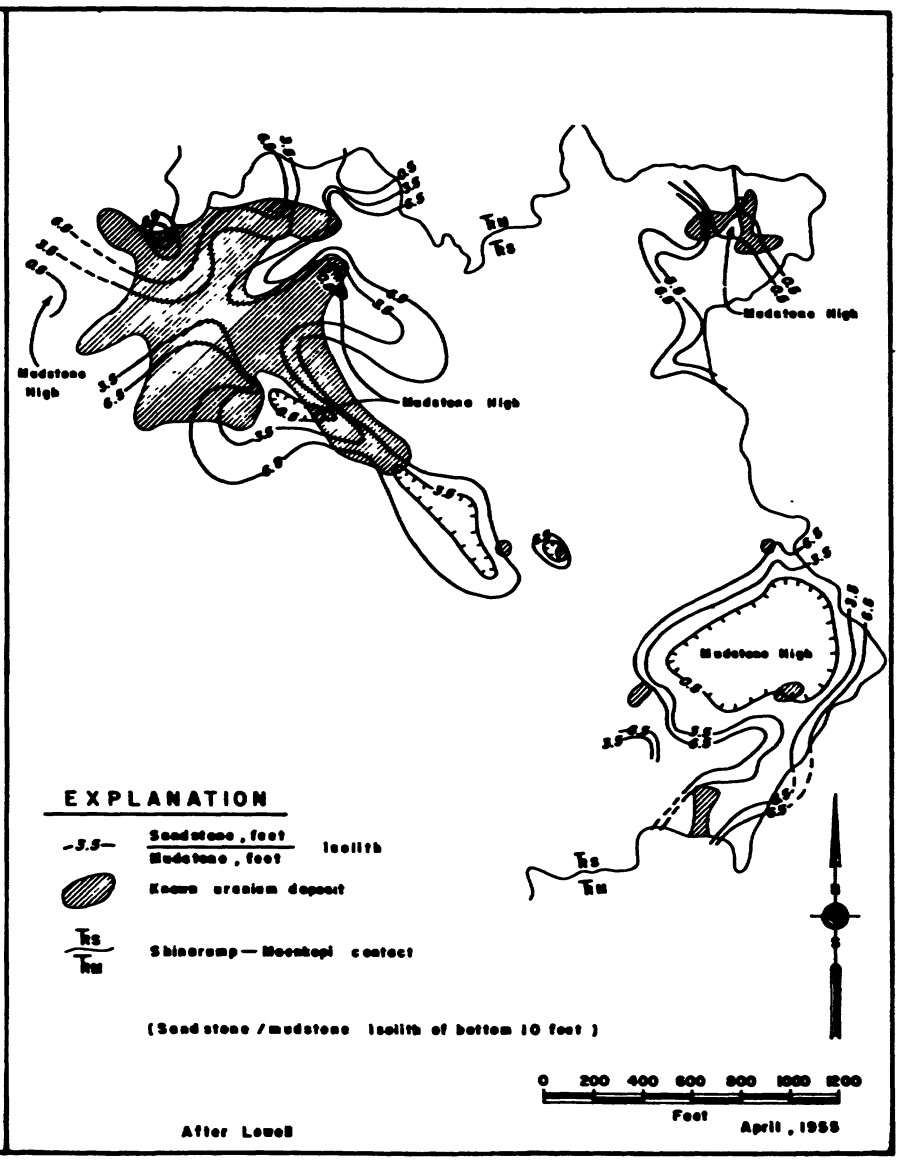


Figure 8. Lithofacies relationship of ore localization to mudstone concentrations in Shinarump fill of channel scours, Happy Jack mine and vicinity, White Canyon, San Juan County, Utah

Primary	*Secondary (Oxidized)*	
Uranium minerals:		
Uraninite	Zippeite	Uranophilite
	Johannite	Schoepite
	Torbernite	Metazeunerite
Copper Minerals:		
Chalcopyrite	Antlerite	Brochantite
Bornite	Chalcanthite	Azurite
Chalcocite	Malachite	Cyanotrichite
Covellite		
Others:		
Pyrite	Goethite	Siderotil
Galena	Jarosite	Erythrite
Sphalerite	Ilsemannite	Sulfur
Gersdorfite	Barite	Gypsum
	$(CO,Fe)SO_4 \cdot 4H_2O$ (unnamed)	
	$MgSO_4 \cdot 6H_2O$ (unnamed and not previously described)	

The major uranium ore mineral in the Happy Jack mine is uraninite, in very fine granular masses and sometimes as colloform blebs less than three microns in size. It replaces fossil wood fragments and, when associated with chalcopyrite, shows preferential replacement of cell walls whereas chalcopyrite fills cells. The contact of uraninite with chalcopyrite, chalcocite, and covellite is always irregular. Miller[9] and Gruner[12] have both commented on quartz boundaries being indented by replacing sulfides, but quartz etching has not been observed except in contact with uranium minerals. Secondary overgrowths on quartz grains, common in the Shinarump, have been locally replaced by uraninite. The clay cement is replaced by uraninite more completely than the quartz sand grains. Uraninite veinlets up to one-half inch wide cut across 2-inch beds of mudstone.

Alteration

The normal hematitic red staining of Moenkopi siltstones and sandstones has been altered beneath many of the Shinarump channels to light gray or tan. It is postulated that this alteration, though often present in barren areas, may be an effect of the mineralizing fluids. Shinarump sediments containing ore are either gray or light orange brown, whereas barren sandstone is often pale red.

The Happy Jack deposit will illustrate changes effected by surface oxidizing conditions on the primary uranium oxide-copper sulfide ore.[10] Because of relatively impermeable overlying rocks, oxidation of the Happy Jack deposit has progressed horizontally inward from the rim exposure rather than vertically. Oxidation has progressed more rapidly than erosion and has developed a secondary ore zone generally paralleling the outcrop in which copper sulfides have been almost completely altered to copper sulfates or carbonates (Fig. 9). Uraninite has altered locally to the hydrated oxide schoepite, or more commonly to the sulfates zippeite and johannite, and rarely to the sulfate uranopilite, or to the phosphate torbernite.

Sulfate waters developed by oxidation have preferentially removed uranium from its radioactive decay products in the oxidized zone during recent time,[10] causing inequilibrium zoning (Fig. 9).

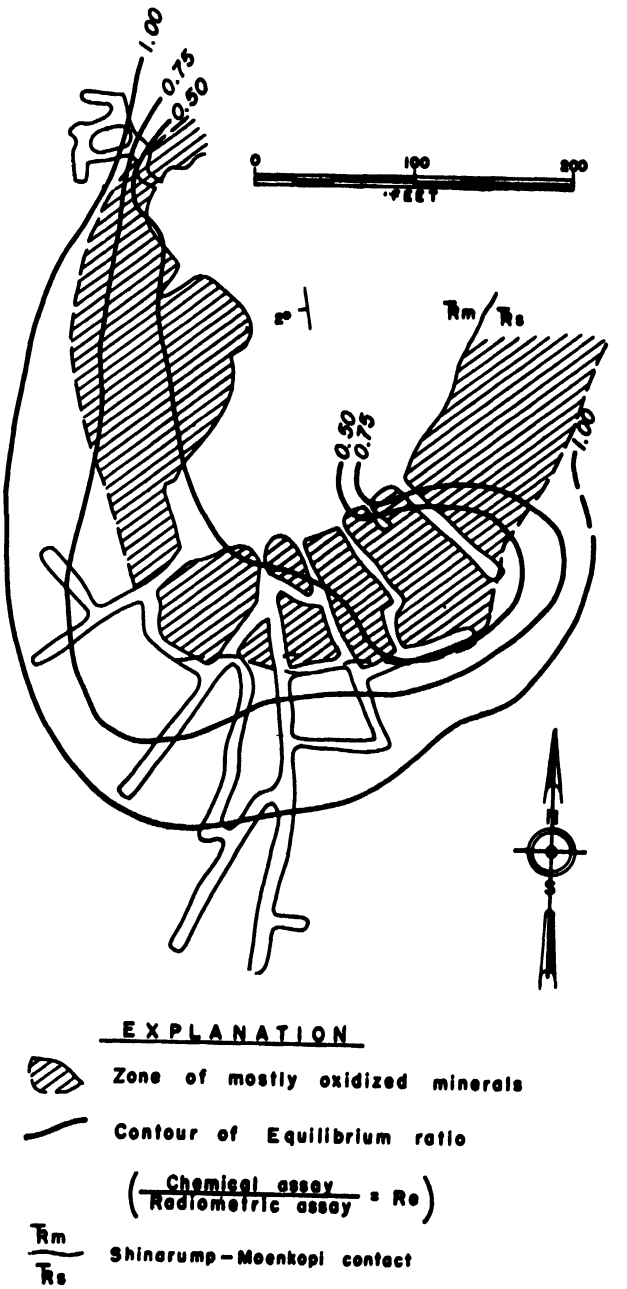


Figure 9. Zone of oxidation and inequilibrium distribution Happy Jack mine, White Canyon, San Juan County, Utah

Genesis

An epigenetic origin for the deposits has been proposed.[9,10] This is corroborated by the isotope age determinations of two specimens from the Happy Jack mine[1] which gave an age of 55 million years. Because of localization of ore in channels it is believed the ore fluids migrated laterally, controlled by permeability. Precipitation appears to have been caused by changes in pH or eH adjacent to changes in host rock content of such substances as carbonaceous material, pyrite, and clay minerals. There is no evidence for temperature or pressure control and the source of the uranium is unknown.

CALYX MINES

The Calyx group of mines are on Temple Mountain near the southern part of the San Rafael Swell, Emery County, Utah (Fig. 1 and insert in Fig. 11).

General Geology

Structure

The San Rafael Swell is a broad, relatively flat asymmetrical upwarp. Temple Mountain, an erosional remnant within the Swell contains a complex altered collapse area described by Keys.[13] The Calyx mines lie south of the collapse area in a gentle, southeast-plunging synclinal cross fold[14] with beds dipping 8 to 11 degrees southeast.

Stratigraphy and Sedimentation

Sedimentary rocks in the San Rafael Swell range from the Coconino sandstone of Permian age to the Jurassic Morrison formation.

Major uranium-vanadium ore in the area occurs in the Moss Back member of the Chinle formation. The host rock is a gray medium- to coarse-grained sandstone containing discontinuous lenses of conglomerate and mudstone. Calcite cement is common in the Moss Back elsewhere in the San Rafael Swell, but in the Calyx area the dominant cement is asphaltic hydrocarbon.[15] Humic hydrocarbons (carbonized wood fragments) are common in the Moss Back. The ore sandstone in the Calyx No. 3 mine rests upon a green mudstone along a gently undulating contact marked by scours up to 3 feet deep, and is overlain by a quartz pebble conglomerate matrix, ranging from 6 inches to 3 feet thick.

Economic Geology

Uranium mineralization occurs in several formations involved in the Temple Mountain collapse area[13] but major production has come from the Moss Back in the Calyx mines area (named from the prevailing method of removing ore through Calyx drill holes). Ore deposits in the Moss Back are ellipsoidal tabular bodies with marginal finger-like extensions projecting outwards as much as 50 feet.[16] Deposits are approximately 300 feet long, 20 feet wide and 4 feet thick, and tend to be elongated down dip.[7]

Within the host rock, ore occurs as disseminations in sandstone around carbonized logs, against contacts with mudstone, as stringers along cross laminae, and as irregular pods and blebs. Asphaltic hydrocarbons are closely associated with ore throughout the area. These hydrocarbons are of three types:[15] liquid asphaltite which is a non-uraniferous dark brown combustible fluid with the viscosity of heavy oil; vitreous asphaltite, a brittle, non-uraniferous solid which melts and burns readily when ignited emitting a petroliferous odor; and uraniferous asphaltite, a brittle sub-vitreous solid which emits a sulfur dioxide odor when heated, but which does not sustain a flame.

Mineralogy

Temple Mountain uranium-vanadium ore is essentially unoxidized. It has been commonly referred to as uraniferous asphaltite. However, Weeks and Thompson[18] advocate classification of the ore on the basis of mineral assemblage as "pitchblende associated with a hard carbonaceous substance variously described as high-rank coal or polymerized petroleum residue (thucolite?)". On the basis of preliminary study, Steiff and Stern[16] have suggested that the chief uranium mineral may be coffinite.

Montroseite is found in unoxidized ore. Corvusite and vanadium hydromica are common. Other oxidized uranium and vanadium minerals reported from Temple Mountain[16] are: carnotite, tyuyamunite, zeunerite, schroeckingerite, zippeite, rauvite, metatorbernite, uvanite, pintadoite, hewettite, and pascoite. The vanadium-uranium ratio of the ores is about 3 to 1.

Age determination of a sample of asphaltic ore from Temple Mountain indicates an age of 60 million years.[19]

Ore Guides and Genesis

Guides to ore in the Calyx area are asphaltic hydrocarbons, carbonized plant remains, and abnormal thickness of the ore sandstone.[16] In the Calyx No. 3 mine, Baumgardner and Noble[15] consider the presence of impermeable mudstone at the base of the ore horizon as a criterion of favorability.

The writer regards the Temple Mountain deposits as primary uranium deposits of the uraninite-montroseite type, similar to the ores of Big Indian Wash, into which were later introduced fluid hydrocarbons which became polymerized to varying degrees by alpha radiation and which replaced uraninite in the process. Such a mechanism for the formation of naturally occurring hydrocarbon-uraninite complexes has been advanced by Davidson and Bowie.[20] By this interpretation, the anomalous circumstance of asphaltite "corroding" and "replacing" quartz sand grains is more easily comprehended as replacement of silica by uraninite from hydrous mineralizing solutions (a phenomenon commonly observed in non-asphaltic orebodies) followed by subsequent replacement of uraninite by introduced hydrocarbons.

BIG INDIAN WASH-LISBON VALLEY MINING DISTRICT

The Big Indian Wash-Lisbon Valley uranium district is in San Juan County, Utah (Fig. 1). The

first uranium mined in the area came from the Big Buck mines in the Cutler formation where small-scale production began in 1948 and continued sporadically until 1953. Uranium was first discovered in the Chinle formation in 1952, and by 1954, more than 1,000,000 tons of ore had been blocked out according to operators, with significant new discoveries still being made.

General Geology

Structure

Large uranium deposits occur on the southern flank of the Lisbon Valley anticline which trends northwest. Large laccoliths occur 6 miles to the north and 25 miles to the southwest (Fig. 1).

The Lisbon Valley anticline is a salt structure, formed primarily by plastic flowage and local thickening of salt and gypsum.[21,22,23] The Lisbon Valley fault, a major displacement, and minor associated faults cut the anticline longitudinally and place the Jurassic Morrison formation into contact with the Pennsylvania Hermosa formation (Fig. 10). This fault dips steeply northeast and has a normal stratigraphic throw of at least 3800 feet. Movement along this fault is thought to result from differential uplift of the footwall block rather than collapse of the hanging wall block. This interpretation is supported by the fact that the upthrown southwest side is considerably more domed, more steeply dipping, and more fractured than the downthrown side.[24]

The major joints along the anticline are longitudinal, a feature shown to be characteristic of flexures resulting from vertical forces.[25] Transverse joints are less evenly distributed and less pronounced than longitudinal joints. In addition to the longitudinal and transverse tension joints, are many oblique shear joints[26] and a number of unevenly distributed fracture zones which lack noticeable displacement but are reflected in the development of small, straight, north-trending valleys. These fracture zones were first described by Bucher[27] who noted that some of them have a close spatial relationship to orebodies. He interpreted such zones as a reflection of deep-seated faults.

Stratigraphy and Sedimentation

Sedimentary rocks exposed in the district range from the Hermosa formation of Pennsylvanian age to Mancos shale of Upper Cretaceous age. Ore in the Chinle is restricted to the basal Moss Back member of the formation. At some places the ore horizon lies directly on beveled beds of the more steeply dipping Cutler formation; at others it is separated from the Cutler by a few feet of barren gray mudstone of the Chinle formation. The Moenkopi formation which underlies the Chinle to the west does not crop out here, perhaps due to pinchout lower on the flanks of the anticline.

Characteristic of a fluvial deposit, rapid horizontal and vertical facies changes are commonplace in the Moss Back. Scour and fill phenomena, crossbedding, and ripple marks, all characterizing turbulent flow, are widespread. Laminar flow is represented in some beds by lineation. Intraformational unconformities are commonly exposed in mine walls, but can seldom be traced more than a few hundred feet. Sedimentary trends in the ore horizons at Big Indian Wash indicate a southeast source area for Moss Back sediments.

Economic Geology

Occurrence of Uranium and Vanadium

In the Big Indian Wash-Lisbon Valley area, uranium deposits lie within a half-mile strip which borders the Chinle escarpment and parallels the strike of beds for a distance of 15 miles. Most known orebodies occur in the northern portion of the anticline, adjacent to Big Indian Wash and all are more or less elongated parallel to the strike of the beds. All except one occur in the interval 6200–6700 feet above sea level. The single exception, which is about 5840 feet above sea level, lies along the Lisbon Valley fault in the southern part or the mining district. Maximum thickness of ore in the Moss Back is 30 feet and the average is 8 feet. Host lithologies include medium- and fine-grained sandstones, siltstones, and conglomerates containing pebbles of mudstone and limestone. The most productive host is fine- to medium-grained sandstone with calcareous cement. Carbonized plant matter is widespread in the orebodies but the average content of carbon, even in rich ore, may not exceed one-half per cent.[28] Ore does not impregnate the host rock uniformly, nor does it follow in detail primarily textures such as bedding; instead, it characteristically occurs in small irregular pods, blebs and stringers which exhibit only crude parallelism with bedding.

Mineralogy

The mineralogy and petrography of the deposits have been described by several investigators.[6,28,29] The dominant ore mineral is uraninite, which contains minute intergrowths of coffinite; the most abundant vanadium minerals are vanadium hydromica and montroseite with very fine intergrowths of dolorisite. The oxidized minerals tyuyamunite, corvusite and pascoite are developed along and adjacent to joint surfaces.

Both uraninite and montroseite replace calcite cement, and uraninite replaces coalified logs and carbonaceous debris. Calcite fills cells in carbonized wood; uraninite replaces cell walls and locally extends into cells by replacement of calcite. Calcite is thought to be diagenetic and to have thus prevented a flattening of logs by compaction. Pyrite is fairly abundant and commonly replaces fossil vegetal material. Small quantities of barite, fluorite, greenockite, sphalerite, and galena, have also been reported. Chalcopyrite and malachite are very rare. Dominant detrital minerals in the sandstones and siltstones are angular to sub-angular quartz, plagioclase, and microcline; muscovite is abundant locally. Calcite fills interstices, corrodes quartz along grain surfaces and in ore replaces feldspar to a minor extent; other cements are quartz, barite, clay aggregates, and

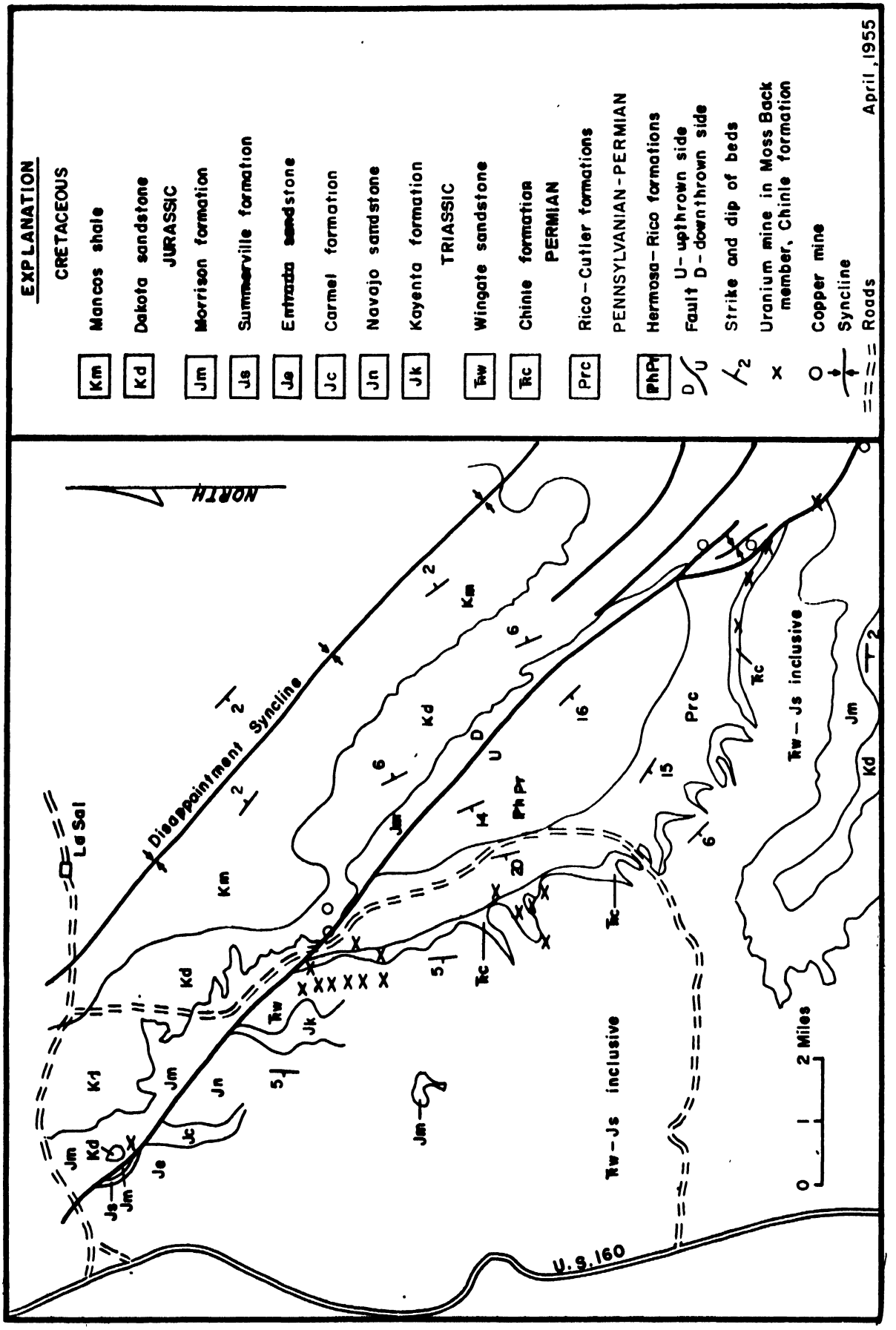


Figure 10. Generalized geologic map of Lisbon Valley anticline, San Juan County, Utah

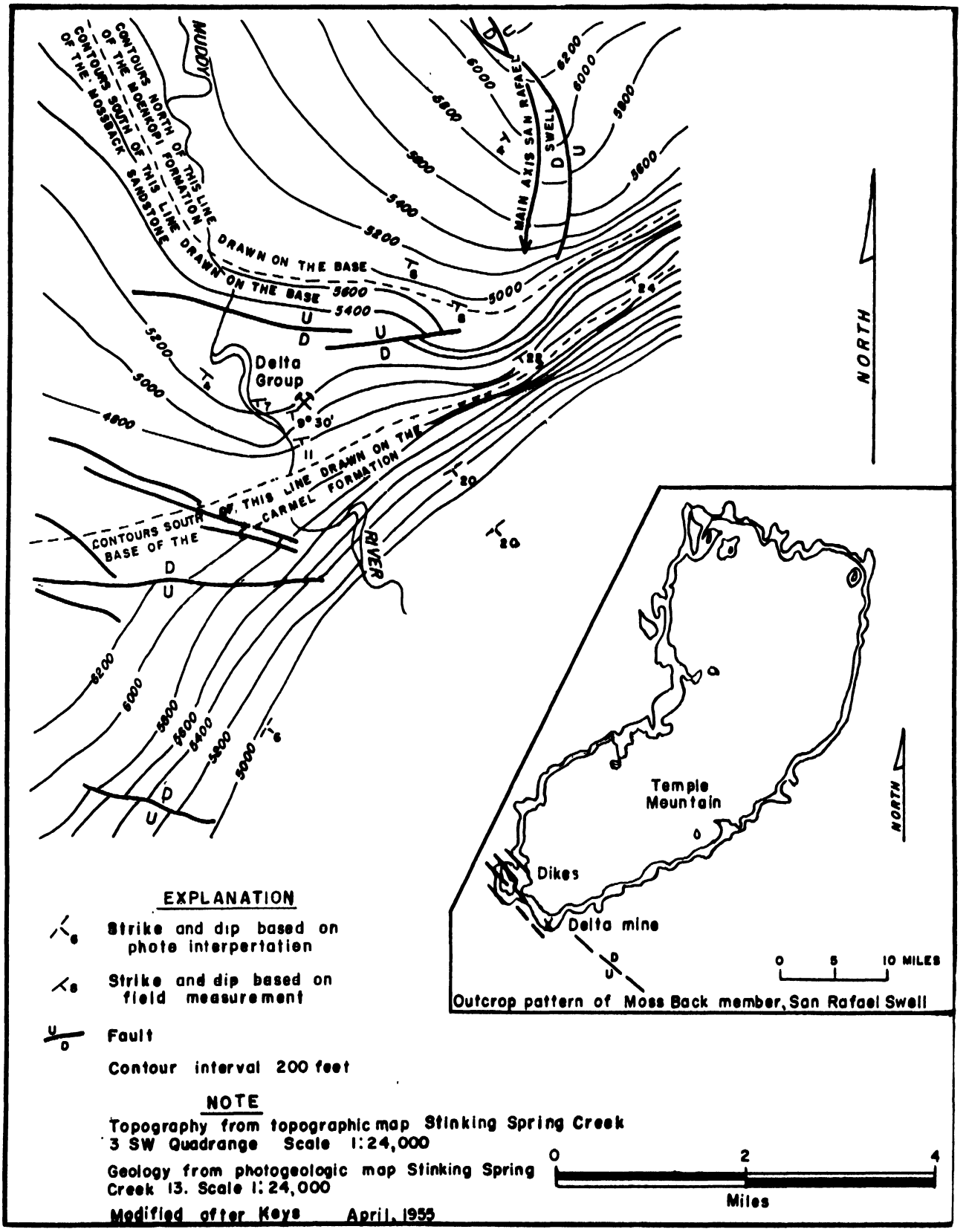


Figure 11. Maps showing structure of the Delta mine area and outcrop pattern of the Moss Back member in the San Rafael Swell, Utah

chlorite. Microscopic examination indicates that primary uranium minerals were introduced contemporaneously with pyrite and chalcopyrite, and later than the cement.[30]

Alteration

In proximity to orebodies there is a tendency for the gray-green color which characterizes the ore horizon to extend into overlying red mudstones of the Chinle formation. This color difference is attributable largely to differences in color of the clay fraction of the mudstones which are not yet understood. According to Keller[31] no difference exists in gross mineralogy between the red and green clays.

Ore Controls and Genesis

Ore controls, both known and postulated, may be classified into three categories: local, areal, and regional.

Local controls: These include permeability as reflected in lithologic types, as well as such substances as carbonaceous matter, pyrite, calcite, and possibly certain clays, capable of causing precipitation of the uranyl ion by changes in eH and pH as well as by absorption or base exchange phenomena.

Localization of ore in paleochannel fill, as advanced by Dix[32] has not been adequately tested by subsurface data compiled to date. The close spatial relationship between ore and north-trending fracture zones strongly suggests a fracture control of ore solutions as advanced by Bucher.[27]

Areal controls: The Lisbon Valley anticline appears to exert the most important areal control of ore as exemplified in the virtual restriction of ore to a narrow elevation interval. Anticline control of ore was initially postulated in 1953.[28]

Two pecularities of stratigraphy associated with the Lisbon Valley anticline which may have influenced ore localization are (1) the absence beneath ore of the relatively impermeable mudstones of the Moenkopi coupled with its probable occurrence down dip as a cap for hypothetical rising ore solutions,[26] and (2) the beveled surface of the Cutler formation beneath the Moss Back which provides permeable arkose lenses as possible conduits for hypothetical ore solutions rising along the Lisbon Valley fault.[33] The occurrence of copper deposits along the fault[24] suggest the plausibility of copper-uranium zoning in the district, with ore solutions gaining entry along the Lisbon Valley fault.

Regional controls: Proximity of the Big Indian Wash-Lisbon Valley mining district to laccoliths to the north and southwest (Fig. 1) is considered significant by many geologists. The laccoliths, consisting mainly of diorite porphyry and monzonite porphyry with minor syenite intrusives[34] may have both a chemical and a structural relationship to neighboring uranium deposits. Shoemaker[35] notes that syenite of the La Sal Mountains is anomalously enriched in copper and suggests that a rough zonal relationship may be indicated between copper and uranium deposits around the La Sal Mountains.

A non-hydrothermal source for the uranium has been proposed by Gruner[29] who suggests that uranium was leached by ground water from volcanic tuffs and reprecipitated in its present sites.

DELTA MINE

The Delta mine is located in the southern part of the San Rafael Swell, Emery County, Utah (Figs. 1 and 11). The anomalous surface radioactivity which evolved to the Delta mine (Fig. 1) was discovered first by members of a US Atomic Energy Commission airborne scintillometer crew in June 1952.[36,37]

General Geology

Structure

The Delta mine is on the southern edge of a structural terrace in a monocline which forms the southern margin of the San Rafael Swell, one of several major upwarps on the Colorado Plateau (Fig. 11). Neighboring faults and dikes of diabase and syenite are shown on Fig. 11. A vertically dipping conjugate joint system is developed in competent beds of the area; joint sets strike northeast and northwest.

Stratigraphy

Sedimentary rocks cropping out in the San Rafael Swell range from the Coconino sandstone of Permian age to the Jurassic Morrison formation. Copper-uranium-vanadium ore occurs in the Chinle and is restricted to the lower third of a sandstone lens 33 feet above the base of the formation.[36] The lens is 31 feet thick at the mine and disappears several hundred feet to the north and south. The Moss Back member of the Chinle is unmineralized at the Delta mine and lies above the ore horizon, separated from it by 23 feet of mudstone.

The host is a massive fine- to medium-grained sandstone containing widespread carbonized plant remains. Within this unit the most favorable lithology is thin-bedded, fine-grained micaceous sandstone with interbedded mudstone. In strongly mineralized areas in the mine, all lithologies, including mudstone, are ore-bearing. Ore rests upon a relatively impermeable basal green mudstone of illite and kaolinite.

Economic Geology

The Delta orebody is crudely semi-circular with the longest dimension trending northeast. Thickness of ore is highly variable; the maximum is 20 feet.[36]

A map showing distribution and intensity of joints (not here reproduced) failed to reveal any relationship to localization of primary minerals.

Irregularities at the base of the ore horizon are shown in Fig. 12. Most ore occurs where the base of ore horizon is undulatory. Whether these undulations are due to scouring, differential compaction, or flexuring is a matter of conjecture. However, inasmuch as the Chinle is a fluvial deposit, the first two alternatives are logical.

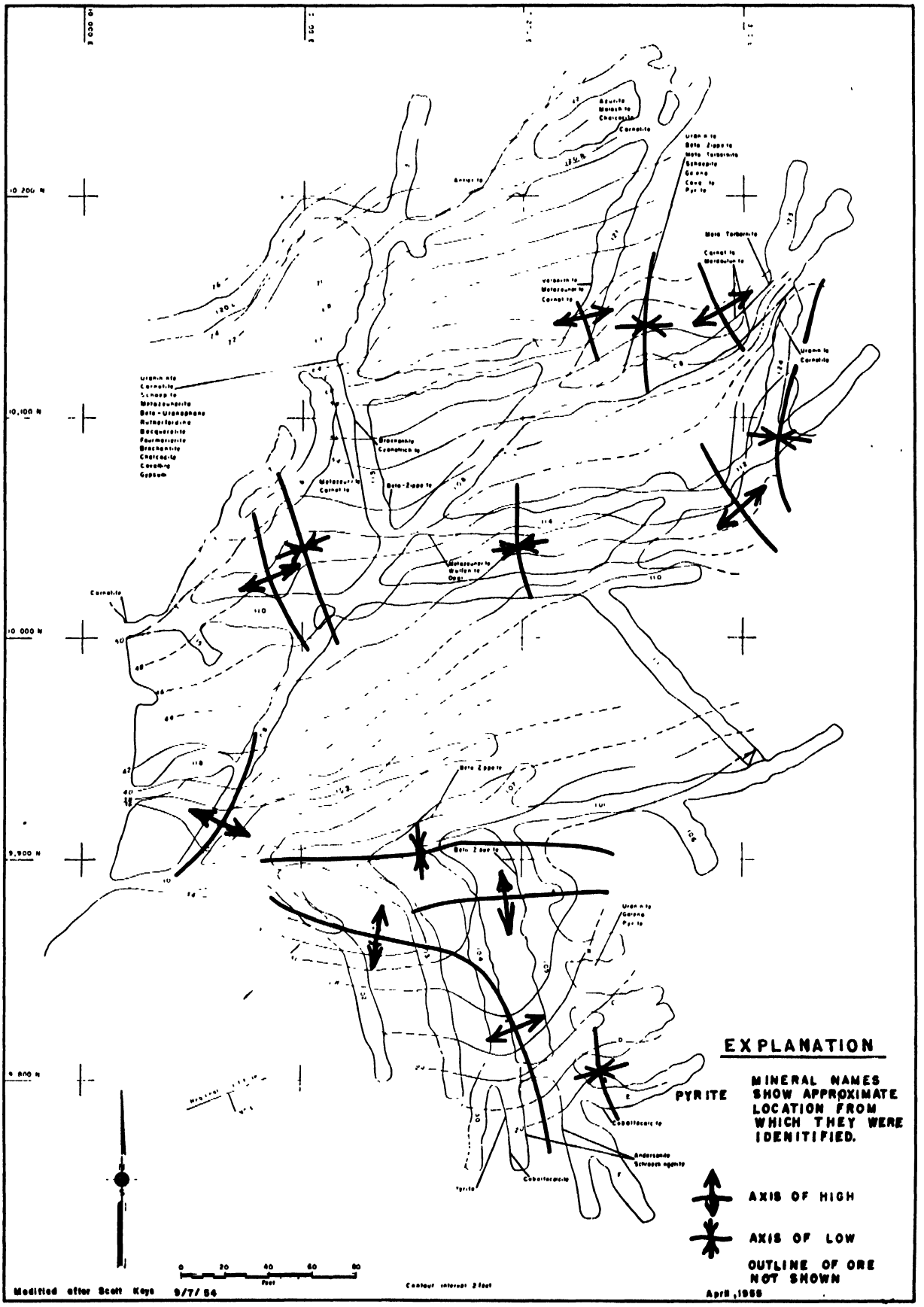


Figure 12. Structure contours on the base of the ore-bearing sand-stone, Delta mine, San Rafael Swell, Emery County, Utah

Mineralogy

Carnotite and zippeite disseminated in sandstone account for most of the ore; uraninite in amounts up to 83.5% U_3O_8 locally replaces fossil logs.[36] Disseminated secondary uranium minerals surround these logs in halos with radii up to 25 feet. Other secondary uranium minerals are listed according to locality from which collected (Fig. 12). Non-uranium minerals, exclusive of detritals, are pyrite, galena, chalcocite, covellite, wulfenite, volborthite, cobalto-calcite, malachite, azurite, brochantite, chalcanthite, and antlerite. The uranium-vanadium ratio is highly variable, ranging between 10 to 1 and 1 to 5.

Alteration

A distinct mineral zoning occurs in the Delta mine; in the northern workings copper minerals are very abundant, particularly malachite and azurite which occur in several two-foot thick beds assaying up to 11 per cent copper.[36] Areas which have escaped oxidation contain uraninite in association with chalcocite and covellite. In the central portion of the mine, the dominant oxidized uranium mineral is carnotite, with torbernite and zeunerite increasing northward, whereas in the southern workings, beta-zippeite is the principal secondary ore mineral. Galena and cobalto-calcite occur in the southern workings but are lacking elsewhere in the deposit.

The copper and uranium were introduced contemporaneously or nearly so, as in the Happy Jack orebody. Zoning of uranium minerals in the Delta mine is considered by the writer to have resulted from down dip supergene redistribution of elements within an original primary copper-uranium-vanadium orebody. Vanadium may have been introduced as montroseite, or as a vanadium clay, or both. However, the absence of montroseite and its oxidation product, corvusite, and the affinity of carnotite for clay-rich sandstone with inter-bedded mudstone, favors the vanadium clay interpretation. The mechanism of redistribution was probably oxidation of copper sulfides to provide the sulfate ion which in turn mobilized the uranyl ion. This ion was then transported down dip and reprecipitated as a relatively insoluble vanadate (carnotite), copper uranium phosphate (torbernite), or copper uranium arsenate (zeunerite). In the absence of these precipitants the uranyl ion could be transported still further until precipitated as a sulfate (beta-zippeite) or one of a number of minor secondary minerals (Fig. 12).

An alteration of red mudstones to green can be noted in the mine but assay values are independent of these color variations.[36]

HUSKON MINES

(Prepared by C. G. Evensen)

Charles Huskon, a Navajo Indian, made the first discovery in 1952 of important uranium mineralization in the Chinle formation near Cameron, Arizona, (Figs. 1, 13). This area, containing about twenty mines, is on the west flank of the Black Mesa Basin, a few miles east of the East Kaibab monocline, where there is a uniform 1 to 2 degree dip to the northeast.[38] Although fracturing is common in prominent joints striking northwesterly and a less apparent set striking northeasterly, no relation between structure and mineralization has been observed.

General Geology

The Permian Kaibab limestone and the Triassic Moenkopi, Shinarump, Chinle, and Wingate formations, as well as scattered basic lava flows and cinder cones of Tertiary age crop out in the area. The important ore deposits (Fig. 13) are all in the lower 60 feet of the "C" member of the Chinle formation.[39] Mineralization is concentrated in the more sandy and silty lenses which occupy paleostream scours. Scours measure up to 40 feet deep and 750 feet wide, with a general northeasterly elongation. Ore is concentrated in the lower portions of scours, particularly in areas of accumulations of carbonaceous debris. In addition to these lenticular deposits, some commercially unimportant scattered pods of ore occur in the vicinity of fossil wood throughout the entire "C" member.

Ore Occurrence

Orebodies are roughly elliptical in plain view and saucer-shaped in cross section. The largest orebody in the Cameron area is 450 feet long and 300 feet wide. The thickest section of ore-grade material measures 11 feet.

Orebodies vary widely in uniformity of uranium deposition within the scour. Huskon No. 1 and No. 3 (Fig. 13) are uniformly mineralized orebodies which fill the lower portions of scours, and have a horizontal upper surface, as does the containing sand lens, although the two are not generally coincidental. Highest grade ore occurs at the base of scours and in carbon concentrations. Huskon No. 2 and No. 10 (Fig. 13) are examples of irregular pod-like orebodies within a scour which were apparently controlled by concentrations of carbonaceous plant material and by variations in sand and silt content of scour-fill sediments. These pods vary in size from less than a ton to a thousand tons and from low-grade ore to high-grade uraninite-impregnated carbonaceous fragments. Huskon No. 7 is a transition between the lens and pod forms.

Mineralogy

Principal ore minerals[40] are meta-torbernite, meta-autunite, and uraninite with minor amounts of uranophane, sabugalite, meta-zeunerite, and zippeite. Gangue minerals are montmorillonite, quartz, kaolin and sericite (from feldspar), gypsum, limonite, jarosite, pyrite, calcite, barite, smaltite, and sphaerocobaltite. The ores are very low in vanadium, having a maximum ratio to uranium of 1 to 7. Orebodies in the area are near-surface and have been almost completely oxidized.

Alteration

All orebodies in the area are surrounded by light-brown to yellowish-brown alteration zones which

cut across the normal purple and gray color of the Chinle "C". These zones are characterized by a high content of jarosite and hydrous iron oxides, seritici-zation of feldspar, as well as an increase in trace amounts of molybdenum toward ore.

Ore Controls and Ore Guides

Ore is restricted to the lower 60 feet of Chinle "C"; is found in paleoscour fills with relatively high sand and silt content; and is closely associated with carbonaceous material, some of which it impregnates. In addition, there has been noted an increase toward ore of cobalt bloom (sphaerocobaltite) and trace amounts of molybdenum.

REFERENCES

1. Stieff, L. R. and Stern, T. W., *The Lead-Uranium Ages of Some Uraninite Specimens from Triassic and Jurassic Sedimentary Rocks of the Colorado Plateau,* US Geol. Survey TEI-322 (1953).
2. Isachsen, Y. W., Mitcham, T. W. and Wood, H. B., *Age and Sedimentary Environments of Uranium Host Rocks, Colorado Plateau,* Econ. Geol., 50: 127-37 (1955).
3. Evensen, C. G. and Gray, I. B., *Shinarump Uranium Deposits of Monument Valley, Arizona and Utah,* US Atomic Energy Comm. report in preparation.
4. Trimble, D. E., *Unclaimed Mineralized Area in the Shinarump Conglomerate Northwest of Oljetch Trading Post, Utah,* US Geol. Survey TEMR-353 (1952).
5. Mitcham, T. W. and Evensen, C. G., *Uranium Ore Guides, Monument Valley District, Arizona,* Econ. Geol., 50: 170-6 (1955).
6. Gross, E. G., personal communication (1955).
7. Butler, B. S. et al., *The Ore Deposits of Utah,* US Geol. Survey Prof. Paper 111 (1920).
8. Hunt, C. B., Averitt, P. and Miller, R. L., *Geology and Geography of the Henry Mountains Region, Utah,* US Geol. Survey Prof. Paper 228 (1953).
9. Miller, L. J., *Uranium Ore Controls of the Happy Jack Deposit, White Canyon, San Juan County, Utah,* US Atomic Energy Comm. RME-33 (1953).
10. Dodd, P. H., *Happy Jack Mine, White Canyon, Utah,* US Atomic Energy Comm. RMO-660 (1950).
11. Lowell, J. D., *Development Drilling of the Happy Jack Mine Area, San Juan County, Utah,* US Atomic Energy Comm. report in preparation.
12. Gruner, J. W. and Gardiner, L., *Mineral Associations in the Uranium Deposits of the Colorado Plateau and Adjacent Regions with Special Emphasis on Those in the Shinarump Formation,* Ann. Report, US Atomic Energy Comm. RMO-566 (1952).
13. Keys, W. S., P/41, *San Rafael Swell, Utah,* Vol. 6, Session 6B, these Proceedings.
14. Wood, H. B., oral communication.
15. Baumgardner, L. and Noble, E. A., *Geology of Calyx No. 3 Mine, Temple Mountain, Emery County, Utah,* US Atomic Energy Comm. report in preparation (1955).
16. Witkind, I. J. et al., *Preliminary Report on the Geology and Uranium Deposits at Temple Mountain and Green Vein Mesa, San Rafael Swell, Emery County, Utah,* US Geol. Survey, TEMR-775 (1954).
17. Keys, W. S., oral communication.
18. Weeks, A. D. and Thompson, M. E., *Identification and Occurrence of Uranium and Vanadium Minerals from the Colorado Plateaus,* US Geol. Survey Bull. 1009-B (1954).
19. Stieff, L. R., *Geochronology, Geologic Investigations of Radioactive Deposits,* US Geol. Survey TEIR-490: 266-7 (1954).
20. Davidson, C. F. and Bowie, S. H. V., *On Thucolite and Related Hydrocarbon-Uraninite Complexes,* Bull. Geol. Survey of Great Britain No. 3: 1-19 (1951).
21. Baker, A. A., *Geology and Oil Possibilities of the Moab District, Grand and San Juan Counties, Utah,* US Geol. Survey Bull. 841 (1933).
22. Dane, C. H., *Geology of the Salt Valley Anticline and Adjacent Areas, Grand County, Utah,* US Geol. Survey Bull. 863 (1935).
23. Stokes, Wm. Lee, *Geology of the Utah-Colorado Salt Dome Region With Emphasis on Gypsum Valley, Colorado,* Utah Geol. and Mineral. Survey Guidebook, No. 3 (1948).
24. Isachsen, Y. William, *Ore Deposits of the Big Indian Wash-Lisbon Valley Area,* Utah Geol. and Mineral. Survey Guidebook No. 9: 95-105 (1954).
25. Gilkey, Arthur K., *Fracture Pattern of the Zuni Uplift,* US Atomic Energy Comm. RME-3050 (1953).
26. Dahl, Harry M. et al., *Progress Report on the Big Indian Wash-Lisbon Valley Area, Utah,* US Atomic Energy Comm. report in preparation.
27. Bucher, oral communication.
28. Steen, Charles A., and others, *Uranium Mining Operations of the Utex Exploration Company in the Big Indian District, San Juan County, Utah,* US Bur. Mines Info. Circ. 7669 (1953).
29. Gruner, John W., and others, *Annual Report*: US Atomic Energy Comm. RME-3094 (1954).
30. Laverty, R. A. and Gross, E. G., P/297 Paragenetic Studies, Vol. 6, Session 6B, these Proceedings.
31. Keller, W. K., oral communication.
32. Dix, George P., Jr., *The Uranium Deposits of Big Indian Wash, San Juan County, Utah,* Atomic Energy Comm. RME/4022 (1953).
33. McLelland, oral communication.
34. Hunt, Charles B., *Structural and Igneous Geology of the La Sal Mountains, Utah,* Science. 119: p. 447 (1954).
35. Shoemaker, E. M., *Distribution of Elements in Sandstone-type Uranium Deposits, Geological Investigations of Radioactive Deposits, Semi-Ann. Progress Report,* TEIR/490 (1954).
36. Keys, W. Scott, *The Delta Mine, San Rafael Swell, Emery County, Utah,* US Atomic Energy Comm. report in preparation (1955)
37. Klosterman, oral communication.
38. Hinckley, D., *Uranium Deposits of the Cameron Area,* US Atomic Energy Comm. report in preparation (1955).
39. Gregory, H. E., *Geology of the Navajo Country,* US Geol. Survey Prof. Paper 93 (1917).
40. Gruner, John W., Gardiner, Lynn and Smith, Deane K., *Mineral Associations in the Uranium Deposits of the Colorado Plateau and Adjacent Regions,* US Atomic Energy Comm. RME/3092 (1954).

Channels and Related Swales at the Base of the Shinarump Conglomerate, Monument Valley, Arizona

By Irving J. Witkind,* USA

Since 1948, the Colorado Plateau, in the southwestern part of the United States, has been the scene of intensive prospecting and exploration for uranium-vanadium deposits. This search has centered in Utah, Colorado, Arizona, and New Mexico. The principal host rocks are the Morrison formation and Entrada sandstone of Jurassic age and the Shinarump conglomerate and Chinle formation of Triassic age.

In Monument Valley, Apache and Navajo Counties, Arizona, (Fig. 1) uraniferous ore deposits are scattered irregularly through channel sediments at the base of the Shinarump conglomerate. Detailed drilling by the US Atomic Energy Commission as well as by private industry has demonstrated this relationship so repeatedly that most of the prospecting in that area has evolved into a search for, and exploration in, channels.

In time, all the channels exposed at the surface will be found. Of prime importance, then, is a method for the discovery of those channels concealed beneath younger strata. This paper suggests that channel sediments in the Shinarump are associated with swales in the Moenkopi and that this relationship offers possibilities for the discovery of concealed channels.

GENERAL GEOLOGY

In Monument Valley about 5000 feet of sedimentary strata are exposed. These range in age from the Cutler formation (Permian) to the Salt Wash sandstone member of the Morrison formation (Jurassic). Of these units, the Shinarump conglomerate of late Triassic age has received the most attention, primarily because it is the host rock for deposits of uranium-vanadium ore.

The Shinarump is a light-gray to buff massive crossbedded conglomeratic sandstone strongly cemented by calcite, iron oxide, and clay. Wherever completely exposed it forms cliffs about 50 feet high. In most localities overlying strata have been removed, and the eroded surface of the Shinarump is hummocky and irregular. Most of the mesas, buttes, and monuments are capped by this unit. Where dissection has not been as extensive, the Shinarump commonly forms a narrow bench above which rise the slopes and cliffs of younger formations. The conglomeratic facies of the unit consists predominantly of pebbles of quartzite, quartz, and chert in a matrix of medium- to coarse-grained quartz sandstone. Commonly, the coarser grained facies are near the base of the unit and finer grained sediments appear near the top. Locally the formation contains fossil wood and clay boulders of all sizes and shapes and in varying amounts. Throughout most of Monument Valley the unit is about 50 feet thick, although in places it thickens erratically and in other places pinches out. The Shinarump rests unconformably upon the red shaly siltstones of the Moenkopi formation (Early and Middle(?) Triassic). Locally, relief on the unconformity is slight and in most places does not exceed 5 feet. Swales and scour channels in the top of the Moenkopi are prominent exceptions and these accentuate the unconformity. Several channels are cut as deep as 75 feet into the underlying strata.

In general, the channels are symmetric and asymmetric scours cut in the top of the Moenkopi formation and filled with Shinarump conglomerate.[1,2,3] Commonly, the channels are exposed along mesa edges as U-shaped scours filled with conglomeratic sandstone and overlain by younger beds of the same material. In some places, however, the overlying beds of Shinarump have been removed, and here the channel sediments appear as ridges of gray conglomeratic sandstone bounded by the red shaly siltstones of the Moenkopi formation. The channels range in width from 15 feet to 2300 feet, and in the Utah part of Monument Valley are scoured as much as 150 feet into the underlying strata. Most of the channels, however, are about 350 feet wide and have been scoured about 75 feet into the underlying strata. Some channels do not exceed 2 miles in length; in gross aspect they resemble the bowl of a spoon. Other channels can be traced for many miles. Commonly, the channels are relatively straight; a few, however, seem to curve in a sinuous fashion. Most of the channels trend northwest, but seem to be distributed at random. The channel floors are irregular and are marked with shallow elongate depressions, many of which contain ore deposits. Channel sediments cannot be differentiated from the remainder of the Shinarump conglomerate, although more fossil wood seems to be in channel sediments than elsewhere.

* US Geological Survey.

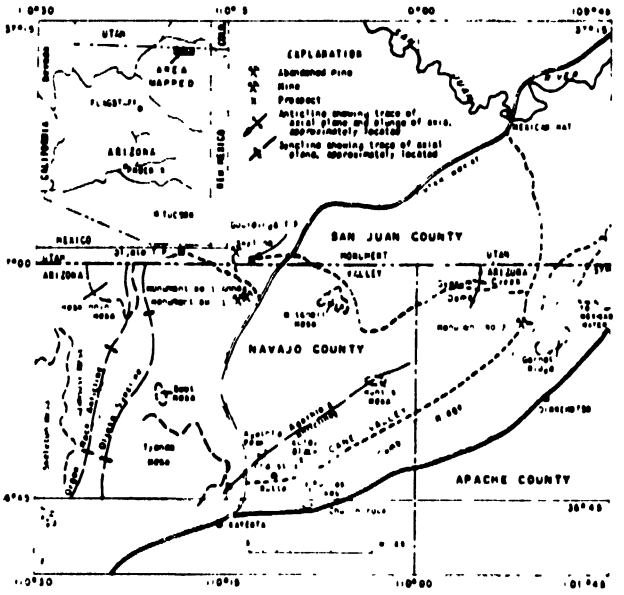


Figure 1. Index map of the Monument Valley area, Apache and Navajo Counties, Arizona and San Juan County, Utah

PRESENT TECHNIQUES FOR LOCATING CONCEALED CHANNELS

Two methods have been used to trace the channels beneath younger strata: the first and most common is drilling; the second relies on geophysical techniques, especially electrical resistivity and seismic refraction. Gravity and self-potential methods have not been successful. Some of the details on the geophysical methods used and results obtained are given in a paper by Wantlund and Casey.[4] Other work on geophysical methods has been done by Black, Jackson, and Hazelwood.[5]

Both drilling and geophysical techniques have been used, particularly where part of a channel was exposed. Thus, it was possible to begin at a known exposure and continue to trace it with a minimum of difficulty and expense. However, as known channels are traced and explored, a rapid and economical method of locating concealed channels becomes more desirable.

If one considers only the relatively small area of Monument Valley—about 700 square miles—the number of completely concealed channels is estimated to be in the hundreds. For example, of these 700 square miles, about 300 contain no Shinarump as a result of either erosion or nondeposition. Shinarump underlies, then, about 400 square miles. Of this area, only about 40 square miles of Shinarump are exposed; the remaining 360 square miles are either concealed beneath surficial deposits or buried, more or less deeply, beneath younger consolidated strata. An examination of these 40 square miles has disclosed about 60 channels. If the channels are distributed at random (an assumption that is yet to be proved), and if this 60:40 ratio persists, about 540 channels might be concealed in the remaining 360 square miles. The prize, therefore, is not small, and parts of the Shinarump, especially those that are concealed beneath relatively thin surficial deposits, seem worthy of investigation.

PROPOSED METHOD OF LOCATING CHANNELS; SWALES ASSOCIATED WITH CHANNELS

Experience in Monument Valley has indicated that the best method of contouring the base of the Shinarump over large areas is to prepare isopachous maps of the underlying strata. These maps are prepared most easily by photogeologic methods. The strata constituting the isopachous interval consist of dark reddish-brown siltstone and sandstone beds which are as much as 350 feet thick in the western part of the area and which thin to about 80 feet in the eastern part. Stratigraphically, they consist of the Moenkopi formation at the top and the Hoskinnini tongue of the Cutler formation at the base. The basal contact of the Hoskinnini tongue is used as a datum, rather than the Moenkopi-Hoskinnini contact, because it is more easily recognized in the field and on aerial photographs. In the field, this basal contact is an unconformity, remarkably free of relief, which separates the slope-forming reddish-brown even-bedded siltstones and sandstones of the Moenkopi and Hoskinnini from the cliff-forming light-tan massive crossbedded De Chelly sandstone member of the Cutler formation. The Hoskinnini, however, makes up only 15 to 40 feet of these strata. The remainder consists of the Moenkopi formation which, in this area, closely resembles the Hoskinnini in lithology and color.

As the unconformity between the De Chelly and the Hoskinnini is featureless, except for the regional eastward thinning of the beds in the interval contoured, whatever local variations appear on the isopachous map are the result of irregularities in the top of the Moenkopi. These local variations represent postdepositional erosion rather than any vagaries in Moenkopi deposition. Over a large area, the top of the Moenkopi is marked by elongate swales of such low relief and great width that they are not readily perceptible from the ground. In general, the swales range from 1 to 3 miles in width and have a relief of about 40 feet.

In a few localities in Monument Valley, isopachous maps of the Moenkopi and associated strata illustrate the association of these elongate broad shallow swales with some channels (Fig. 2). Specifically, the channel seems to be in the center of the swale and may reflect the swale axis. It is suspected, though not proved, that all channels are associated with swales.

In Apache County, northeastern Arizona, the Monument No. 2 channel and its accompanying swale afford a good example of such a relationship (Fig. 2). In this locality the Shinarump crops out in a series of jagged serrated hogbacks. In one of these the channel is exposed. This channel contains rich deposits of uranium and vanadium ore. The channel is about 1¾ miles long, as much as 700 feet wide in its central part, and is cut about 50 feet into the

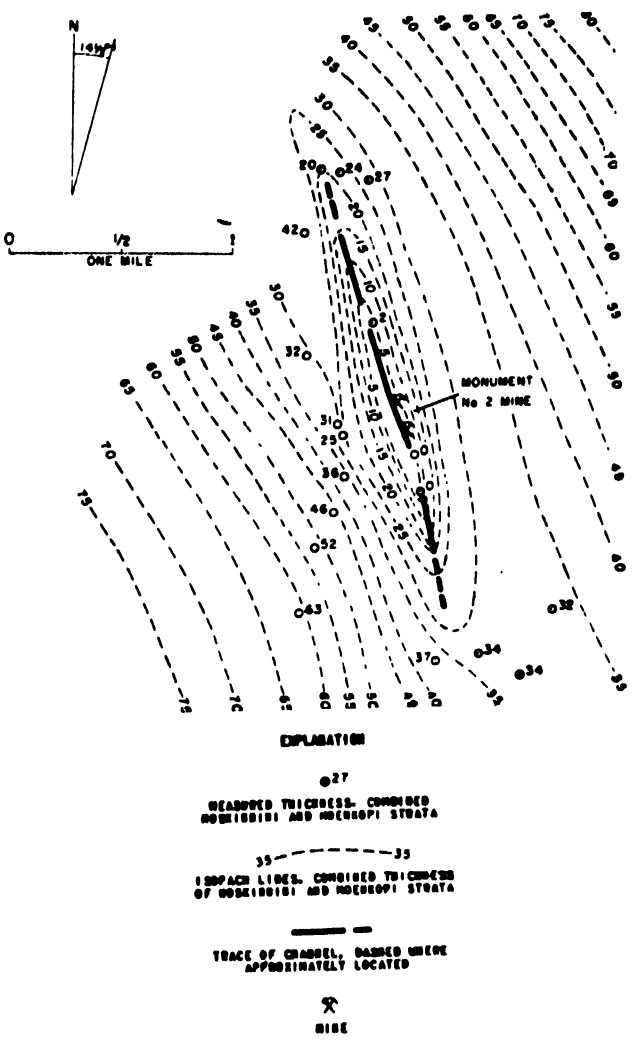


Figure 2. Isopachous map showing channel-swale relationship in the Monument No. 2 area, Apache County, Arizona

underlying strata. It trends about N 18° W. An isopachous map of Moenkopi and Hoskinnini strata in the general area suggests that the channel lies along the axis of an elongate swale that trends parallel to the channel, is about 3 miles wide, and can be traced 3 to 4 miles. Relief in the swale is about 50 feet. In this general area the combined thickness of the Moenkopi and the Hoskinnini tongue of the Cutler formation is about 80 feet. The west edge of the swale is about 1½ miles west of the channel. From that point eastward across the swale, the combined thickness of the units decreases gradually to about 30 feet at the edge of the channel. Here, the channel has been scoured about 50 feet into the underlying strata; thus about 30 feet of Moenkopi and Hoskinnini have been removed as well as an additional 20 feet of underlying sediments. East of the channel the strata show an even increase in thickness until the regional figure of 80 feet is once again attained about 1½ miles to the east.

Of prime importance is the knowledge that the swales can be traced beyond the limits of the channels. The swale accompanying the Monument No. 2 channel cannot be traced to the northwest due to lack of exposures; however, it can be traced to the southeast. Similar conditons exist elsewhere. Tracing swales beneath cover either by geophysical methods or drilling may permit the location of concealed channels.

The extent and position of swales can best be noted on isopachous maps, which are compiled most easily by photogeologic methods. Field measurements, although more accurate, are difficult and time-consuming. Isopachous maps of different parts of Monument Valley, Arizona, have been prepared by both methods. The coincident relations of channels and swale axes, as indicated by these studies, suggest that swale areas outlined on isopachous maps are favorable areas for exploration in the search for concealed channels.

CONCLUSIONS

As yet, a consistent association of all channels with swales has not been established. Although the channels seem to follow the axes of the swales in the areas studied, there may be exceptions. Moreover, the habits of channels are not completely known, adding to the perplexities and difficulties. In some parts of Monument Valley several channels are close together. In these areas the accompanying swales do not present as clear-cut a relationship as that shown by one channel and one swale. Despite these difficulties and uncertainties, the relationship of channels and swales may make possible the location of at least some of the channels that do not crop out at the surface. A basic need is the compilation of adequate isopachous maps of the area to be studied. This can be done most easily by photogeologic techniques. The swales thus delineated probably constitute favorable ground to be explored for concealed channels. Either geophysical methods or drilling programs might then be used to determine whether channels are in the swales.

REFERENCES

1. Bain, G. W., *Uranium Deposits in Southwestern Colorado Plateau,* US Atomic Energy Commission RMO-982, Technical Information Service, Oak Ridge, Tennessee (1952).
2. Witkind, I. J., *Monument Valley, Arizona Project* in Staff (US Geological Survey) *Search for and Geology of Radioactive Deposits, Semiannual Report,* US Atomic Energy Commission TEI-330, Technical Information Service, Oak Ridge, Tennessee, 34-36 (1953).
3. Witkind, I. J., *Localization of Uranium Minerals in Channel Sediments at the Base of the Shinarump Conglomerate, Monument Valley, Arizona,* Abstract, Economic Geology 49: 804-805 (1954); Abstract, Geological Society of America Bulletin 65: 1327 (1954).
4. Wantlund, Dart and Casey, R. D., *Field Tests for the US Atomic Energy Commission on the Use of the Seismic Geophysical Method for Tracing "Buried Channels" in the Monument Valley Area, Arizona,* US Bureau of Reclamation, Engineering Geology Branch, Geology Report 6-123 (1952).
5. Black, R. A., Jackson, W. H., Hazelwood, R. M., written communication.

Deep Drilling in the Temple Mountain Collapse, San Rafael Swell, Utah

By W. Scott Keys,* USA

Temple Mountain is located on the southeastern flank of the San Rafael Swell, Emery County, Utah. Of interest is the Temple Mountain collapse, a structural depression, caused by removal of material from below (Figs. 1 and 2). The normal rock color has been greatly bleached, and this collapse feature is unique on the Colorado Plateau for its wide stratigraphic distribution of uranium ore. This paper summarizes the results of drilling the collapse area.

GEOLOGY

Structure

The San Rafael Swell, one of several similar structures on the Plateau, is an asymmetric anticline with a north-south length of 100 miles and a width up to 45 miles. Temple Mountain lies 7 miles south of the axis of the San Rafael Swell (Fig. 1). The average trend of this axis is N 20° E, except north of Temple Mountain, where it swings to N 70° E. The swing of the axis may denote an area of structural weakness to which is related the several collapses in the vicinity of Temple Mountain.

The eastern flank of the Swell is characterized by steep dips up to 85° east, but the beds flatten within a short distance to the north and south. Near Temple Mountain the regional dip ranges from 4° to 9° southeast. Field measurement has established that Temple Mountain and the collapse lie in a synclinal warp on the flank of the anticline.

Faults in the southern half of the San Rafael Swell strike generally east, are nearly vertical, and have a minor displacement measured in several tens of feet. Major joints have similar strike and dip. The Temple collapse and collapse No. 5 are approximately aligned along this trend (Fig. 1), and some relationship between these dominant fractures and the 7 known collapses within a radius of 5 miles of Temple Mountain is postulated.

Recent discovery of a large collapse on the western flank of the Swell extends the collapse province 17 miles to the west of Temple Mountain.

The relationship between the collapse structures and the ore-producing areas in the Moss Back sandstone has not been proved. Ore found in other horizons, however, is clearly related to the collapse structure.

* US Atomic Energy Commission.

Stratigraphy

Permian Rocks

Coconino sandstone: All drill holes on the present project have been completed in the Coconino sandstone, an eolian deposit over 700 feet thick. This formation is a cross-stratified, gray fine- to medium-grained quartz sandstone cemented with calcite. In the Temple Mountain area the upper 30 feet are usually saturated with petroleum residues, and as much as 45 feet of this petroliferous Coconino has been cored in the collapse. Uranium mineralization is present in several drill holes at the top of the Coconino. Significant, also, is the fact that the Coconino sandstone appears to be undisturbed by the collapse.

Kaibab limestone: The Kaibab limestone ordinarily overlies the Coconino sandstone, but it is not present in any of the holes drilled in the Temple Mountain collapse. A 30-foot bed of this massive limestone crops out less than one mile north of Temple Mountain, and a 90-foot section occurs 13 miles southwest of the collapse. Locally, however, the Kaibab was completely removed prior to deposition of the Moenkopi formation. The Kaibab normally consists of a dark gray sandy limestone with abundant chert geodes and nodules in the upper part. Within the collapse, however, these chert concretions are all that remain of the Kaibab and, although similar material may form a basal conglomerate in the Moenkopi, this bed will herein be termed the Kaibab "conglomerate". Most of the ore grade uranium mineralization has been encountered in this unit.

Triassic Rocks

Moenkopi formation: The Moenkopi formation is 556 feet thick to the north of Temple Mountain, somewhat less than average thickness for the Swell. It is composed of red to brown shaly siltstone and fine-grained sandstone in lenticular beds from a fraction of an inch to more than ten feet thick. Throughout the swell the Moenkopi contains a marine unit, the Sinbad limestone member, which lies 90 feet above the base of the formation. At Temple Mountain the Sinbad is 30 feet thick.

Within the collapse, the Sinbad limestone is missing and much of the rest of the Moenkopi is structurally disturbed and bleached. Some uranium mineralization is present in rock thought to be Moenkopi.

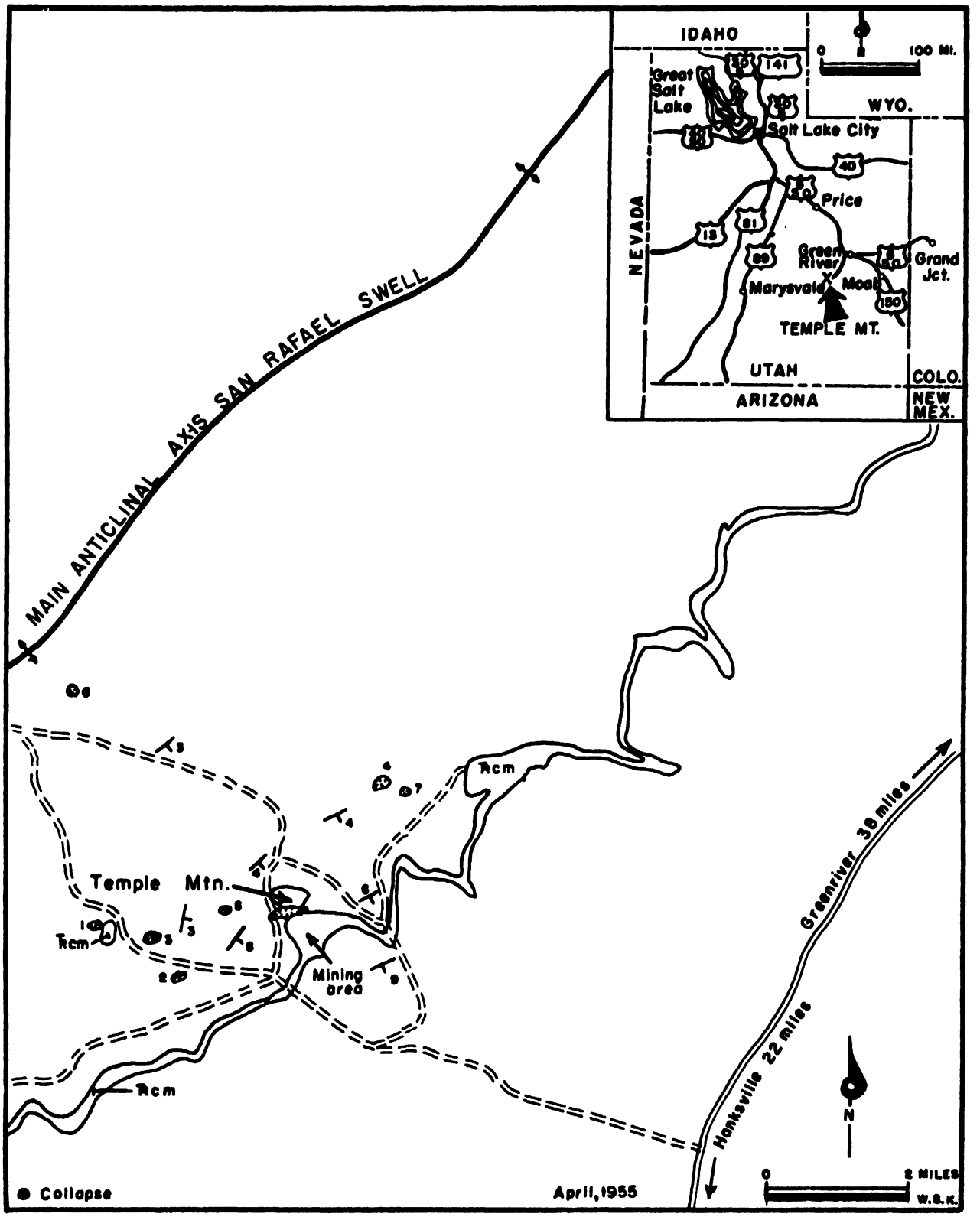


Figure 1. Location of the Temple Mountain area, Emery County, Utah

Chinle formation: The Chinle formation is of fluviatile origin and consists primarily of lenticular beds of sandstone and conglomerate separated by mudstone.

The lower Chinle is 25 to 40 feet of gray to maroon variegated siltstones which appear to rest disconformably on the Moenkopi.

The middle Chinle Moss Back member consists of 50 to 125 feet of gray to brown, poorly sorted, limy sandstone with some conglomerate. It is the most important host rock at Temple Mountain and throughout the San Rafael Swell. The uranium is in a hard asphalt which impregnates the clastics to form irregular-shaped bodies up to 15 feet thick.

The Upper Chinle thickness averages 200 feet in this area. The lithology of this portion is extremely variable and is characterized by lenticular beds of sandstone and conglomerate in a variegated mudstone. Such uranium mineralization is present in this unit near the collapse.

The Chinle has undergone considerable structural disturbance and bleaching within the collapse zone, and it is only through recognition of the coarser clastic fragments that it may be identified.

Wingate sandstone: The Wingate sandstone caps both the north and south peaks of Temple Mountain with vertical cliffs estimated to be 360 feet high. It is the youngest rock unit definitely known to be affected by the collapse, but it is possible that some of the Kayenta formation (Jurassic) crops out on the inaccessible top of north Temple Mountain. The Wingate is a light brown to buff cross-stratified fine-grained quartz sandstone throughout the San Rafael Swell except at Temple Mountain where it is white on weathered surfaces and gray, due to the presence of petroleum residues, on fresh surfaces. In addition, extensive areas of the Wingate have been dolomitized, and uranium mineralization is present in the lower two-thirds.

SURFACE FEATURES OF THE TEMPLE MOUNTAIN COLLAPSE

Structure

The collapse, or collapses, located on Temple Mountain are within an elliptical area 1500 to 2000 feet long and 500 feet wide, within which Wingate, Chinle and Moenkopi sediments have settled into a structural depression and are characterized by brecciation, altered blocks and plastic flow. Around the edge of the collapse, normal and altered sediments dip 25° toward the disturbed core.

On the surface, large blocks composed mostly of Wingate sandstone have slumped into the collapse with little brecciation. On the portion of the structure locally called the "tongue". (Fig. 3), sediments apparently of Chinle derivation subsided in large blocks, but intense alteration and brecciation makes identification difficult. Because of weathering, brecciation is not readily recognized.

No faults have been traced from the normal sedimentary rocks into the Temple Mountain collapse.

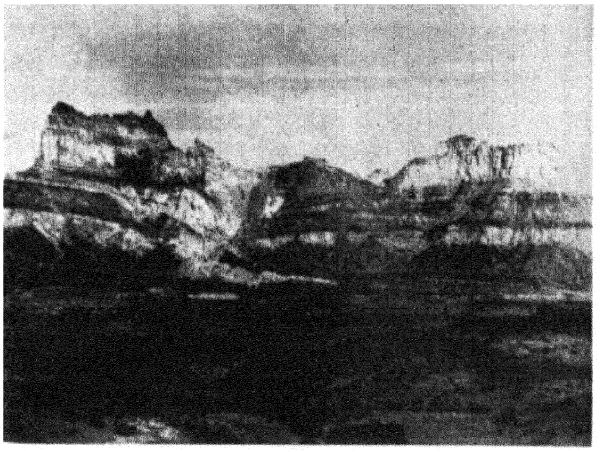


Figure 2. West side of Temple Mountain. Note dip of bed toward collapse where ferrugination and bleaching are prominent

Several faults found outside of the collapse strike directly toward it but lose all vertical displacement before reaching the subsidence. Several of these faults form a graben which may be an extension of the collapse to the west of Temple Mountain. Within the area of structural disturbance, faulting is due to adjustment between slumped blocks.

Alteration

Bleaching of red beds is one of the most obvious chemical effects on the surface and is probably caused by the reduction of iron perhaps related to the introduction of asphaltic material. Bleaching centers on the collapse core and decreases in intensity toward the margin of the synclinal depression. Bleaching also extends further from the collapse laterally in the stratigraphically higher rock units.

The base of the Wingate is extensively dolomitized in and near the collapse zone. Dolomite lenses up to 80 feet thick on both north and south Temple Mountain undoubtedly represent erosional remnants of more extensive dolomitization. Dolomitization appears to have originated at numerous centers through the sandstone and expanded as spherical concretions.[1] Where these spherules coalesce, dolomitization is most complete. Vugs lined with rhombohedral dolomite crystals are common in this stage, and the texture of the original sandstone may be obliterated.

Ferrugination is common in the Chinle just below the base of the Wingate. Siderite, hematite and goethite form lenticular masses which have partially or wholly replaced Chinle sandstone.

Mineralization

Although all of the present and most of the past production from Temple Mountain is from the Moss Back sandstone, some uranium-vanadium mineralization of ore grade is also found in probable Chinle sediments on the end of the "tongue", in the upper Chinle in place, and in the lower two-thirds of the Wingate. Nearly all unoxidized deposits are found in hard brittle asphaltite similar to that found in the Moss Back.[2] The asphaltite occurs as small pellets,

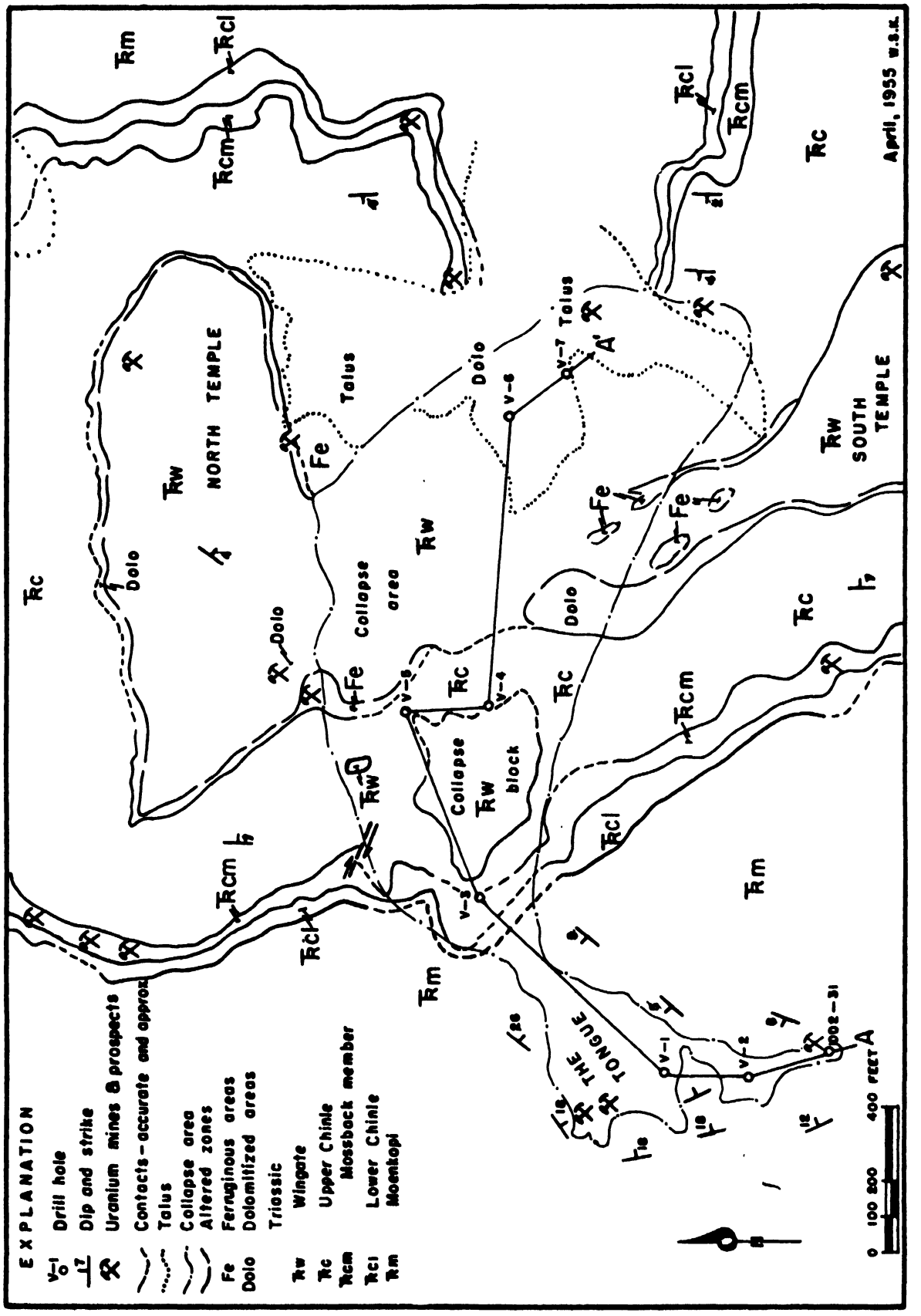


Figure 3. Geologic map of Temple Mountain collapse area, Emery County, Utah

as ovoid masses up to several feet long, as concentrations along fractures, and as massive bedded replacements of sandstone up to several feet thick. The thickest and most extensive uranium mineralization in the vicinity of the collapse is found in the Wingate sandstone. In the collapse, average vanadium assays are higher and arsenic minerals more abundant than in the normal Moss Back. Pyrite and native arsenic nodules along with traces of sphalerite are found in the Fumerole mine on the end of the "tongue" (Fig. 3).

DESCRIPTION OF THE CORE

Structure

At least 50 per cent of the core from holes V-1 through V-7 (Fig. 3) is characterized by breccia, flow structures, fractures, alteration and pyritization. In those portions of the core that show normal sedimentary features, bedding planes are commonly inclined up to 80° from horizontal.

Sandstone "dikes", several feet long and an inch wide, are prevalent in the core (Fig. 4a).

Figure 4a. Sandstone dikes in siltstone. Center core shows fragments of mudstone in sandstone with black pebble of Chinle origin

These dikes, which normally occur at a steep angle to the bedding planes usually consist of medium-grained sandstone with abundant interstitial asphalt; it is this rock type which carries some of the uranium mineralization. The dikes extend into areas where rocks appear to be undisturbed. Some bifurcate or swell and contain angular inclusions of the surrounding matrix. Alignment of clay chips within a few dikes suggests flow.

Contortion of bedding planes is common and best observed where asphalt selectively impregnates sandstone beds (Fig. 4b). Small bent clay chips are interspersed in sandstone units, and they usually show parallel orientation, as if by flow.

In sediments that did not yield by flowing, fracturing is common, with displacements usually less than one inch. Successive ages of fracturing demonstrate the varied and repeated stresses involved in subsidence. Many small faults have been invaded by sandstone dikes and gypsum and pyrite veins.

Breccias are prevalent, consisting of poorly sorted, sub-angular to angular fragments of asphaltic sandstone in a mudstone matrix, or contorted mudstone fragments in a sandstone matrix. Stream-worn quartz pebbles, undoubtedly derived from the Chinle, are also observed in breccia zones nearly 300 feet below the base of the Chinle. Regardless of this brecciation, most of the rock is well cemented by dolomite, clay or asphalt, (Fig. 4c).

Alteration

Most non-asphaltic portions of the core are altered from the typical red color of Chinle and Moenkopi sediments to green or white, due to reduction of included iron and in places to the formation of kaolinite and illite. Bleaching is obscured in places by the presence of asphalt as a thin film coating grains. The formation of clay represents one of the early stages in the alteration of the sediments. Kaolinite and illite (or sericite?) are present as veinlets concentrated along contacts between frag-

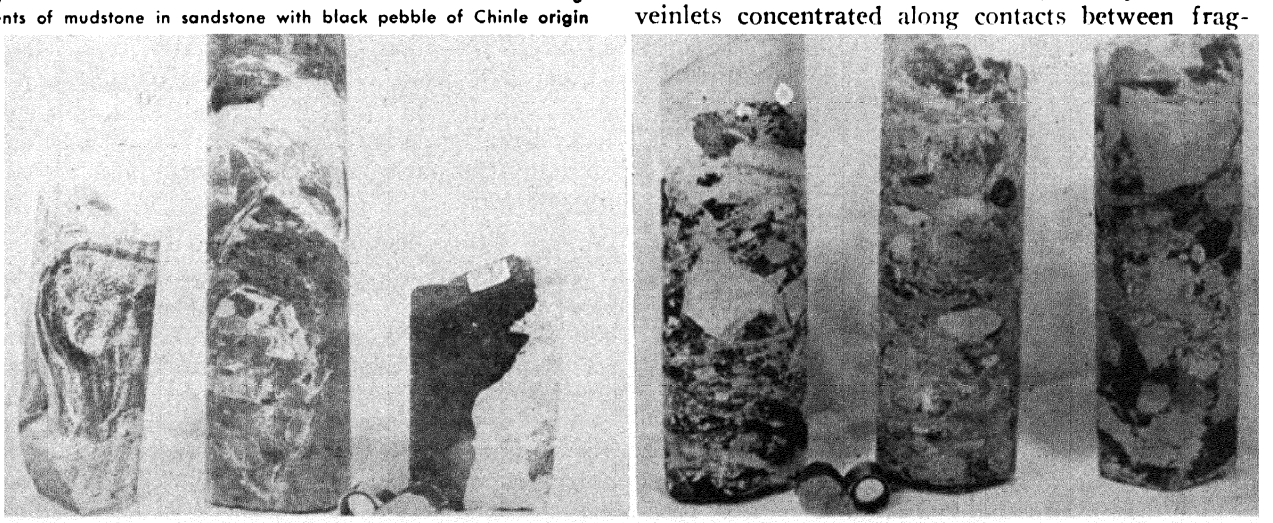


Figure 4b. (left). Asphalt impregnated sandstone and siltstone. Partial asphalt saturation has emphasized fractures in center core and possible flow structures in left core. Figure 4c. (right). Typical breccia fabric with fragments cemented by asphaltic sandstone. Pebbles in center core are of Chinle derivation

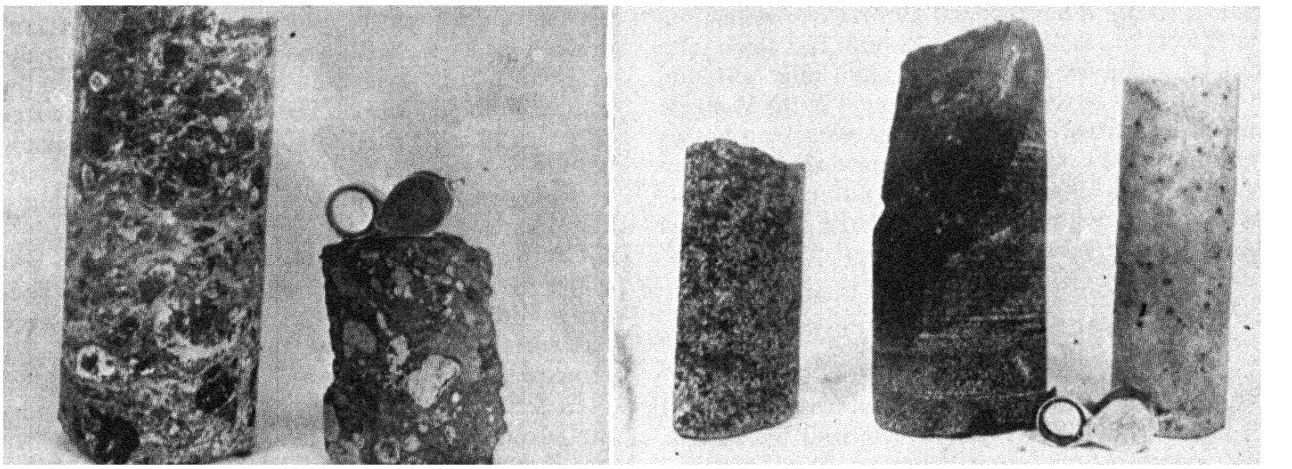


Figure 4d. (left). Kaibab "conglomerate" composed of chert geodes and nodules cemented by asphaltic sandstone. The larger specimen is unmineralized asphalt while the smaller specimen is cemented by hard asphaltite-bearing pitchblende, pyrite, galena and arsenopyrite. Figure 4e. (right) Conconino sandstone showing partial and complete asphalt saturation. Right core contains concentrations of galena which have partially replaced quartz grains

ments, and as veinlets replacing some original interstitial kaolinite. Secondary kaolinite also rims some ore-bearing nodules in the Kaibab "conglomerate" (Fig. 4d).

Silicification on both a microscopic and megascopic scale is observed in the core. It has resulted in the formation of brown chalcedonic quartz veinlets up to six inches wide.

Dolomite and iron in the form of siderite and limonite were introduced after silicification and before the emplacement of sulphides and uranium-bearing hydrocarbons. Although a large part of the original cement of the coarser-grained sediments was calcite, it is mostly absent from the core, and dolomite is prevalent. Dolomite has slightly corroded some of the quartz grains. Nodular development of dolomite, so common at the surface, is also observed in the core from the Coconino.

Mineralization

Pyrite, galena and arsenopyrite, along with the uranium-bearing hydrocarbon, were introduced last. Pyrite is the most common mineral in this group and in places comprises as much as 25 per cent of the core. It occurs most commonly as disseminated euhedra and fine-grained masses. It replaces mudstone, quartz grains and quartz cement in sandstone and occurs as veinlets along fractures. Pyrite is scattered throughout the disturbed zone and shows no spatial relationship to the uranium.

Galena occurs as fine disseminations in the breccia, as subhedral fragments in the ore zones, and as small masses partially replacing quartz grains and dolomite in the upper Coconino. In hole V-1 abundant galena occurs below the asphalt zone in otherwise normal Coconino (Fig. 4e). It is also present with pyrite in uranium-bearing hydrocarbon nodules, and shows a slight spatial relationship to the uranium.

Uranium-vanadium mineralization is sporadically distributed in the cores, especially those drilled on the "tongue"; however, the highest concentrations are in and near the Kaibab. Four feet of uranium ore were cored in this conglomerate in hold V-1 (Fig. 3); two thinner ore zones are immediately below the conglomerate in hole V-5. Thin stringers of ore grade material were cored from 30 to 60 feet above the Kaibab "conglomerate" in holes V-6 and V-7. Uranium mineralization in hole 2-31 was encountered at considerable distance above the Kaibab horizon. Uranium-vanadium ratio in deposits of the collapse range from 1 : 1 to 1 : 5 and are usually higher than the average ratio for the Moss Back mining area southeast of Temple Mountain.

The highest grade material consists of hard asphaltic nodules and pellets in asphaltic sandstone. Although all of the aforementioned minerals occur with the uranium, realgar is probably the best guide to ore, as its concentration increases notably above the ore zones. X-ray diffraction of asphaltite from hole V-1 has disclosed the presence of both pitchblende and arsenopyrite. Microscopic work on the core indicates that both the pyrite and the galena were deposited prior to the asphalt, but age relationships of the pitchblende, arsenopyrite and asphalt are not clear.

Subsurface Structure

From drilling information it seems certain that the zone of brecciation and flow does not extend into the Coconino sandstone (Fig. 5). The top of the Coconino, which is asphaltic in every hole, shows no disturbance.

Varying directions of dip of slump blocks on the surface suggest that there are two and possibly three separate collapses on Temple Mountain; however, drilling leaves little doubt that the structure is one large collapse at depth with a complex surface expression. Large blocks, such as one drilled in V-5,

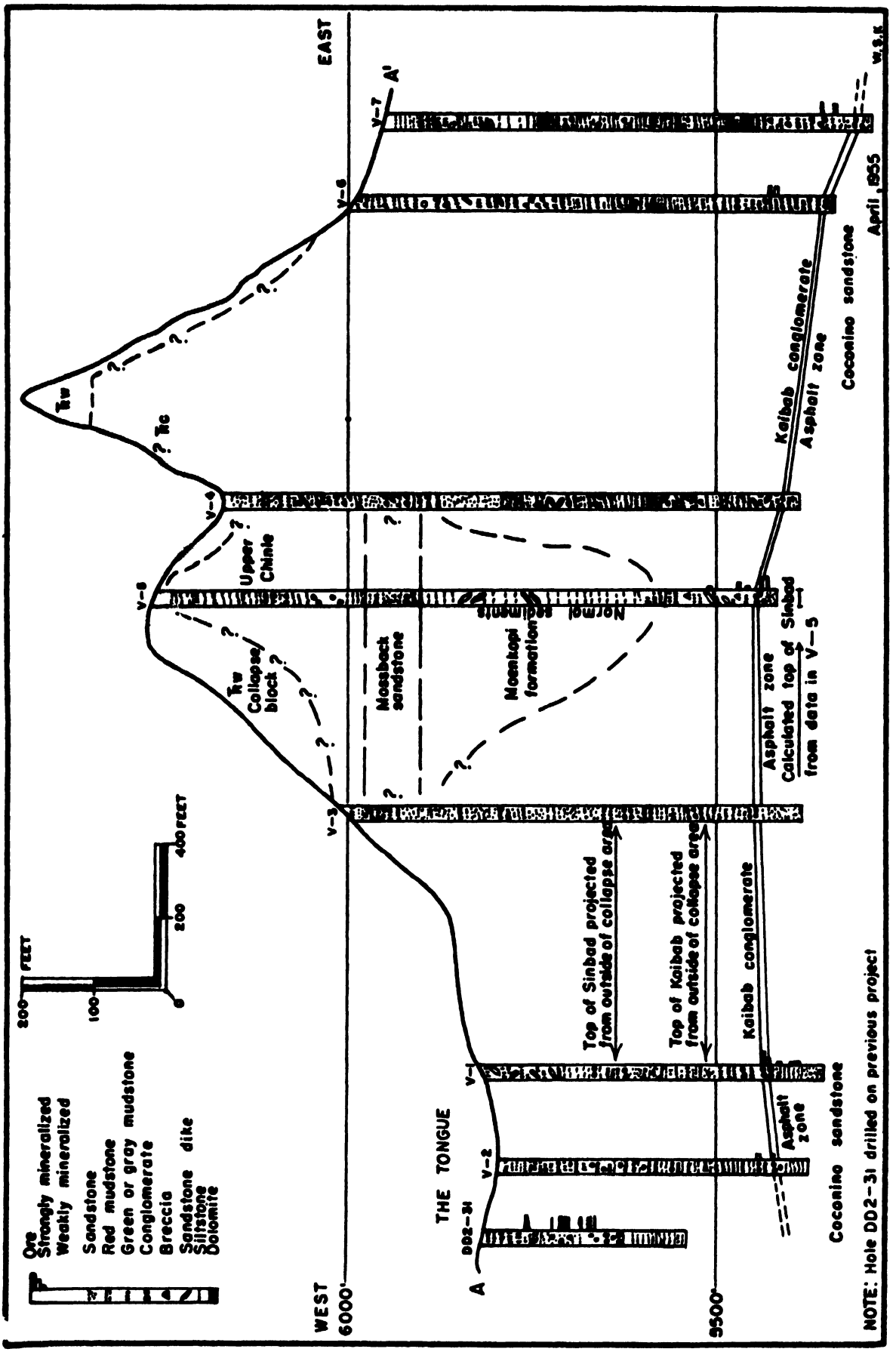


Figure 5. Cross section A-A' through diamond drill holes, Temple Mountain collapse

appear to be in normal position, but subsurface information proves that material has been removed from below and the sedimentary mass has slumped into this space.

Using the regional strike and dip, tops of both the Kaibab and Sinbad limestones have been projected into the collapse area to indicate the approximate vertical relief of the syncline in which the collapse has occurred (Fig. 5).

COLLAPSE MECHANISM AND RELATIONSHIP TO URANIUM DISTRIBUTION

Absence of the Kaibab and Sinbad limestones supports the theory that the collapse was caused by solution of carbonate rocks. The aggregate thickness of the two limestone units is probably between 70 and 150 feet, based on measurements throughout the Swell. There are places in the Swell where the Kaibab was removed by pre-Triassic erosion; however, as the Sinbad is present everywhere else in the Swell, and the Kaibab crops out less than one mile to the north, it is assumed that under the collapse both of these limestones were probably removed at the same time. Nevertheless, the removal of 70 to 150 feet of limestone does not appear to furnish enough space for the approximately 300 feet of subsidence.

In hole V-5, where 700 feet of normal sediments were cored before entering altered rocks, at least 90 feet of lower Moenkopi siltstones and mudstones are missing in addition to the limestone. The numerous flow structures observed in the core from the lower zones indicate that this clastic material may have been unconsolidated and flowed under pressure to another part of the collapse. Such flow could have been facilitated by solution of cement and lubrication by asphalt. If the limestones were removed for a considerable distance outward from the collapse area, surface disturbances indicate the unconsolidated material may have been forced upward when large blocks began to slump into the solution cavern.

Although the formation of the collapse is quite similar to the formation of a sink hole, the degree of alteration and the assemblage of associated minerals disproves the theory that normal circulating ground water was responsible. However, even though several minerals in the alteration and mineralization sequence are indicative of a hypogene origin, considerably more laboratory work will be necessary to establish the genesis of the solutions.

Uranium-vanadium ore in the collapse bears a close spatial relationship to that structure and this relationship may also be true for the Moss Back mining area. It is plausible that brecciation which accompanied subsidence provided a permeable channelway for the mineralizing solutions. As the paragenetic sequence does not indicate two separate periods of solution activity, a tenable hypothesis is that the solution activity, subsidence, and mineralization were caused by waters derived from a single source.

REFERENCES

1. Kerr, P. F., P/502, *Rock Alteration Criteria,* Vol. 6, Session 7B, these Proceedings.
2. Isachsen, Y. W., P/39, *Shinarump and Chinle Formations,* Vol. 6, Session 6B, these Proceedings.

Uranium Deposits in the White Canyon Area, San Juan County, Utah

By A. F. Trites, Jr., T. L. Finnell and R. E. Thaden,* USA

The White Canyon area, near the center of the Colorado Plateau, is between the Colorado and San Juan Rivers in southeastern Utah (latitude 37°40'N, longitude 110°15'W). The area is in the west-central part of San Juan County, about 60 miles by road west of Blanding, Utah. The White Canyon project is a part of a regional mapping program on the Colorado Plateau. Approximately 560 square miles have been mapped in the White Canyon area at a scale of 1:48,000.

GENERAL GEOLOGY

Rocks in the White Canyon area range in age from Pennsylvanian to Jurassic and comprise a sedimentary section more than 4,000 feet thick. The nearest exposed igneous rocks are in the Henry Mountains about 12 miles west and in the Abajo Mountains about 25 miles northeast of the boundaries of the area. A generalized stratigraphic section of the rock formations is presented in Table I.

The area is on the west flank of the Monument upwarp, and beds have a regional dip of 2° to 3° southwest and strike generally northwest. Small local flexures occur in parts of the area.

Many normal faults cut the Moenkopi and Cutler formations in the northwestern part of the White Canyon area and cut rocks of the Glen Canyon group in the southwestern part. Most of the faults in the northwestern part strike N 65° to 75° W and their maximum vertical stratigraphic displacement is about 100 feet. Many of the surfaces of the faults in the northwestern part of the area have been coated by limonite or calcite. The red sandstones and siltstones have been bleached as much as 3 feet on either side of the faults. The faults in the southwestern part of the area strike N 30° E to N 30° W and the displacement along these faults is as much as 250 feet. Joints are abundant throughout the White Canyon area, and the major trends are N 65° to 80° W, N 70° E to due E, N 30° to 40° E, and N 10° W to N 10° E.

URANIUM DEPOSITS

The uranium deposits in the White Canyon area occur in channels that have been cut into beds of the Moenkopi formation and filled by sandstone, siltstone, claystone, and conglomerate of the Shinarump conglomerate. Most of these channels are within a broad outcrop belt of Shinarump conglomerate ranging from 8 to 15 miles wide. This belt extends across the area, from beyond Deer Flat on the east to beyond the Colorado River on the west, a distance of more than 20 miles. The northern edge, or pinchout, of the belt of Shinarump is, in general, irregular with many lenses of Shinarump extending outward from the main mass. A few isolated patches of Shinarump conglomerate occur in the area north of the main belt. The southeast edge of the belt of Shinarump conglomerate (near head of Red Canyon, Fig 1) is more regular and has a general trend of N 80° E. The extent of the Shinarump conglomerate is not known southwest of Red Canyon, because it is deeply buried beneath younger rocks. Most of the Shinarump conglomerate within the belt ranges from 8 to 80 feet in thickness, although locally it is absent.

Sixty-four channels have been mapped in the White Canyon area (Fig. 1); 16 of these channels are known to contain at least one uranium deposit with a minimum grade of 0.10 per cent U_3O_8. Eight additional channels—possibly more—contain low grade uraniferous material. The trend of channels in the area is shown in Fig. 2. Channels range from 30 to 650 feet in width and from 4 to 50 feet in depth. Uranium deposits do not show a preference for channels of a particular size or shape, but rather seem to have selected a lithologic setting. All the known high-grade deposits are in Shinarump-filled channels that are within 3000 to 15,000 feet of the pinchouts of the Shinarump.

The emplacement of the uranium deposits is believed to have been controlled principally by the lithology of the sediments filling the channels. Channel segments filled with a high percentage of sandstone and containing few, if any, mudstone or siltstone beds appear to be unfavorable for deposits; channel segments with too high a percentage of mudstone or siltstone beds are equally unfavorable. Within favorable channels a sandstone lens immediately overlying a bed of mudstone or siltstone, and containing a high percentage of clay cement and pebbles, appears to be the most highly mineralized bed in many of the mines in the area. Trashy carbonaceous material is present in most of the ore-bearing beds and may have been important in de-

* US Geological Survey.

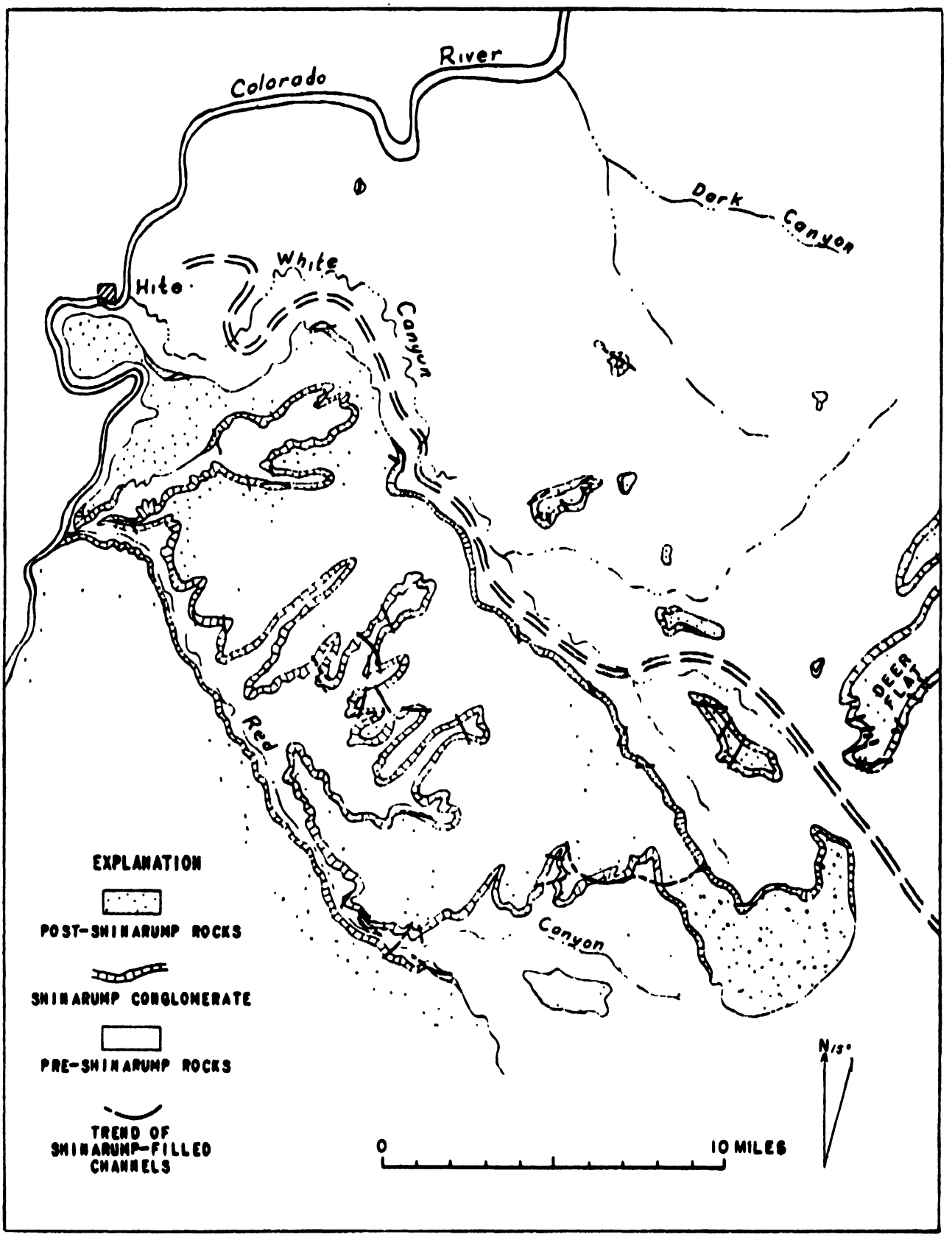


Figure 1. Geologic map of White Canyon area, San Juan County, Utah

Table I. Generalized Stratigraphic Section, White Canyon Area, San Juan County, Utah

System or series	Group	Formation	Member or Tongue	Thickness (feet)	Description
Middle and Upper Jurassic	San Rafael group undifferentiated			800+	Red calcareous shale and sandstone.
Jurassic and Jurassic(?)	Glen Canyon	Navajo sandstone		600+	Cream-yellow massive crossbedded sandstone
Jurassic(?)		Kayenta		200±	Dark-red thin-bedded sandstone.
Upper Triassic		Wingate sandstone		300±	Reddish-brown massive crossbedded sandstone.
		Chinle	upper member	100±	Reddish-brown thin-bedded calcareous sandstone, siltstone and mudstone.
			middle member	250-425	Variegated calcareous and bentonitic mudstone and siltstone.
			sandstone member	0-100	Gray sandstone and brown conglomerate.
			lower member	150-245	Gray to variegated clays and gray to brown lenticular sandstone and conglomerate.
		Shinarump conglomerate		0-75	Yellow to gray sandstone; siltstone, claystone, and conglomerate.
Lower and Middle(?) Triassic		Moenkopi		175-350	Dark-brown to grayish-red thin-bedded fissile siltstone and very fine-grained ripple-marked sandstone, brown to yellow shale, and white to pink fine-grained sandstones with local clay balls; mica abundant.
Permian		Cutler	White Rim sandstone member	0-20	Cream-yellow fine-grained sandstone.
			Hoskinnini tongue	80-100	Reddish-brown massive-bedded siltstone to fine-grained sandstone. Contains interbedded cream-yellow limestone-pebble conglomerate in western part of area.
			Organ Rock tongue	100-300	Reddish-brown micaceous siltstone and very fine-grained sandstone.
			Cedar Mesa sandstone member	1,000±	Cream-yellow cross-bedded sandstone with local red shale near the top.
Pennsylvanian and Permian(?)		Rico		575±	Interbedded gray, red, and purple sandstone, siltstone, shale, and limestone.
Pennsylvanian		Hermosa		400-1,000	Gray cherty limestone with gray, buff, and red calcareous sandstone and shale.

a) In part from Gregory (1), and Benson, and others (2).

Table II. Secondary Uranium Minerals from Deposits in the White Canyon Area, San Juan County, Utah

Type	*Mineral*	*Composition*	*Major occurrences (mines)*
Hydrous oxide	Becquerelite	$2UO_3 \cdot 3H_2O$	Posey
Silicates	Cuprosklodowskite	$Cu(UO_2)_2Si_2O_7 \cdot 6H_2O$	Posey
	Uranophane	$Ca(UO_2)_2Si_2O_7 \cdot 6H_2O$	North Point
Sulfates	Zippeite	$(UO_2)_2(SO_4)(OH)_2 \cdot 4H_2O$	Happy Jack
	Johannite	$Cu(UO_2)(SO_4)_2(OH_2 \cdot 6H_2O$	Happy Jack
	Uranopilite	$(UO_2)_6(SO_4)(OH)_{10} \cdot 12H_2O$	Happy Jack
Phosphates	Phosphuranylite	$Ca_3(UO_2)_5(PO_4)_4(CH)_4 \cdot 2H_2O(?)$	North Point, Posey
	Torbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 12H_2O$	North Point
Arsenate	Metazeunerite	$Cu(UO_2)_2(AsO_4)_2 \cdot 8H_2O$	Markey, Jomac
Carbonates	Bayleyite	$Mg_2(UO_2)(CO_3)_3 \cdot 18H_2O$	Hideout
	Schroeckingerite	$NaCa_3(UO_2)(CO_3)_3(SO_4)F \cdot 10H_2O$	Hideout

positing the uranium minerals. Trashy material and finer grained material appear to be concentrated at branches and bends along the channels.

Uraninite occurs in most of the deposits that have been mined behind the oxidized rim outcrops. Secondary uranium minerals are abundant in many of the deposits and are listed in Table II.

Sulfide minerals, including chalcopyrite, pyrite, bornite, and sphalerite are disseminated with the uranium minerals in many of the deposits, and galena and marcasite occur in the Happy Jack mine. In deposits exposed at the surface, crude supergene and oxide zones have been developed. Supergene sulfide minerals are chalcocite and covellite. Many of the secondary uranium minerals, copper carbonates and sulfates, and abundant iron oxides have been formed in the zones of oxidation.

GUIDES TO FAVORABLE AREAS

The guides to favorable areas in the White Canyon area are divided into three groups: primary guides, secondary guides, and tertiary guides. Primary guides are closely associated with the ore deposits and extend only a few feet from the deposits. They include covellite pods, secondary uranium minerals, abnormal radioactivity, and carbonized wood (coal). The presence of jarosite in some of the deposits suggests its usefulness as a primary guide.

Secondary guides may extend from tens of feet to hundreds of feet beyond the limits of the deposits. These secondary guides may prove useful in core drilling to suggest the presence of a nearby ore deposit. Included in secondary guides are: branches, bends, and basins in channels; clayey sandstone overlying siltstone or mudstone in the channel; disseminated sulfide minerals, especially chalcopyrite, covellite, and bornite; secondary uranium minerals; secondary copper mnierals; carbonized wood and trashy material; and abnormal radioactivity.

Tertiary ore guides are large-scale features that may be useful in determining large areas favorable for deposits. Pinchouts of the Shinarump conglomerate may have restricted and concentrated uranium deposits in some parts of the area and may be useful as large-scale guides. Channels may also be considered as tertiary ore guides.

The large number of Shinarump-filled channels that have been mapped in the White Canyon area, and the frequency of uranium deposits within these channels, suggests that the area is favorable for the discovery of additional deposits. Any channel with a scour deeper than 5 feet may contain significant quantities of uraniferous rock somewhere along its length. The best guides for favorable areas for uranium deposits along the channels seem to be branches, bends, and basins in the channels; clayey sandstone overlying siltstone or mudstone, disseminated chalcopyrite, covellite, and bornite; carbonized wood and trashy material, and abnormal radioactivity.

REFERENCES

1. Gregory, H. E., *The San Juan Country, a Geographic and Geologic Reconnaissance of Southeastern Utah,* US Geological Survey Professional Paper 188 (1952).
2. Benson, W. E., Trites, A. F., Jr., Beroni, E. P. and Feeger, J. A., *Preliminary Report on the White Canyon Area, San Juan County, Utah,* US Geological Survey Circular 217 (1938).

Uranium in Shoreline Sandstones of Terrestrial and Marine Origin, Colorado Plateau

By L. W. Carithers and N. J. Clinton,* USA

Most of the uranium ore produced on the Colorado Plateau has come from fluvial sandstones, represented chiefly by members of the Morrison and Chinle formations and by the Shinarump formation, which have accounted for nearly 90 per cent of uranium production. However, uranium also occurs on the Plateau in sandstones that originated in marine, littoral and coastal plain environments. Some of these are beach sands, others are fluviomarine sands, lagoonal and swamp deposits of mudstone, carbonaceous shale and coal, all of which are related to transgression and regression of the strand line.

Shoreline sandstones have at many places the same lithologic and sedimentary features generally believed to be related to the deposition of uranium in the highly productive fluvial sandstones, namely; (1) shales or mudstones interbedded with sandstone in a proportion of about 50 per cent each (others suggest 25 per cent mudstone as about the optimum); (2) carbonized plant matter; (3) light tan or grey rather than the prevailing reddish shades; and (4) feldspar or mica.[1] The uranium occurrences are generally clustered on or near positive tectonic structures but their genetic relation to these is yet to be proven.

DISTRIBUTION

The known uranium occurrences in the sandstones of shoreline origin are shown in Fig. 1. These are in two general groups on the Plateau; the first is in the Curtis formation of Jurassic age at Skull Creek, Moffat County, Colorado, which accumulated in a sea that invaded the northern part of the Colorado Plateau.

The second group is in sandstones of Upper Cretaceous age deposited along the shore and coastline of a sea that extended northwestward across the Plateau. Uranium occurs in the Toreva sandstone member of the Mesaverde group in the Black Mesa basin of northeastern Arizona, and in the Dakota sandstone, Pictured Cliffs sandstone, and Fruitland formation and the Point Lookout, Hosta and Menefee members of the Mesaverde group in the San Juan Basin, northwestern New Mexico. In addition, uranium has been reported in the Ferron and Emery sandstone members of the Mancos shale in southeastern Utah.

* US Atomic Energy Commission.

URANIUM IN THE CURTIS FORMATION

Uranium occurrences are known in the Curtis area at Skull Creek, Moffat County, Colorado. A few hundred tons have been mined during the past 50 years, first for radium, later for vanadium, and finally for uranium.

The Curtis formation is a near-shore marine deposit that accumulated in a Jurassic sea that advanced over the northern part of the Colorado Plateau from the north or northwest.[2] It is composed of conglomerate, sandstone, limestone and shale containing upper Jurassic fossils. Most of the Curtis is a thinly laminated, very fine-grained sandstone. The formation is as much as 200 feet thick.

The deposits[3] are at the base of the Curtis, which overlies the eolian Entrada sandstone. This basal Curtis is water-laid, ripplemarked, thinly bedded sandstone ranging in thickness from 6 to 36 inches; it grades upward into fossiliferous marine sandstone. The ore horizon is considered to be a marginal marine facies marking the transition from a terrestrial to a marine environment.

The deposits are tabular bodies a foot or two thick containing generally less than 100 tons each of carnotite disseminated in sandstone. Associated with the carnotite are vanadium, iron, and copper minerals together with varying amounts of organic material. The uranium content of the bodies is low, but at places there are concentrations of as much as 7 per cent U_3O_8.

The Skull Creek deposits are situated on the south flank of the Skull Creek anticline which trends east. Local cross-folding has resulted in erratic changes in strike and dip and has developed many small fracture zones, some of which show a few inches displacement. At one deposit fractures appear to have affected the deposition of ore.

URANIUM IN UPPER CRETACEOUS SANDSTONES

General Geology

During Upper Cretaceous time a section of rocks about 5000 feet thick was deposited in the Colorado Plateau region near the western edge of a geosynclinal sea that extended northwestward across the region from the Gulf of Mexico.[4,5] This sea is believed to have been separated from highlands to the west by a broad coastal plain, and sediments derived from the erosion of those highlands were deposited

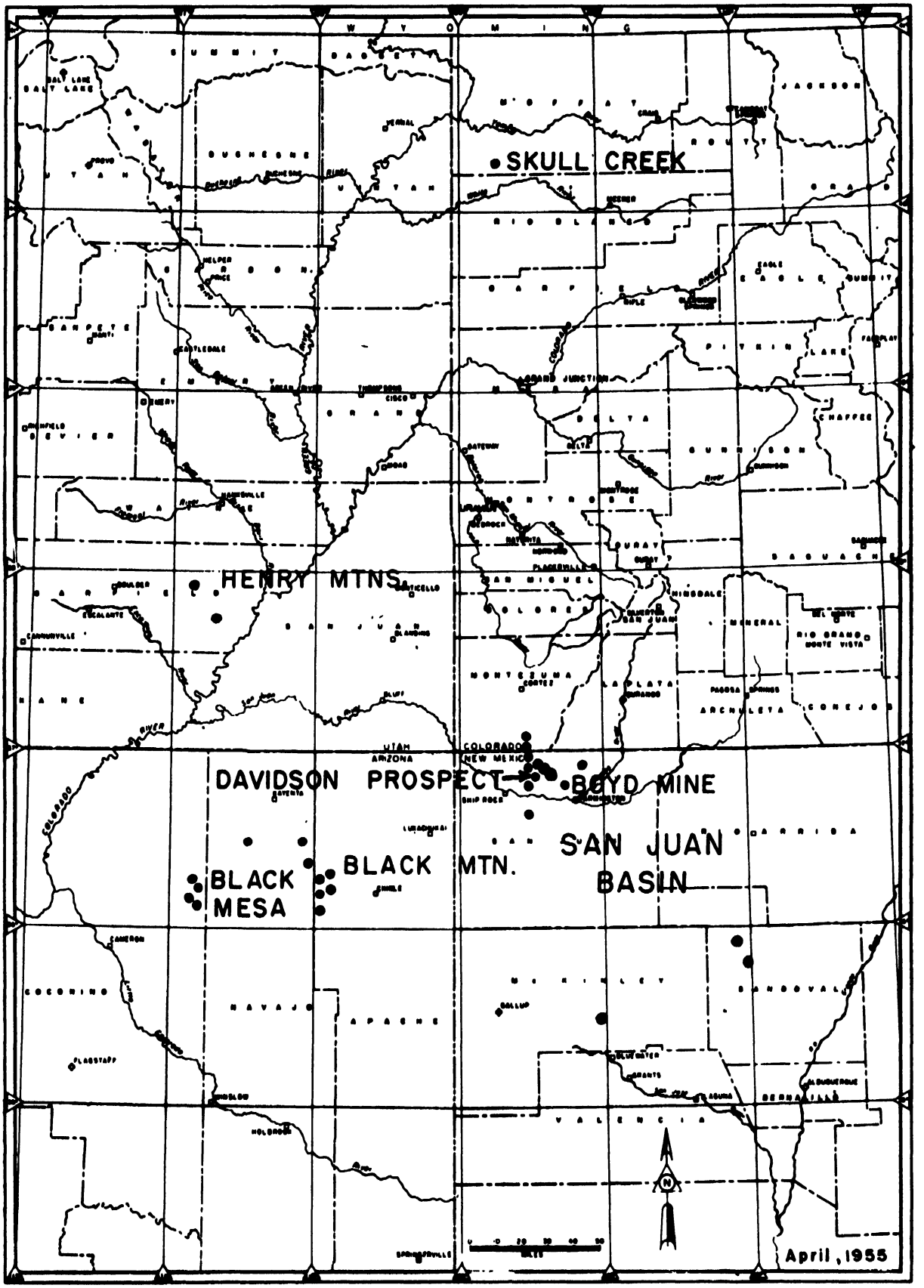


Figure 1. Map of Colorado Plateau showing uranium occurrences in Jurassic Curtis and Upper Cretaceous sandstones

on the plain as well as in the sea. Fluviatile deposits, chiefly flood plain type, accumulated on the coastal plain, and lagoonal, paludal and carbonaceous swamp deposits formed adjacent to the coast. Near the strand, sands accumulated on beaches and bars.

At times the rate of sinking of the geosyncline exceeded the rate of influx of sediments; at other times a reverse condition prevailed. As marine waters transgressed and regressed, the coastline oscillated from southwest to northeast many times during Upper Cretaceous time.[6] These changing environments are reflected in the intertonguing of marine, littoral, swamp and terrestrial deposits of shale, carbonaceous material and sandstones through much of the Upper Cretaceous section on the Plateau.

Figure 2, from Silver,[6] shows diagrammatically the inter-relation of several sandstones deposited during advances and retreats of marine waters. Terrestrial deposits are mostly to the southwest, and marine deposits are to the northeast.

The earliest sandstone of the Upper Cretaceous is the Dakota, which unconformably overlies lower Cretaceous and Jurassic rocks everywhere on the Plateau except where removed by erosion. Above the Dakota many sandstone tongues are interbedded with thick marine shale and thinner carbonaceous deposits. Most of the sandstone units are members of the widespread Mesaverde group. In the southeastern part of the Plateau the Mesaverde and overlying Lewis shale are overlain by the Pictured Cliffs sandstone, the Fruitland formation and later sediments that mark the final retreat of the Late Cretaceous sea from the region and a transition from a marine thru littoral to continental environments.

Uranium occurs in several sandstone members of the Upper Cretaceous on Black Mesa, Arizona, and in the San Juan Basin, New Mexico; deposits are reported in Cretaceous rocks in the Henry Mountains, Utah. Uranium occurs in carbonaceous shale and coal of Upper Cretaceous age as well, but deposits of this environment are not here discussed.

Black Mesa Deposits

The Black Mesa basin is in the center of the Navajo Indian Reservation, in Apache and Navajo Counties, Arizona. The Mesa is a highland from 7000 to 8000 feet in altitude capped by sandstones of the Mesaverde group dipping gently toward the center of the Basin. These overlie Mancos shale and Jurassic rocks. The area is remote, and access is difficult.

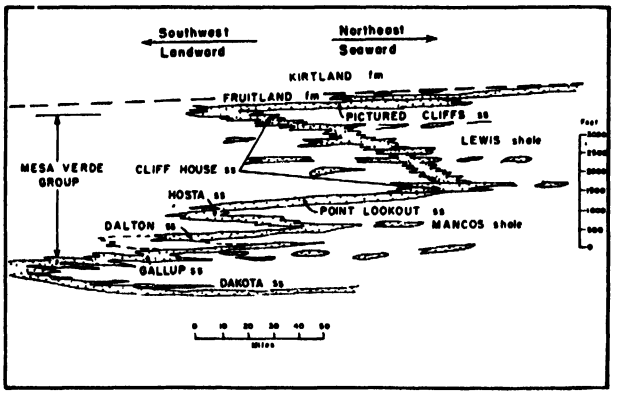


Figure 2. Sectional diagram showing time and geographic relationships of some Upper Cretaceous sandstones in the San Juan Basin, New Mexico

Uranium was discovered in 1953 near Black Mountain Trading Post on the eastern edge of Black Mesa. More than 30 mineralized outcrops are known but only 100 tons of ore have been shipped.

Uranium deposits in the Black Mountain area are in the Toreva sandstone, the lowest of three members of the Mesaverde group here. The orebodies are all within a 35-foot zone at the top of an arkosic unit which is a lower member of the Toreva. This zone is overlain successively by an argillaceous middle member and by an upper sandstone unit of the Toreva.

The orebodies are tabular, and average about 30 feet long, 15 to 20 feet wide and 0.5 to 1.5 feet thick. These lenses are commonly between carbonaceous mudstone beds 3 or 4 feet thick. The color of the ore sandstone is altered from a reddish tan normal in the area, to light gray.

The ore mineral is carnotite or tyuyamunite together with other vanadium-bearing minerals disseminated in a fine-grained quartz sandstone. Carbonized plant matter is abundant.

Black Mesa is a topographic high in a broad shallow basin tipped slightly southwestward. At Black Mountain, on the northeast margin, several shallow synclines and anticlines trend northwestward and are superimposed on the structural basin. A fracture pattern, apparently related to the later folds, is composed of three sets: one parallel to the structural axes of the shallow folds; the other two oblique to it. No relation has been discerned between these and the uranium mineralization.

San Juan Basin Deposits

The San Juan Basin is a region of several thousand square miles in northwestern New Mexico and southwestern Colorado. It is a structural and sedimentary basin rimmed by Upper Cretaceous rocks and containing in its center a large area of sandstone and shale of lower Eocene age.

Prior to 1955 two uranium occurrences were known in the northern part of the San Juan Basin: the Boyd deposit in the Fruitland formation and the Davidson prospect in the Menefee shale. Early in 1955 an airborne radiometric survey by the Atomic Energy Commission detected several radiometric anomalies on outcrops of the Point Lookout and the Pictured Cliffs sandstones. These occurrences are similar to the Boyd and Davidson deposits in that they are all on or near the Hogback monocline, a major tectonic feature of the area, and they are associated with carbonaceous material.

The Boyd deposit is 12 miles northwest of Farmington, San Juan County, New Mexico. It is in a

tuffaceous sandstone of the Fruitland formation, which caps a mesa here. About 40 tons of ore assaying 0.15 to 0.20 per cent U_3O_8 have been mined from a sharply defined light-pink zone at the base of the tuffaceous sand. Just above is a one-foot zone of gray sandstone grading upward into barren buff-colored tuffaceous sandstone. Beneath the ore is a thin zone of gray sandstone underlain by a sharp contact with a one-foot bed of mudstone and sandstone containing carbonaceous fragments and marine (or brackish water?) gastropods. Bentonite and tuffaceous beds underlie the fossil-bearing unit.

The ore, as exposed in an open pit, is from 3 inches to as much as 36 inches thick, over an area of about 25 by 50 feet. No uranium minerals have been identified. The pink of the ore unit is due to iron oxide. The orebody appears to have occupied a shallow depression scoured into the subjacent tuffaceous sediments. The deposit is on the flank of the Hogback monocline; and beds at the mine dip 12 degrees southeastward.

The Davidson occurrence, in the Menefee shale of the Mesaverde, is about 9 miles east of Shiprock, San Juan County, New Mexico. A dark gray-green sandstone one to two feet thick overlies a light-gray sandstone and underlies 2 to 3 feet of sandstone mixed with coal which is beneath a 4-foot bed of coal. This gray-green sandstone is uranium-bearing and consists of iron-stained fine-grained quartz sandstone together with mica, feldspar, clay, tiny flecks of hydrocarbon and a few grains of an unidentified pink mineral. No uranium minerals have been observed. Pyrite and calcium carbonate concretions are abundant just above and beneath the mineralized zone. No ore has been shipped from the deposit; assays from material at the surface run less than 0.10 per cent U_3O_8.

Uranium occurs in the Dakota sandstone and in the Hosta sandstone of the Mesaverde group in the southern part of the San Juan Basin. Here, carnotite occurs in sandstone lenses associated with carbonaceous material. The Dakota deposits are described by Gabelman,[8] together with other uranium deposits occurring in black shales interbedded with the Dakota sandstone in that area.

CONCLUSION

Production of uranium from sandstones originating as shoreline deposits has been minor in comparison with production from fluvial sandstones. However, the lithologic and sedimentary features considered favorable to occurrence of uranium have only recently been recognized in these rocks. Study and prospecting for uranium, which has been directed largely toward currently productive rocks, is barely underway in these sandstones of shoreline origin.

REFERENCES

1. Wright, R. J., *Ore controls in sandstone uranium deposits of the Colorado Plateau*: Econ. Geol. 50:135–154 (1955).
2. Baker, A. A., Dane, C. H. and Reeside, J. B., Jr., *Correlations of the Jurassic formations in parts of Utah, Arizona, New Mexico, and Colorado,* US Geol. Survey Prof. Paper 183 (1936).
3. McDougald, W. D., *Wagon drilling in the Skull Creek area, Moffat County, Colorado,* US Atomic Energy Comm. RME in process (1955).
4. Pike, W. S., Jr., *Intertonguing marine and non-marine Upper Cretaceous deposits of New Mexico, Arizona, and southwestern Colorado,* Geol. Soc. Amer., Memoir 24 (1947).
5. Sears, J. D., Hunt, C. B. and Hendricks, T. A., *Transgressive and regressive Cretaceous deposits in southern San Juan Basin, N. Mex.,* US Geol. Survey Prof. Paper 193–F (1941).
6. Silver, C., *Cretaceous Stratigraphy of the San Juan Basin,* N. Mexico Geol. Society Guidebook of the south and west sides of the San Juan Basin (1951).
7. Spieker, C. M., *Late Mesozoic and Early Cenozoic history of central Utah,* US Geol. Survey Prof. Paper 205–D (1946).
8. Gabelman, J. W., P/50, *Paludal Black Shales,* Vol. 6 Session 6B, these Proceedings.

Uranium in Clastic Rocks of the Basin and Range Province

By Dudley L. Davis and Donald L. Hetland,* USA

The Basin and Range physiographic province of the United States includes Nevada and parts of Arizona, Utah, and California. It consists of rugged, nearly parallel, north-south trending mountain ranges and broad, arid troughs with interior drainage. Elevations range from 4000 feet to 14,000 feet above sea level. The valleys are filled with thick accumulations of waterlain pyroclastics, silts, fanglomerates, and evaporites. Ephemeral saline lakes and playas are found in many of the valleys as a result of interior drainage and arid climate. Gently sloping alluvial fans extend from the mouths of canyons toward the low central portions of most of the valleys.

Evidence of alpine glaciation is apparent in the higher mountains while shore lines of Pleistocene lakes can be observed locally along the foothills. The highly alkaline soil of many of the valleys supports little vegetation other than salt grass and sage, but several types of conifers abound in the mountainous areas. The climate is semi-arid to arid, and the region is sparsely settled as habitable areas are dependent upon surface water supplies. Figure 1 shows the geographic location of individual deposits discussed and the general outline of the province.

The region was a geosyncline during much of the Paleozoic and Mesozoic eras and great thicknesses of sedimentary rocks accumulated. In late Jurassic time, the Nevadan orogeny accompanied the uplift of the Sierra Nevada Mountains; subsequent erosion has exposed the granitic core of this range which bounds the province on the west. During late Cretaceous and early Tertiary time, folding and thrusting of the Laramide orogeny deformed the sediments in a north-south zone extending from Canada to Mexico.

High angle faulting subsequent to the Laramide orogeny determined the present topography of long, graben valleys partially filled with alluvial debris from the intervening mountains. Some of the faults are still active as evidenced by local displacement of alluvial fans along the flanks of some mountain ranges.

The uranium minerals in all the deposits described generally are not in radioactive equilibrium and radiometric analyses are usually lower than chemical analyses. This would suggest recent formation of the uranium minerals. Structural control is not readily apparent in any of the deposits but small fractures and faults may have localized mineral concentrations.

* US Atomic Energy Commission.

DESCRIPTION OF INDIVIDUAL DEPOSITS

Tonopah, Nevada

Geography

Tonopah is situated in the southwestern part of the state in a region of typically arid desert climate and physiography. Vegetation consists of sparse sage and greasewood, and mean annual precipitation is less than ten inches. Relief is moderate with elevations ranging from 5600 feet in the intermontané valleys to 7160 feet at the crest of Butler Mountain.

Geology[1, 2]

Recently discovered uranium occurrences lie about three miles west of the central part of the Tonopah district in lake bed tuffs of the Siebert series. Weak shearing associated with the better uranium locality may be the surface expression of north-south normal faulting which largely preceded deposition of the Siebert tuff. The lacustrine tuffaceous beds at the uranium occurrence are flat-lying and are covered in part by a thin mantle of soil and recent alluvium.

The Siebert lake beds consist of more than 600 feet of uniform finely stratified rhyolitic pyroclastics and diatomaceous earth beds and are either late Miocene or early Pliocene in age. They rest unconformably upon older Tertiary lavas and are conformably overlain by andesitic and rhyolitic flows and welded tuffs. To the northwest, Pleistocene basaltic flows overlie these rocks with angular unconformity. The waterlain tuffaceous host rock for the uranium deposit is interbedded with discontinuous lenses of uraniferous opal and collophanite which are usually less than one foot thick. Ferruginous sandstone is exposed near the northern end of the radioactive area. The relationship between this rock and the tuff is unknown, but the sandstone may represent shore or delta feature.

Ore Deposit

Anomalous radioactivity extends over an area about one mile wide and eight miles long with local concentrations of higher grade material. Gamma-ray logging of a few bore holes indicates radioactivity to a depth of forty feet along a north-south trend marked by weak vertical shearing and iron staining. No distinctive uranium minerals have been identified at this locality, although yellow radioactive coatings are found on collophanite and opal. Samples contain as much as fifty per cent collophanite intimately mixed with bentonitic clay, and preliminary tests

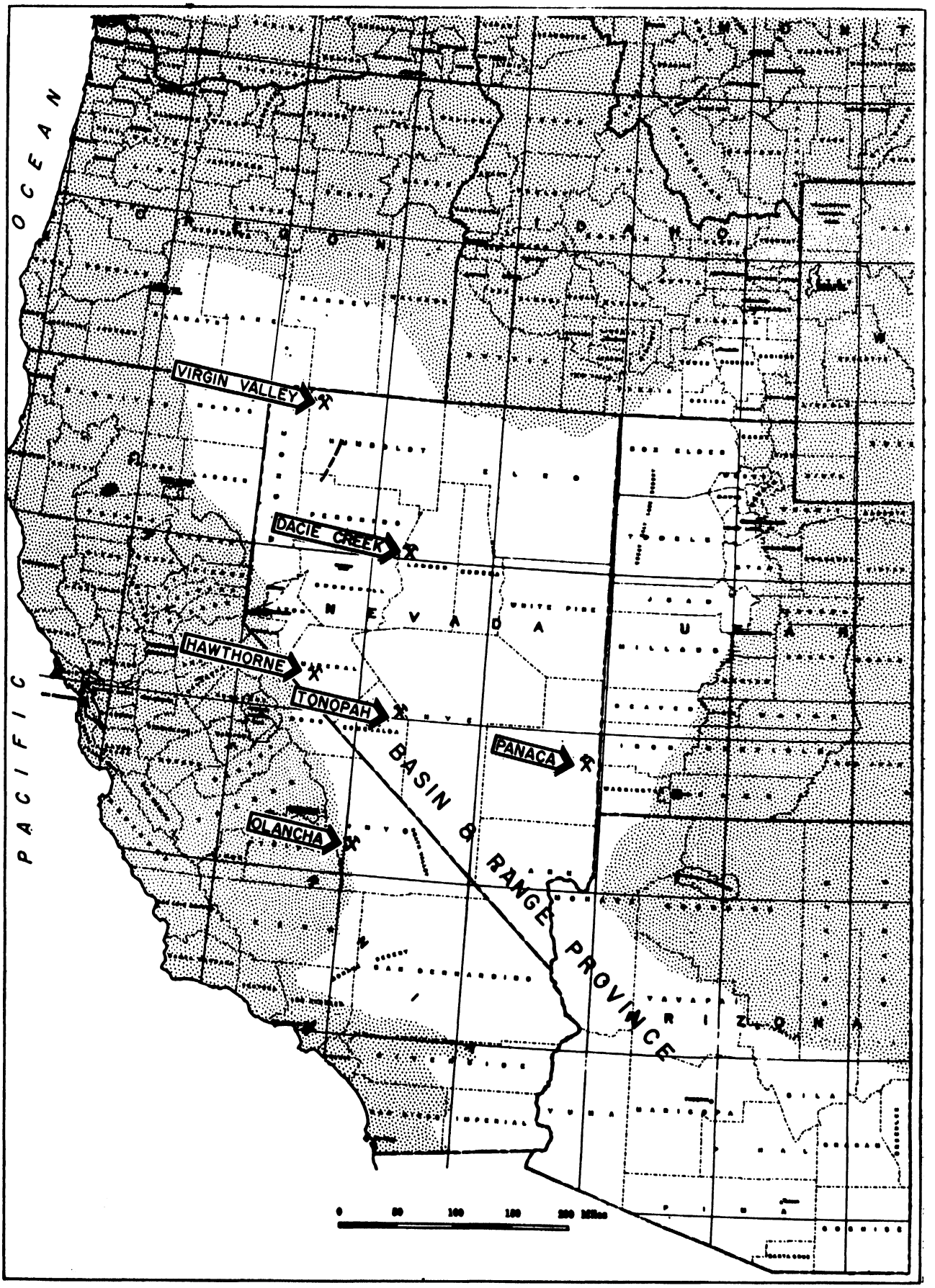


Figure 1. Index map showing uranium deposits in clastic rocks of the Basin and Range province

indicate that most of the uranium is contained in the collophanite. No vanadium has been reported.

There is some evidence that the uranium is of hydrothermal origin. It may have been concentrated along a north-trending shear zone which shows conspicuous iron staining in contrast to the normally white beds. The geologic map of the Tonopah quadrangle shows that a strong north-south Basin and Range type fault disappears under the Siebert beds near the north end of the anomalous area.[2] Weak north-trending shearing present in areas of better mineralization may be the surface expression of this fault. Recurrent movement along the fault, subsequent to deposition of the Siebert tuffs, may have accompanied late Pliocene (or younger) volcanism, and the uranium minerals may have been introduced along the fault zone at that time.

Another suggestion is that the entire tuffaceous horizon contains small percentages of uranium which has been leached during normal erosion and reconcentrated in the present mineralized beds. This concept is supported by evidence of widespread anomalous radioactivity and by the possibility of base exchange adsorption of uranium from ground water by naturally activated bentonitic clays. Additional field study and careful sampling will aid further in evaluating this hypothesis.

Olancha, California

Geography

Olancha is near the southern end of the Owens Valley, immediately east of the Sierra Nevada mountain range. Owens Lake, now partly filled with a thick accumulation of evaporites, sand, and volcanic debris, occupies the central portion of the valley just north of Olancha.

The region is characterized by extremely rugged topography along the east front of the Sierra-Nevada mountain range, deep valleys partly filled by alluvial fans and volcanic debris, and deeply dissected Paleozoic sediments which form the Panamint and Argus ranges to the east. The climate is as varied as the topography. The high Sierras receive heavy, snowfall during winter, but annual precipitation in the Panamint Valley, fifty miles to the east, averages less than five inches.

General Geology

The older rocks of the Argus and Panamint ranges were folded, faulted, and intruded in pre-Tertiary time. In the area mapped (Fig. 2) Cenozoic structures involve both Jurassic(?) and younger rocks. Block-faulting of relatively recent movement uplifted the Coso Range and depressed the Owens Valley. Post-basalt movement has displaced the lava sheets as much as 600 feet along the west flank of the range.

The Coso formation is essentially flat-lying and minor variations in dip from ten to twenty degrees are due to tilting by the relatively recent faults. Movement along some of these faults has continued to the present time.

The Coso lake sediments and tuffs in which the uranium minerals occur have been described.[3,4] The formation is either late Pliocene or early Pleistocene in age and consists of alluvial gravels, fanglomerates, tuffs, pumice, and lake bed sediments. It has an exposed thickness of approximately 500 feet, in the area mapped, where it rests upon an erosion surface cut in granitic rocks of the Coso Range and is conformably overlain by basaltic lava flows. The basal 300 feet consists of reddish arkose, sandstone, and gravel derived from the Coso granite. Above these, about 200 feet of well-stratified, thin-bedded white and light-buff lake beds are interbedded with white rhyolitic tuff, pumice, and greenish clay beds. The volcanic material is well sorted and was probably laid down in a lake. Fish bones have been found in the lake sediments.

East of the deposit, basalt flows rest directly upon late Jurassic(?) granite of the Coso Range. The Coso beds may abut against the Quaternary fault zone which bounds the east front of the Sierra Nevada range. Recent alluvium covers this contact.

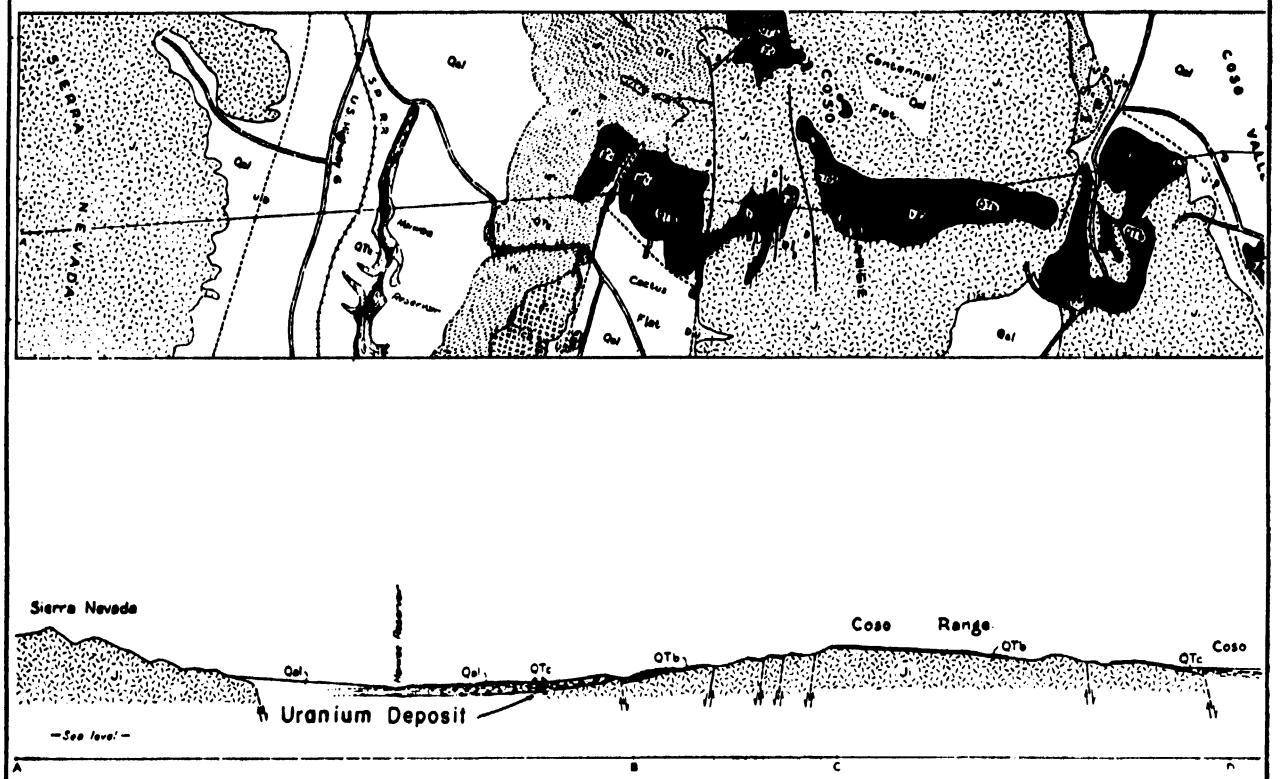
Ore Deposits

Uranium minerals occur in greenish bentonitic clay beds in the tuffaceous horizon of the Coso formation. Three zones of caliche, separated by a sequence of lake sediments and tuffaceous beds, lie above the radioactive horizon. These zones range in thickness from two to six feet and consist of well-indurated coarse, angular, arkosic sandstone cemented by caliche. The uranium-bearing strata usually occur from 30 to 40 feet below the lower caliche zone.

Three persistent radioactive horizons, ranging from eight to twenty-four inches thick, are found in a twenty-foot zone which crops out for 2000 feet along the south side of an east-west canyon which has been cut in the soft tuffs. All three of the radioactive layers are within, or contiguous to, prominent bands of iron oxide staining which vary from one inch to four feet in thickness.

Radioactive minerals are autunite and uraniferous opal which fill tiny fracture planes in bentonitic clay beds and fine sandstone. Some layers of strongly radioactive sandstone show no discrete uranium minerals. No channeling or carbonaceous trash was observed. About one mile north of the uranium deposit the bentonitic beds have been mined for clay and there anomalous radioactivity indicates the presence of uranium. A pumice deposit about one mile south of the uranium locality exhibits weak radioactivity. Jurassic(?) granite which crops out two and one-half miles to the east is not abnormally radioactive nor are the basal Coso arkosic sandstones.

The uranium may have been deposited syngenetically with the tuffaceous material and later leached by ground waters and reprecipitated in the bentonitic clay beds. Evidence supporting this concept is the lateral extent of the radioactive outcrop and uniform mineralization of thin clayey beds. However, the presence of the caliche-cemented arkosic beds, above the ore zone, would hinder downward migration of



GEOLOGIC MAP & SECTION OF OLANCHA AREA

LEGEND

IGNEOUS ROCKS

	Map	Section	
Tertiary or Quaternary			QTb Basalt flows and basaltic cinders
			Tvb Basalt of the Nova formation
Tertiary			Tva Andesite of the Panamint Range (includes some rhyolite and dacite)
			Tca Andesite of the Coso Range
Jurassic			Jn Late Jurassic plutonic intrusives, ranging in composition from granite to gabbro

Sedimentary Rock

QTc Coso Formation

Horizontal and Vertical Scale

1 ½ 0 1 2 3 Miles

Geology by R. H. Hopper
1937

Figure 2. Geologic map and section of Olancha area

vadose water. Absence of carbonaceous plant debris suggests an adsorptive effect of the bentonite.

It is also possible that the deposit is of hypogene origin. Hydrothermal solutions, rising along fault zones exposed to the east of the deposit, may have been trapped by the clayey horizon with resultant deposition of uranium minerals. Pyrite, presumed to have been deposited with the uranium, may have oxidized to form the iron-stained bands which now accompany the more intense radioactivity.

Virgin Valley

A uranium occurrence in the Virgin Valley of northwestern Nevada is similar to those discussed above.[5,6]

Rocks of the area consist of early Pliocene Clarendonian) waterlain vitreous tuff and diatomaceous earth beds, capped locally by basalt flows and lake terrace gravels. Silicified rhyolite dikes have intruded the tuff series. The tuff and diatomaceous earth beds contain numerous discontinuous lenses of opal.

Uranium minerals consist of carnotite and a fluorescent yellow mineral believed to be schroeckingerite. Carnotite occurs principally as fracture coatings in the opal and schroeckingerite is disseminated in the diatomite and tuff.

Dacie Creek

This area is situated in northwestern Lander County, Nevada. The deposit occurs in a topographic basin near the source of Dacie Creek which is surrounded by mountains that consist of rhyolite and andesite capped by basalt flows. The host is thin-bedded, waterlain tuff overlain by rhyolite. Thin lenses of opal conform with the bedding of the tuff.

Uranium minerals have not been identified. Both rhyolite and tuff show anomalous radioactivity with the highest anomalies confined to minor fractures in the tuffs. The bedding is nearly horizontal with many small fractures throughout, but no major faults have been mapped in the immediate area.

Hawthorne, Nevada

This deposit is in the Garfield Hills about ten miles southeast of Hawthorne. The host is a medium to fine-grained tuffaceous sandstone, a member of the Tertiary Esmeralda formation. The area is capped by andesite and basaltic flows. What appears to be a small rhyolite plug is in fault contact with the uranium-bearing sandstone northwest of the deposit. Carnotite is concentrated along closely spaced vertical fractures exposed by a cut approximately 200 feet long. Many pebbles and boulders in recent alluvium are coated with yellow secondary uranium minerals.

Panaca, Nevada

Carnotite(?) occurs in a thin bed of soft, waterlain tuff in the Pliocene(?) Panaca formation in Lincoln County, Nevada. This formation consists of a series of stratified waterlain tuffs which are fine-grained, ranging from silt to medium sand. Occasional thin layers of coarser material are found near the contact with underlying Cambrian sedimentary rocks or earlier Tertiary volcanics. The beds are essentially flat-lying but near the contacts with older rocks, may dip as much as four degrees toward the center of the valley. No post-Panaca deformation was observed.

The formation has been assigned to the Pliocene on the basis of mammalian fossils, but it may actually belong in late Pliocene or early Pleistocene since deposition followed a period of mid-Pliocene orogeny.[7]

The bed in which the uranium occurs is a thinly laminated, very fine-grained tuff, containing minor amounts of carbonaceous material. The horizon has been exposed for 200 feet and ranges from six inches to two feet in thickness. There is no apparent alteration or silicification of this bed although occasional lenses of opal occur stratigraphically above it.

REFERENCES

1. Spurr, J. E., *Geology of the Tonopah Mining District, Nevada,* US Geol. Survey Prof. Paper 42 (1905).
2. Ferguson, H. G. and Muller, S. W., 1949, *Structural Geology of the Hawthorne and Tonopah Quadrangles, Nevada,* US Geol. Survey Prof. Paper 216 (1949).
3. Knopf, Adolph and Kirk, Edwin, *A Geologic Reconnaissance of the Inyo Range and the Eastern Slope of the Southern Sierra Nevada,* US Geol. Survey Prof. Paper 110 (1918).
4. Hopper, R. H., *Geologic Section from the Sierra Nevada to Death Valley, California,* Geol. Soc. Amer. Bull. *58*: 393–432 (1947).
5. Staatz, M. H. and Bauer, M. H., *Virgin Valley Opal District, Humboldt County, Nevada,* US Geol. Survey TEM–227 (1951).
6. Thurlow, E. E., written communication.
7. Wheeler, H. F., oral communication.

Uranium Deposits in Tertiary Clastics in Wyoming and Northern Colorado

By Eugene W. Grutt, Jr.,* USA

Uranium discoveries in Tertiary clastics of Wyoming were made in the Red Desert of the Great Divide Basin in 1936 on recognition of schroeckingerite in shales of the Wasatch formation (Eocene) and in 1951 by identification of carnotite in sandstone beds of the Wasatch formation in the Pumpkin Buttes area, Powder River Basin. These were followed by discovery of uranium phosphates in the Wind River formation (Eocene) in the south central part of the Inyan Kara formation (Cretaceous) in the Black Hills of South Dakota and Wyoming during 1951. (see Fig. 1). These deposits occur in outwardly dipping strata that flank the Black Hills uplift.

GEOLOGIC SETTING

Rugged mountains with pre-Cambrian granite cores flanked by strata of Paleozoic and Mesozoic age which dip beneath Tertiary formations in intermontane basins dominate Wyoming topography. Much of the present relief is due to Tertiary faulting commonly localized near the margins of basins.

Sedimentary rocks in the uranium areas range in age from Cambrian to Pliocene, with only the Silurian period missing (Fig. 2). In general, sedimentary rocks are thicker in the Western part of the state. All rocks of Paleozoic and Mesozoic eras, up through the Sundance formation of upper Jurassic age were deposited in seas tributary to the Cordilleran geosyncline which lay to the west. The Morrison formation of uppermost Jurassic age is of fluviatile origin and, in general the Cretaceous strata are of brackish water or marine origin.

Tertiary sedimentary rocks are fluvial, derived from erosion of local highlands and deposited in valley fill environment. The Eocene, Oligocene and Miocene formations, the most frequent hosts for uranium, are comprised of shales, siltstones, and fine to very coarse-grained arkosic sandstones and conglomerates. Coal beds are present in the Paleocene and Eocene sediments. Oligocene, Miocene, and Pliocene strata in addition may also contain large quantities of tuffaceous materials and, locally, other volcanic debris.

Correlation is difficult within Tertiary formations as few strata are continuous over large areas. As a rule formational attitudes are near horizontal or gently dipping except in areas of local faulting or folding where dips as steep as 60 degrees have been measured. It is partially due to the widespread occurrence of permeable arkosic sandstones within the Tertiary formations of this region that makes much of the area favorable for occurrence of uranium.

OCCURRENCE OF URANIUM

Uranium occurs in Tertiary clastics in widely scattered localities in the eastern two-thirds of Wyoming, in southeastern Montana, and in a small portion of northern Colorado. Commercial grade ore in at least 5 ton test lots has been produced from almost 50 individual properties.

Most production has been from deposits detected by reason of their abnormally high surface radioactivity, in sandstones of the Wind River, Wasatch, and Browns Park formations.

Although sandstone is the most favorable host rock, uranium has been found in granite and schist, shale, mudstone, lignite and limestone. Stratigraphic and lithologic features are the major controls for mineralization, but structural features may also be important.

Mineralogical Pattern

Figure 3 has been prepared to show the outlines of fairly well defined mineral provinces, as suggested by data available. The mineralogical types are arranged in order of importance from left to right under each listed area. No explanation for this pattern can be offered at present.

Recent discoveries of uraninite in both the Wind River and Powder River Basins and the probable occurrence of uraninite in the Washakie Basin suggest that many of the near-surface secondary ores may have been derived from oxidation of uraninite.

Descriptions of Representative Uranium Deposits

Lucky Mc Mine

The Lucky Mc Mine is located near the southwest limb of the dissected Gas Hills anticline, Fremont County, Wyoming, 50 miles east of Riverton, Wyoming. In that area the Wind River formation (Eocene) was deposited unconformably on an irregular eroded surface of Mesozoic strata. Rocks are exposed on the flanks of the Gas Hills anticline ranging from the Triassic Chugwater formation to the Frontier sandstone of Cretaceous age. Tertiary sedimentary rocks ranging from Eocene to Miocene are

* US Atomic Energy Commission.

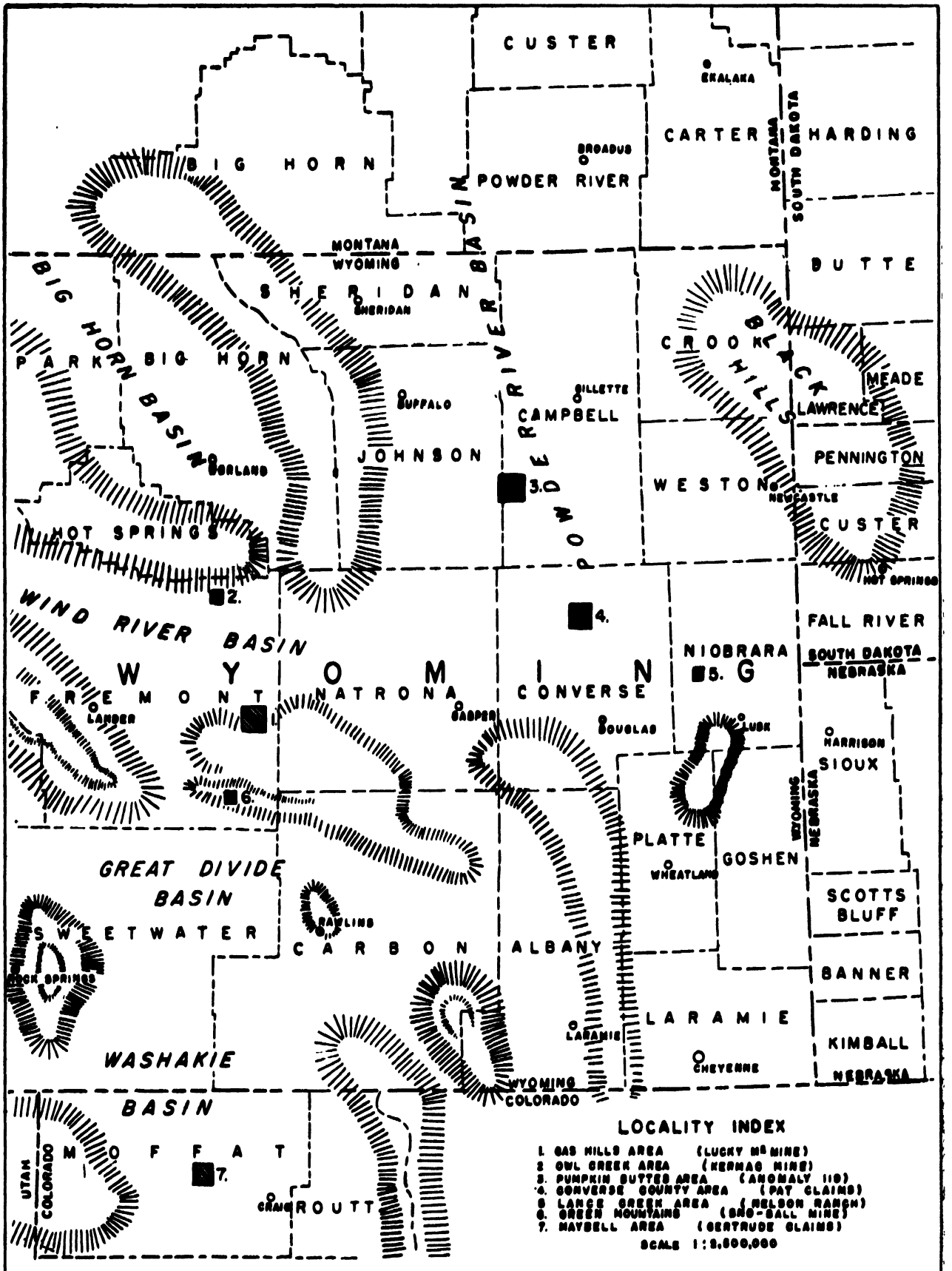

CUSTER
EKALAKA
CARTER
HARDING
MONTANA
SOUTH DAKOTA
BIG HORN
POWDER RIVER
BROADUS
BASIN
MONTANA
WYOMING
BUTTE
SHERIDAN
SHERIDAN
BIG HORN BASIN
BLACK HILLS
CROOK
PARK
BIG HORN
BUFFALO
GILLETTE
CAMPBELL
MEADE
LAWRENCE
JOHNSON
POWDER RIVER
PENNINGTON
WESTON
NEWCASTLE
CUSTER
HOT SPRINGS
HOT SPRINGS
WIND RIVER BASIN
FALL RIVER
NIOBRARA
SOUTH DAKOTA
NEBRASKA
WYOMIN
FREMONT
NATRONA
CONVERSE
LANDER
CASPER
DOUGLAS
LUSK
HARRISON
SIOUX
PLATTE
GOSHEN
WYOMING
NEBRASKA
WHEATLAND
GREAT DIVIDE BASIN
SWEETWATER
RAWLINS
CARBON
ALBANY
SCOTTS BLUFF
ROCK SPRINGS
BANNER
LARAMIE
LARAMIE
KIMBALL
NEBRASKA
CHEYENNE
WASHAKIE BASIN
WYOMING
COLORADO
MOFFAT
UTAH
COLORADO
CRAIG
ROUTT
LOCALITY INDEX
1. GAS HILLS AREA (LUCKY Mc MINE)
2. OWL CREEK AREA (KERMAC MINE)
3. PUMPKIN BUTTES AREA (ANOMALY 110)
4. CONVERSE COUNTY AREA (PAT CLAIMS)
5. LANCE CREEK AREA (NELSON RANCH)
6. GREEN MOUNTAINS (BIG-BALL MINE)
7. MAYBELL AREA (GERTRUDE CLAIMS)
SCALE 1:2,000,000

Figure 1

A GENERALIZED STRATOGRAPHIC CHART OF WYOMING

SYSTEM		FORMATION	CHARACTER
TERTIARY	PLIOCENE	North Park Formation	Tuff, Sandstone, Bentonitic claystone
	MIOCENE	Browns Park Formation	Tuffaceous sandstone, Conglomerate, Marl
	OLIGOCENE	White River Formation	Tuffaceous claystone, Arkosic conglomerate
	EOCENE	Green River Formation	Shale, Marlstone, Sandstone
		Wasatch Formation	Sandstone, Shale, Claystone
		Wind River Formation	Sandstone, Shale, Conglomerate
	PALEOCENE	Fort Union Formation	Sandstone, Shale, Coals
CRETACEOUS	UPPER	Lance Formation	Sandstone, Shale, Coals,
		Lewis Formation	Gray shale, Lenticular sandstone beds
		Mesaverde Formation	Sandstone, Shale, Coals
		Cody Shale	Gray shale, Lenticular sandstone
		Frontier Formation	Shale, Sandstone
		Mowry Shale	Shale, Some bentonite beds
	LOWER	Thermopolis Shale	Black shale, Some sandstone
		Cloverly Formation	Sandstone, Conglomerate, Bentonitic claystone
JURASSIC	UPPER	Morrison Formation	Siliceous claystone, Silty sandstone
		Sundance Formation	Glauconitic sandstone, Shale
	MIDDLE	Gypsum Springs Formation	Siltstone, Gypsum, Anhydrite
	LOWER	Nugget Sandstone	Massive bedded sandstone
TRIASSIC		Chugwater Formation	Red shale, Siltstone, Gypsum beds
		Dinwoody Formation	Dolomitic siltstone, Shale, Sandstone
PERMIAN		Phosphoria Formation	Phosphatic dolomite, Mudstones
PENNSYLVANIAN		Tensleep Formation	Sandstone, Limestone, Chert
		Amsden Formation	Shale, Limestone, Some Sandstone
MISSISSIPPIAN		Madison Limestone	Massive bedded limestone
DEVONIAN		Darby Formation	Dolomite, Shales
SILURIAN		(Missing)	
ORDOVICIAN		Bighorn Dolomite	Massive dolomite
CAMBRIAN		Gallatin Limestone	Shaley limestone, Limestone
		Gros Ventre Formation	Fissile shale, Some limestone
		Flathead Quartzite	Conglomeratic sandstone
PRE-CAMBRIAN			Granite - Shist

Figure 2.

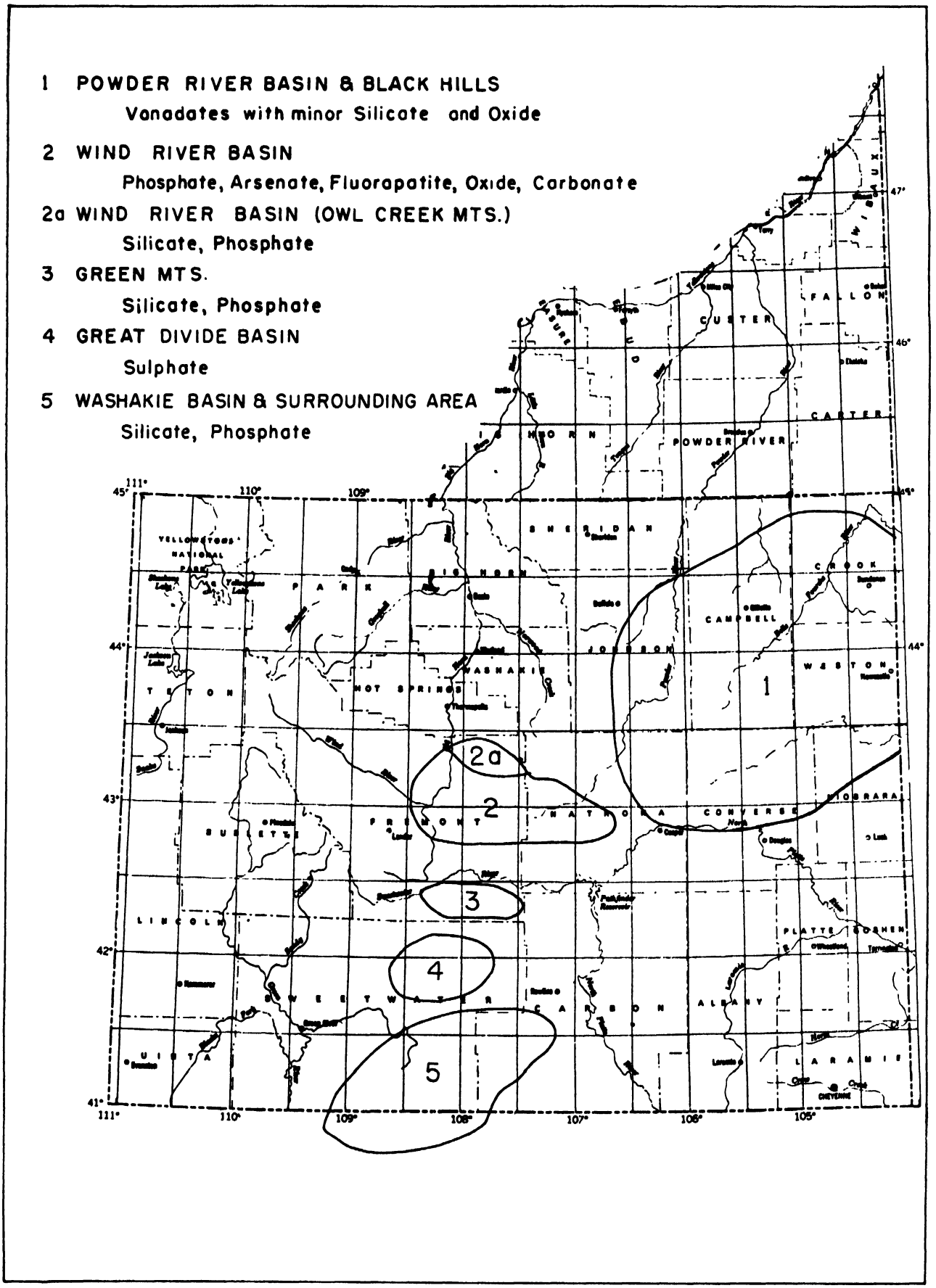


Figure 3. Map of Wyoming showing approximate outlines of mineralogical areas as presently known

exposed on the Beaver Rim escarpment several miles to the south. This southward receding escarpment, the southern margin of the Wind River Basin, has a relief of 500 to 1000 feet.

The Lucky Mc Mine is in the upper Wind River formation, the host for most other deposits in the area. This formation which dips from 3 to 6 degrees to the south ranges from a feather edge to over 300 feet in thickness. Claystones and siltstones predominate in the lower part but the upper consists largely of cross-bedded arkosic sandstones, thin mudstones and lenses of conglomerate.

The host rocks are friable, coarse-grained, gray and brown arkosic sandstones and conglomerate interbedded with thin gray and brown lenses of carbonaceous shale and mudstone. The lenticular nature of beds and torrential cross-bedding are universal features and indicate deposition in turbulent streams. Some carbonaceous fossil plant remains are disseminated in the sandstone along with ferruginous, argillaceous and calcareous cementing materials.

Open pit mining has exposed the shallow southward dipping ore body which has an irregular shape and typically follows bedding and sedimentary structures but locally may transect such features by following fractures.

The dark primary ores usually occur as elliptical deposits within the main layer of mineralization. These ore lenses, which are up to several feet thick and from 1 to 15 feet wide, characteristically pinch and swell. Uranium seems to be most concentrated in places of greatest fracture density and in permeable lenses of coarse-grained sandstone. Vertical fractures which strike from N70°W to N35°E are prominent and appear to have been important in localizing ore.[1]

Primary ore minerals are uraninite and coffinite[2] in microscopic particles disseminated in dark colored, very coarse-grained angular arkosic sandstone cemented by gypsum and calcium carbonate. This type ore is charged with finely divided pyrite which imparts the dark coloration and often liebigite, a light green secondary mineral, occurs on fracture faces and fills seams in the primary ore. Waxy, gray-green uraniferous carbonate-fluorapatite found as intergranular cement and as fracture fillings, may be another primary mineral.

A host of secondary minerals is found in this deposit and in addition to liebigite, several others are present such as meta-autunite, yellow uranium phosphate (unidentified), phosphuranylite, rutherfordine, metazeunerite and metatorbernite.[3] Secondary uranium minerals surround the primary ores as halos or are irregularly disseminated throughout the oxidized sandstone strata in pockets, bands or "rolls". The entire ore deposit as presently exposed is a partially oxidized primary body in which unoxidized remnants of original ore remain (Fig. 4).

The most noticeable alteration effect is a pronounced halo of soft white sandstone containing brown and rust colored splotches and areas of limonite staining. These zones which appear to surround the ore deposit for distances up to at least 100 feet are thought to be related to acid sulphate conditions resulting from oxidation of pyrite.

Oxidation is manifested by abundant limonite, and oxidized ores usually show equivalent uranium to be higher than uranium determined chemically. However, the reverse of this situation is often true in the case of primary or relatively unoxidized ores.[3]

At the Lucky Mc deposit mineralization is concentrated in areas of higher than average fracture density and sandstone beds of higher than average porosity. Although a very small amount of carbonaceous material is present, it is not in such abundance to be called a control. Higher than normal content of calcium carbonate in the sandstone cement may be an important factor, and proximity to the underlying surface of unconformity and impervious shales which could have regulated solution flow may have been important.

Two other deposits in the Wind River Basin which occur in environment similar to that of the Lucky Mc are:

1. Bullrush claims (Gas Hills area) Sec. 29, T33N, R90W, Fremont County, Wyoming.[4]

Uranium mineralization is concentrated in blanket-like zones following bedding in coarse-grained arkosic sandstones. Meager data suggests that mineralogy may be somewhat similar to that at the Lucky Mc. This deposit, which has not been mined, has been investigated by drilling. (Fig. 5).

2. Kermac claims, Sec. 3, T39N, R92W, Fremont County, Wyoming.[4] This deposit lies in the Wind River Basin at the southern foothills of the Owl Creek Mountains. The host rock is a sequence of silt-stones and bentonitic mudstones of Eocene or Miocene age. Meta-autunite occurs in small fracture networks along bedding in mudstones.

Anomaly No. 119 Mine

This mine is located northeast of the Pumpkin Buttes in Campbell County, Wyoming about 45 miles southwest of Gillette. The region near the synclinal axis of the Powder River Basin, is rolling, well-dissected terrain with Pumpkin Buttes attaining a relief of almost 1000 feet over the general area.

All rocks exposed within miles of this mine belong to either the Wasatch formation of Eocene age or to the White River formation of Oligocene age. The Wasatch formation is up to 1500 feet thick and comprised of shales, mudstones, interbedded lenticular beds of fine-to-coarse-grained cross-bedded sandstones and several persistent coals. The White River formation capping the Buttes is a coarse-grained to conglomeratic sandstone with siliceous cement.

The Wasatch formation is host for all occurrences of consequence in the area, and essentially all of the 121 uranium occurrences, of which Anomaly No. 119 is one, occur in a red sandstone zone which is up to 500 feet thick and which is stratigraphically near

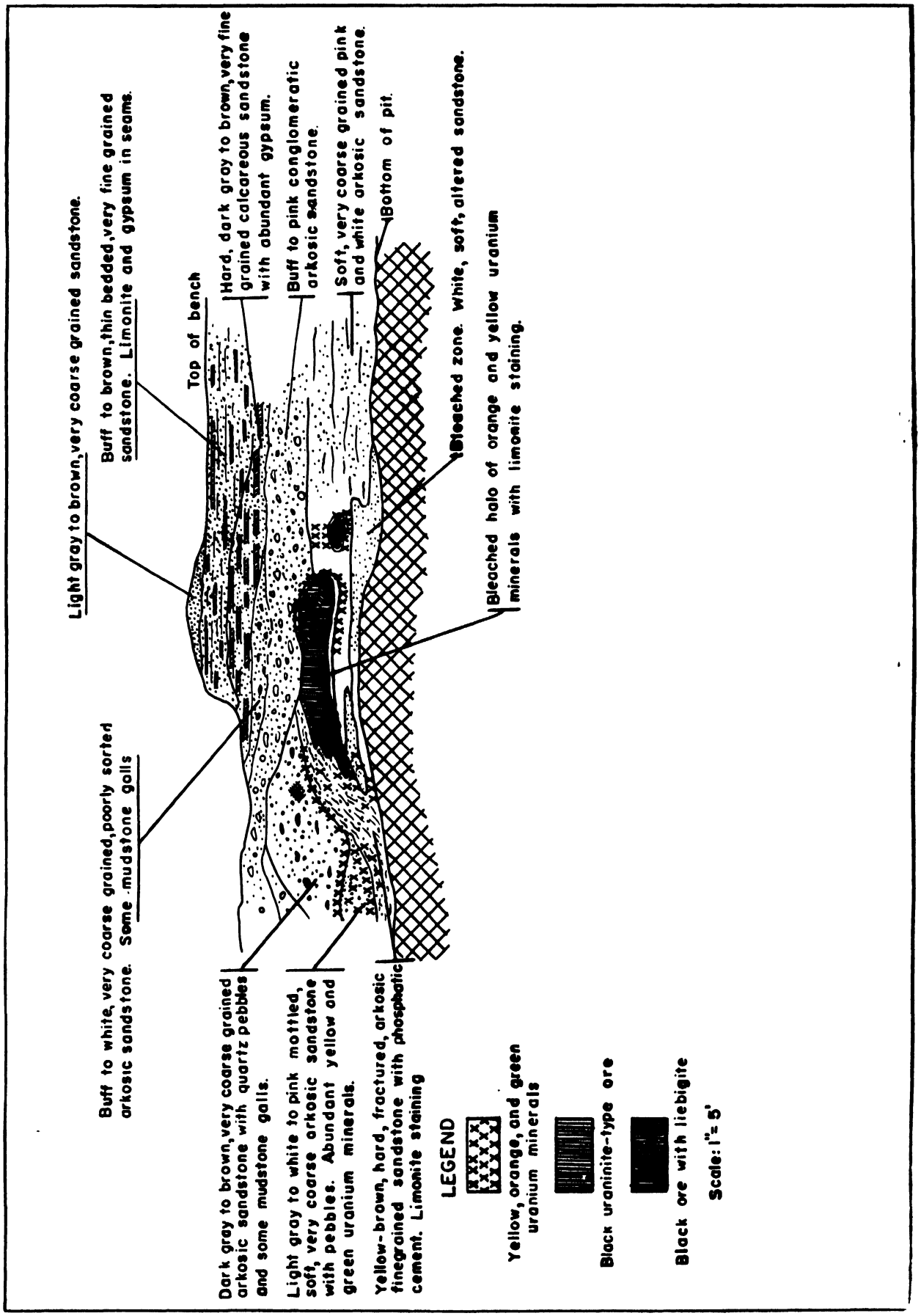


Figure 4. Vertical section through an ore bench in the Lucky M° open pit showing occurrences of black uraninite type ores and liebigite veinlets Sec. 23, T33N, R90W; Fremont County, Wyoming

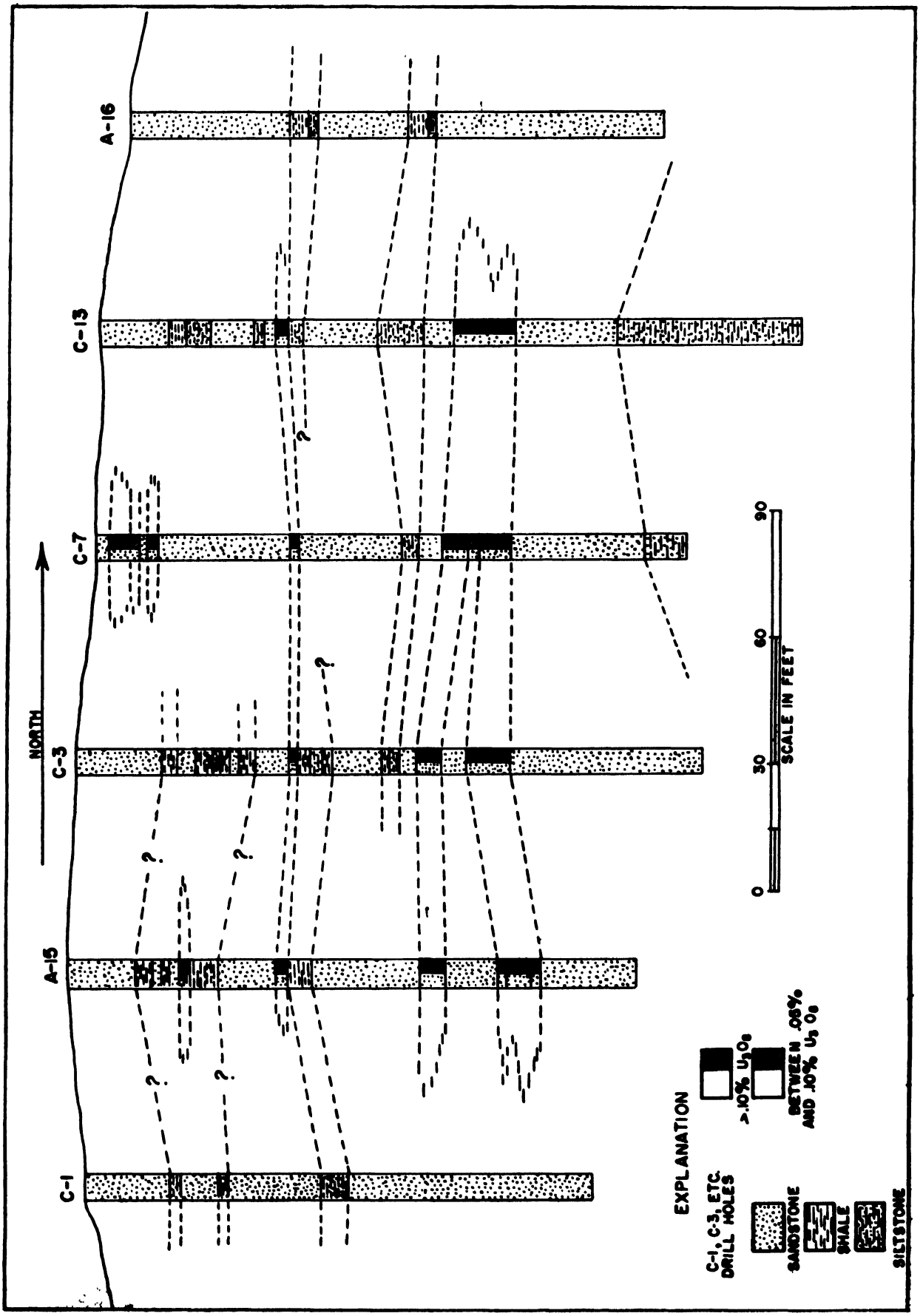


Figure 5. Cross section through Bullrush ore deposit Sec. 29, T33N., R90W, Fremont Co., Wyoming

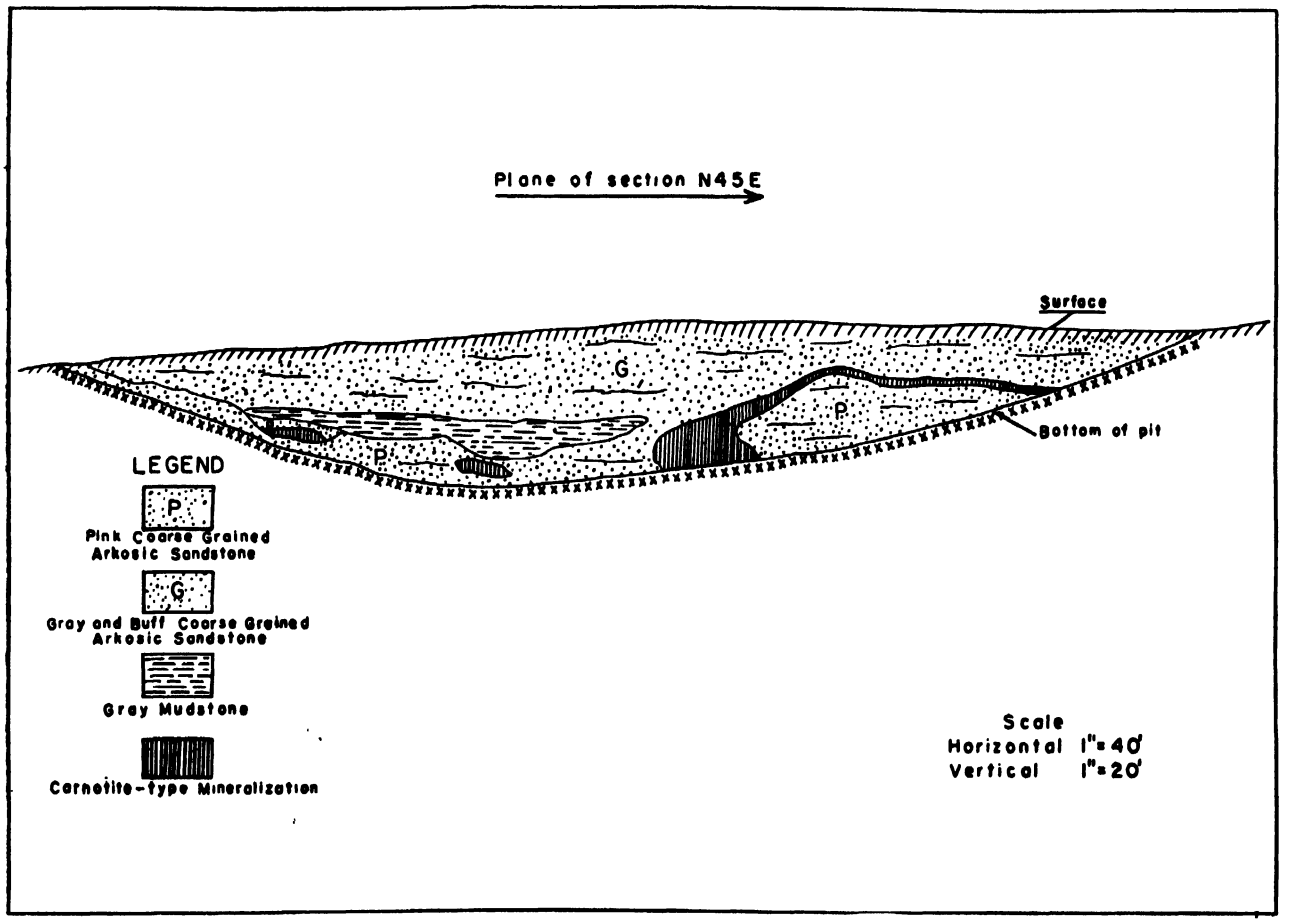


Figure 6. Vertical cross section through open pit on Anomaly 119 Sec. 11, T45N, R75W, Campbell County, Wyoming

the middle of the formation.[5] The sandstone zone is arkosic and contains much calcareous and ferruginous cement and in places considerable quantities of fossil carbonaceous material.

Uranium mineralization has been disclosed by two elongate pits. The host is a thin- to massive-bedded coarse-grained arkosic sandstone with abundant cross-bedding. Uranium occurs in extremely irregular zones and impregnations, controlled in a few places by bedding but elsewhere transecting all sedimentary structures. No unique recognizable feature seems to outline the ore deposit. Hard layers and concretions of calcareous sandstone occur sporadically throughout the areas exposed by mining and often, uranium ore is removed from these areas; most of the friable mineral-bearing sandstone contains uranium as grain coatings or interstitially between sand grains. Carbonaceous plant material is disseminated in the sandstone and in places is associated with high grade pockets of ore.

The uranium mineralogy is relatively simple compared with that of the Wind River Basin. The primary mineral, uraninite, was discovered in an unoxidized part of the deposit intimately associated with disseminated pyrite.[6] However, the dominant minerals are carnotite and tyuyamunite. Uranophane has also been identified but is minor. The secondary minerals are disseminated in irregular and tortuous bands which range in size from seams a fraction of an inch thick up to bodies several feet wide. The most striking feature of the entire deposit is the concentration of uranium along the zones of contact between pink sandstone and gray or buff sandstone which may also show a bleached appearance. Ore is more plentiful on the gray and brown sandstone side of the contact zone (Fig. 6).

In all probability the mineralizing solutions were responsible for the alteration of the pink sandstones to brown and gray. This color change is the best single guide to ore.

Coarse-grained sandstones of high permeability and lenticular mudstone lenses may have exercised control over deposition by directing the flowage of mineralizing solution. Some ore zones are concentrated in areas of higher than average fracture density with abnormal amounts of calcareous cement.

A deposit similar in many respects to Anomaly 119 is the Jeanette Mine in Sec. 22, T45N, R75W, also in the Pumpkin Buttes area. Pink sandstones of the Wasatch formation are altered to gray in carnotite-bearing zones and uranium shows marked tendency to concentrate in and around fossil carbonaceous material. Uraninite has also been reported from this mine in intimate association with pyrite.[6]

Another deposit in coarse-grained sandstones of the Wasatch formation, but which shows marked

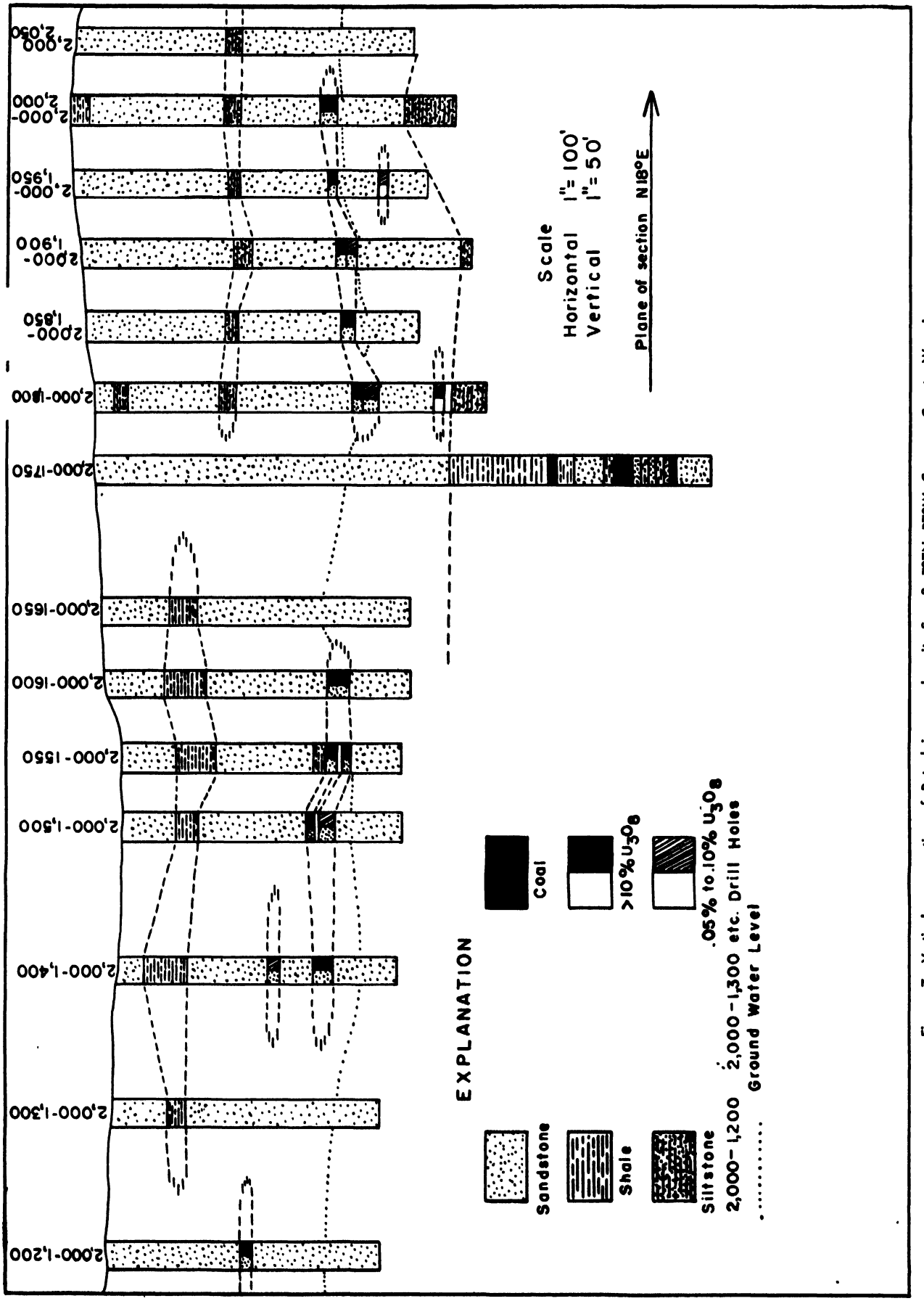


Figure 7. Vertical cross section of Pat claim ore deposits Sec. 3, T37N, R73W, Converse County, Wyoming

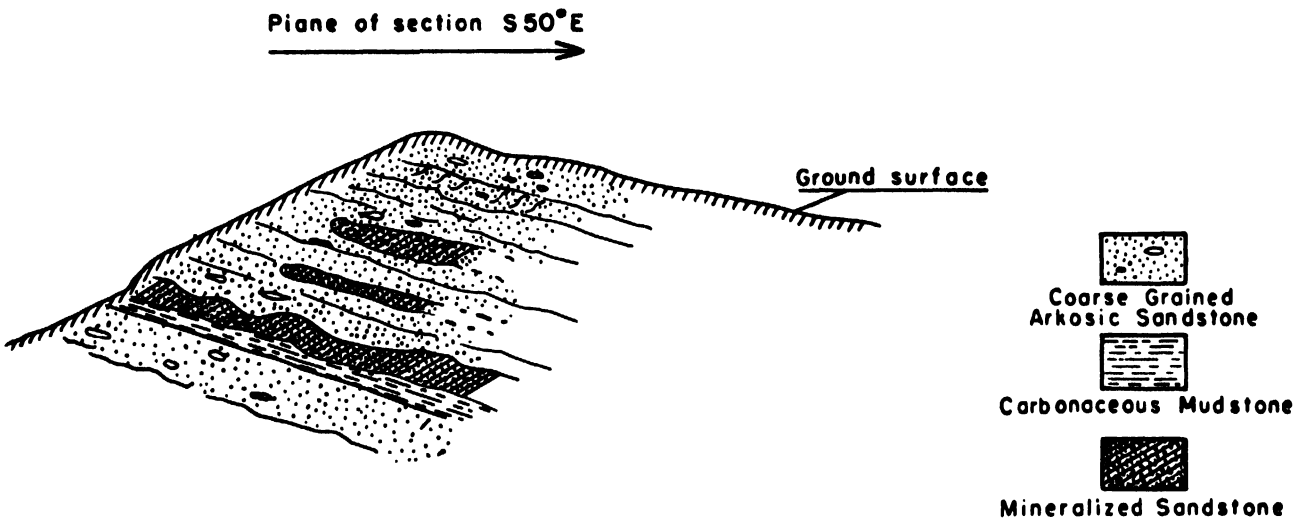


Figure 8. Generalized vertical cross section through outcrops on Sno-Ball claim; Sec. 28, T28N, R92W, Fremont County, Wyoming

differences to the ones already described, is the Browns' Ranch deposit in Sec. 22, T43N, R76W, Pumpkin Buttes area. A cluster of concretionary uranium occurrences, which ranged individually in size from a fraction of a cubic foot up to several cubic feet, has produced over 200 cubic feet of ore which assayed about 5 per cent U_3O_8. Uranophane and small amounts of carnotite occurred in these concretions intergrown with manganese, iron oxides and calcium carbonate. Color changes and carbonaceous materials were not guides to favorable ground in this deposit.

On the Pat claims in Sec. 3, T37N, R73W, Converse County, Wyoming, carnotite-type minerals occur disseminated in deposits in gray sandstone strata of the Wasatch formation. This deposit has been developed only by drilling and many details of occurrence are not known, but deposition favored coarse-grained arkosic sandstones containing carbonaceous materials and some calcareous cement. A distinct change in lithology, which seems to influence the local ground water level, takes place at the disconformable contact with the Fort Union formation and may have been a factor in localization of the ore (Fig. 7).

Sno-Ball Mine

The Sno-Ball mine, discovered by airborne radiometric equipment, is in the Crooks Gap section of the Green Mountains in Sec. 28, T28N, R92W, Fremont County, Wyoming, about 65 miles north of Rawlins.

The Green Mountains, which trend in a northwesterly direction, locally attain an elevation in excess of 8000 feet and are comprised largely of Eocene strata. A large northerly dipping thrust faults bounds the range on the north and the Great Divide basin is the topographic boundary to the south. This fault, active over much of the Tertiary period, influenced local sedimentary deposition during the Eocene period by continually rejuvenating source highlands.[7,8] The Fort Union formation (Paleocene) and older rocks were strongly folded prior to deposition of the Wasatch formation (Eocene), but continued movement also caused folding in the Wasatch strata which overlies the older rocks with angular discordance. Sedimentary rocks present range in age from Cambrian to Miocene.

Most deposits occur in the Wasatch formation which averages 800 feet in thickness and is comprised of an alternating series of lenticular boulder beds, arkosic conglomerates, fine-to-coarse-grained arkosic sandstones, siltstones and carbonaceous shales.

At the Sno-Ball mine, mineralizaiton is confined to the lower Wasatch beds and lenses of very coarse grained angular arkosic sandstone and conglomerates of granite cobbles. Extreme irregularity in bedding is accompanied by abundant torrential crossbedding. Thin, dark colored carbonaceous mudstone layers are intercalated in the section. The mineralized zones are irregular and may be sporadic in distribution.

Most of the production has come from the top of a persistent carbonaceous mudstone layer which dips approximately 15 degrees to the east. This ore zone, up to several feet thick, swells and pinches in the direction of dip and is irregular and variable along the strike. Uranium is disseminated as grain coatings and as interstitial or cementing material in lenticular beds of coarse-grained poorly sorted angular arkosic sandstone, and in upper parts of the carbonaceous mudstone immediately underlying or interbedded with sandstone ore.

An abundance of carbonaceous fossil plant fragments in present throughout the ore zones and frequently associated with the highest grade ore. A few small steeply dipping faults and fractures have been mineralized, but bedding structures seem to contain more of the uranium.

A white sandstone zone of variable thickness in the basal Wasatch formation is visible for several thousand feet along the strike and is especially prominent in the mine area. This bleached effect may be the

result of alteration accompanying mineral deposition and may be a widespread halo effect localized in the more permeable sandstone layers.

The dominant ore mineral is uranophane, in earthy yellow grains and as paint-like smears along fractures in granite cobbles and boulders. Phosphuranylite is the only other important mineral present and it occurs with the uranophane. Limonite, the dominant gangue mineral, is present as earthy interstitial fillings and as a staining in and around mineralized areas. Ore deposition was favored by lenses of permeable sandstone and layers of carbonaceous mudstone or sooty fossil plant hydrocarbon. There is some suggestion that the extremely variable nature of the sandstone in the mined areas may be due to channel deposition but proof will require more data.

Other significant deposits also containing uranophane as the dominant mineral occur in the Washakie Basin of southern Wyoming and northern Colorado in the Brown's Park formation of Miocene age which covers several thousand square miles in this area (Fig. 1). This formation comprised of sandstones, shales and tuffaceous beds unconformably overlies older strata. Two of these deposits are the Poison Basin claims (Sec. 4 T12N, R92W), west of Baggs, Sweetwater County, Wyoming, and the Gertrude claims (Sec. 17, T7N, R94W), north of Maybell, Moffat County, Colorado which are similar to each other in many respects.

Uranophane (with minor schroeckingerite and meta-autunite) is disseminated in lenticular bedded deposits in medium-to-coarse-grained highly cross-bedded sandstones. The deposits have not been outlined by mining but indications are that limonite staining and bleaching of sandstones are the common alteration effects. An outstanding difference from the Sno-Ball mine is that significant visible quantities of fossil plant hydrocarbon are conspicuously lacking.

REFERENCES

1. Hadfield, J. P., oral communication.
2. Coleman, R. G., oral communication.
3. Coleman, Robert G., *Mineralogical and geological investigations of the uranium deposits of the Wind River District, Wyoming,* US Atomic Energy Commission, RME–4056 (1954).
4. Grutt, Eugene W., Jr., *et al., Preliminary report on uranium deposits in the Wind River Basin, Wyoming,* US Atomic Energy Commission, RME–1056 (1954).
5. Troyer, Max L. *et al., Summary of investigations of uranium deposits in the Pumpkin Buttes area, Johnson and Campbell Counties, Wyoming,* US Geol. Survey Cir. 338 (1954).
6. Sharp, W. N., *Occurrence of uraninite in Tertiary clastic sediments of Wasatch formation, Powder River Basin, Campbell County, Wyoming,* US Geol. Survey TEM–570 (1955).
7. Gruner, John W., *Deposits in the Black Hills and vicinity; comparison of southern Black Hills deposits with Colorado Plateau,* Report on US Atomic Energy Commission Contract AT–30–1–1610 (1954).
8. Whalen, J. F. and Norton, David, *Preliminary report on uranium deposits in the Crooks Gap area, Fremont County, Wyoming,* US Atomic Energy Commission report in preparation.

Geology and Uranium Deposits of the Pumpkin Buttes Area, Powder River Basin, Wyoming

By W. N. Sharp, F. A. McKeown, E. J. McKay and A. M. White,* USA

The Powder River Basin—about 12,000 square miles in area—is a region of prairies and rounded hills in northeastern Wyoming. It is bounded on the east by the Black Hills, on the south by the Laramie Range, and on the west by the Bighorn Mountains. Much of the Basin ranges in elevation from 4000 to 5000 feet. In the south-central part of the Basin several prominent buttes, known as Pumpkin Buttes, rise to an altitude of 6000 feet (Fig. 1).

Deposits of uranium-bearing minerals were first discovered in the vicinity of Pumpkin Buttes in October 1951. This paper briefly describes the mineralogy of the uranium deposits and some of the relationships of the deposits to the regional and local geologic features.

GEOLOGY

The Powder River Basin is underlain by fluvial clastic rocks assigned to the Wasatch formation of Eocene age. Unconformably overlying the Wasatch and capping Pumpkin Buttes are remnants, less than 100 feet thick, of coarse-grained siliceous clastic rocks of the White River formation of Oligocene age. Older rock units are exposed around the periphery of the Basin. These include the nonmarine Fort Union formation of Paleocene age, which is about 3000 feet thick; and an underlying sequence of marine and nonmarine sedimentary rocks that range in age from late Cretaceous to Cambrian and have an aggregate thickness of at least 16,000 feet.

The Basin is essentially a broad northwest-trending asymmetrical syncline with its axis close to the Bighorn Mountains on the west. Faulting is prominent at a few places around the rim of the basin, and a few small faults with 2 to 10 feet of displacement have been observed in the clastics of Tertiary age near the center of the basin. The regional dip of the Wasatch formation east of the axis is 50 to 100 feet per mile toward the northwest.

The results of regional mapping indicate that the axis of a broad, north-trending, low-amplitude anticline lies just east of the Pumpkin Buttes. Dips of this structure generally range from 30 to 100 feet per mile.

Regionally the Wasatch formation is made up predominantly of interbedded siltstones, claystones, carbonaceous shales and lignite with sandstone lenses dispersed throughout; the ratio of fine- to coarse-grained rocks is greater in the north, east, and west, than in the south near the principal source area. The orientation of festoon crossbedding, the long dimensions of sandstone lenses, and the axes of scour channels in siltstones underlying sandstone lenses indicate that the sediments were derived from a source area lying to the southeast. This interpretation is further supported by lateral facies changes; fine-grained clastics and lignite predominate in an arcuate belt west, north, and east of the center of the Basin, whereas coarser grained rocks are dominant to the south.

In the Pumpkin Buttes area, the Wasatch formation is about 1500 feet thick and is composed of claystone, siltstone, lignite in thin discontinuous beds, carbonaceous shale, a few limestone lenses as much as 3 feet thick, thin-bedded sandstone and lenticular crossbedded, fine- to coarse-grained arkosic sandstone. About a third of the formation is made up of sandstone lenses that are from 500 feet to several miles wide, 1 to 8 miles long, and 10 to 100 feet thick. Such lenses are dispersed at random throughout a sequence of siltstone, claystone, and lignite.

Many of the sandstone lenses in the vicinity of the Buttes characteristically are partly or entirely reddish, ranging from dark red brown to pink. These colors contrast sharply with the normal buff or gray color of most of the sandstone in the Wasatch formation in other parts of the Powder River Basin. The contact between red and buff is generally very sharp and transects all variations of lithology and sedimentary structures within the sandstone lenses.

The sandstone is generally poorly sorted and friable; it ranges from very fine- to coarse-grained. Festoon crossbedding is the most conspicuous sedimentary structural feature. At many places, however, the bedding is extremely contorted, and the beds contain abundant debris, such as carbonized twigs, clay galls, and leaf impressions. Such contorted zones were probably the result of deposition in turbulant water. Some of the contorted beds occur in zones 5 or 10 feet thick, contain no debris, and may be the result of slumping shortly after deposition. Calcite concretions (sand grains cemented with calcite) are another characteristic feature of Wasatch sandstone in the Pumpkin Buttes area. The concretions vary in size. Some are less than an inch in

* US Geological Survey.

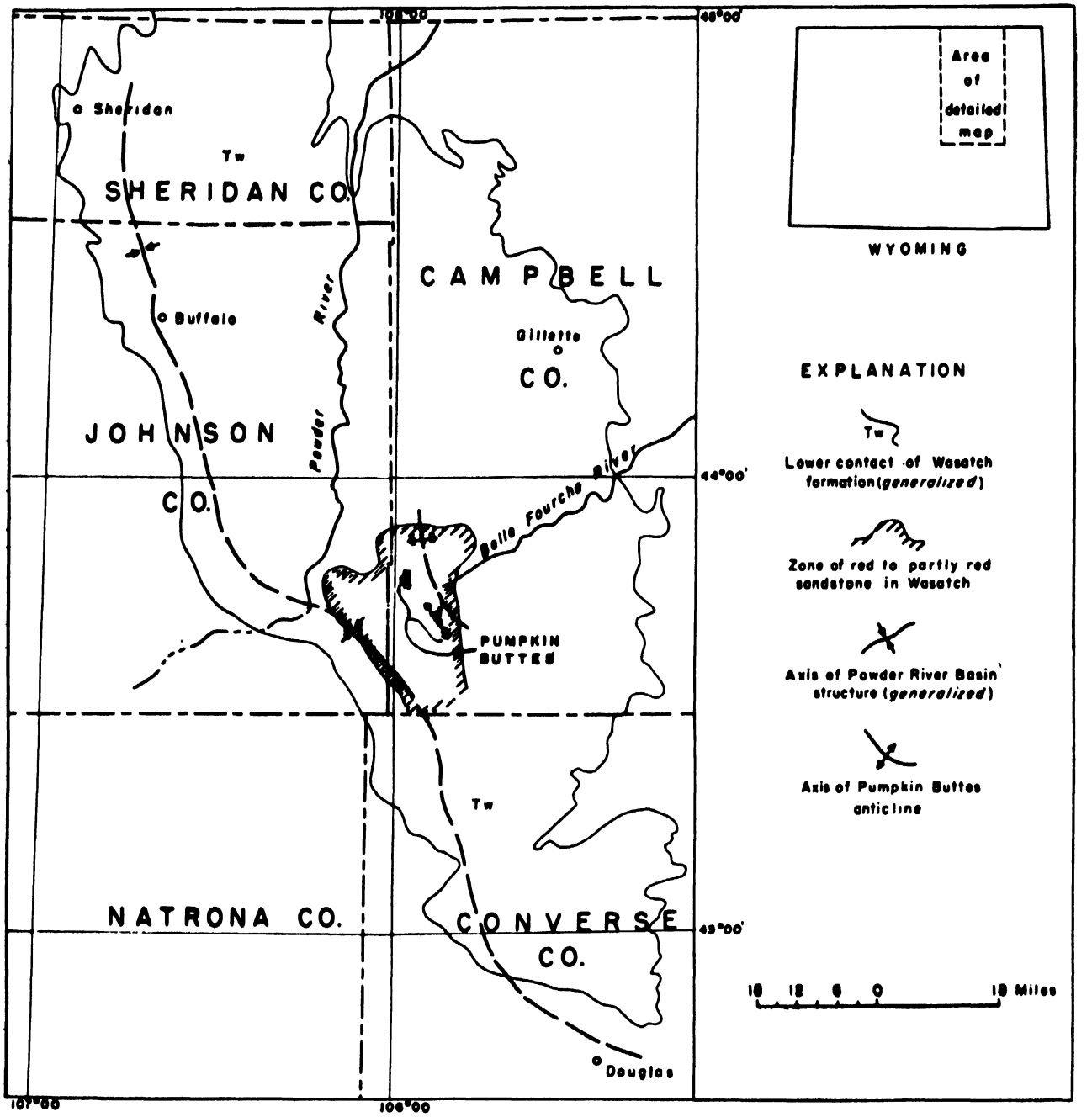


Figure 1. Generalized geologic map of Powder River Basin, Wyoming

diameter; some are cigar-shaped masses 20 or 30 feet long. The small concretions are generally round; the large ones elongated. Cementation transects bedding planes as well as changes in composition and grain size. In general, the elongated concretions are oriented to the northwest. They do not, however, always parallel the direction of streamflow, which also was generally to the northwest.

The claystone and siltstone are predominantly drab brown or gray, though in places purple, green, and pink tints are common. The siltstone is friable, generally thick bedded, and massive. Lateral changes in the composition and grain size may be abrupt. Claystone, siltstone, fine-grained sandstone, and carbonaceous shale commonly grade laterally into one another.

URANIUM OCCURRENCES

More than 250 occurrences of uranium-bearing material have been examined in the Pumpkin Buttes area. Uranium minerals are visible in most of the occurrences, though in some the only indications of mineralized material are anomalous radioactivity readings. The large deposits, containing as much as 2000 tons of ore each, commonly contain about 0.3 per cent uranium. The deposits all occur within an elliptical area of approximately 350 square miles with Pumpkin Buttes in the center. Within this area about

1000 feet of Wasatch formation is exposed. The sandstone lenses that contain concentrations of uranium are in the lower half of this exposed interval.

The chief uranium minerals are uranophane, metatyuyamunite, carnotite, and uraninite. The major vanadium mineral is paramontroseite, associated with secondary uranium minerals at several deposits.

The sandstone from the Pumpkin Buttes area, in which the deposits of uranium-bearing material occur, contains 40 to 70 per cent quartz, quartzite fragments and chert, about 15 per cent feldspar, and minor amounts of chlorite, muscovite, biotite, clay, pyrite, marcasite, garnet, tourmaline, epidote, hornblende, aegirine, elbaite (?), hypersthene, and zircon. Calcite, as cement, is a major component at places. The grains of sandstone are generally subangular to subrounded; alteration of feldspar to sericite and allophane is rare. Manganite, pyrolusite, and psilomelane are common in black nodular concretions.

It is convenient to classify the occurrences of uranium by their different habits and mineralogic associations. Three main types of occurrences are recognized: (*a*) disseminated uranium minerals in porous sandstone or concentrated around calcite-enriched sandstone; (*b*) manganese oxide concretions closely associated with oxidized uranium minerals; and (*c*) uraninite concretions with pyrite.

In general, disseminated uranium minerals are found in buff sandstone lenses, especially at or near the contact of buff sandstone and red sandstone. The largest concentrations occur where this color contact is irregular. These irregularities seem favorable places for elongate concretionary masses of calcite to form in the buff sandstone. Uranium minerals commonly saturate the sandstone between closely spaced concretions. At some places yellow uranium minerals occur in a narrow zone, several inches to several feet wide, parallel to the red-buff contact.

Study of thin sections of rocks from disseminated types of occurrence shows that the uranium-bearing minerals metatyuyamunite, carnotite, and uranophane, calcite, and—rarely—the vanadium-bearing mineral hewettite occur chiefly as interstitial filling. Metatyuyamunite and carnotite occur as irregular microcrystalline masses and rarely have a platy habit; uranophane is generally acicular. Hewettite, also acicular, is rare, and the crystals are very small; they range from 1 to 10 microns wide and 5 to 40 microns long. The uranium minerals commonly replace calcite and in places fill cracks in calcite. At many places, however, the uranium minerals, hewettite, and calcite seem to be contemporaneous. Rarely uranium minerals and hematite replace both potash and plagioclase feldspars.

In most of the uranium deposits in the Pumpkin Buttes area, secondary uranium minerals are associated with concretionary nodules of black, iron-rich manganese oxides which cement and replace sandstone. Some nodules are spherical or tubular and have a core of gray sand speckled with manganese oxide and abundant secondary uranium minerals; other nodules are flat or irregular in shape, and uranium minerals are mixed with specks of manganese oxide in zones peripheral to the black mass. Secondary uranium minerals are associated with manganese oxides not only in isolated discrete concretions but also disseminated in sandstone in zones from 2 inches to 10 feet across. Ferruginous to coaly fossil plant material is associated with many of the manganese nodules. Manganese nodules are found within red sandstone and seem to have no consistent areal or stratigraphic pattern of distribution within individual sandstone lenses.

Thin sections of rocks from concretionary types of occurrences show manganite, pyrolusite, and psilomelane rimming detrital grains of quartz and feldspar, filling interstices and replacing a little feldspar and quartz. Uranophane, metatyuyamunite, and carnotite fill interstices. In places the manganese minerals and uranophane are intergrown.

Uraninite that cements sand in rounded to elongate concretionary nodules, found at two of the larger mines, is commonly associated with pyrite. The pyrite occurs either as the core of a rounded mass of uraninite or as small blebs at the edge of or within the mass of uraninite. In places fossil plant material is found in contact with or nearly surrounded by uraninite, and no pyrite is visible. All uraninite concretions are surrounded by a thick layer of oxidized uranium materials.

In thin and polished sections of uraninite-rich sandstone, uraninite rims sand grains and fills interstices. Calcite also fills interstices and is later than uraninite. Radial clusters of uranophane needles occur rarely on patches of interstitial uraninite. Pyrite in some nodules forms the core and presumably was deposited before uraninite.

Paramontroseite, an unoxidized vanadium mineral, occurs much like uraninite. It is found in dull black irregular masses as much as a foot across in red sandstone. The mineral coats and fills interstices between sand grains. It commonly replaces feldspar and quartz. Pyrite blebs are found at the outer surface of these masses, and green vanadium minerals coat much of the outer surfaces. Coaly fragments occur at places in the pyrite, or in contact with the paramontroseite mass.

CONDITIONS DURING DEPOSITION

Oxidized uranium and vanadium minerals and manganese oxides probably formed in an alkaline oxidizing environment. Studies of thin sections indicate these minerals formed both later than and contemporaneously with calcite. Mineralization is therefore inferred to be related to the same processes that caused a redistribution and crystallization of calcium carbonate.

Polished and thin section studies show that paramontroseite, uraninite, and pyrite developed before and probably contemporaneous with the calcite. This further supports the suggestion that the solution and

subsequent precipitation of uranium, vanadium, and iron minerals were closely related to the solution of limy material and deposition of calcite.

Concentrations of uranium, vanadium, iron, and manganese minerals and calcite may best be explained by the redistribution and concentration of these original components of the sandstone lenses. This is suggested by the apparent redistribution of limy material within sandstone lenses, the epigenetic buff to red color change associated with uranium deposits in sandstone lenses, the general unaltered condition of clay and the low uranium content of coal and carbonaceous shale between sandstone lenses, and the lack of faults and widespread sandstone units that would serve as channels for interformational distribution of mineralizing water.

Lithologic, Structural, and Geochemical Controls of Uranium Deposition in the Southern Black Hills, South Dakota

By H. Bell III, G. B. Gott, E. V. Post and R. W. Schnabel,* USA

Uranium deposits were discovered in 1951 along the southwest flank of the Black Hills, a small isolated mountain range about 160 miles long and 60 miles wide in western South Dakota and eastern Wyoming. By 1954 uranium ore was being mined from several dozen deposits in a 30 square mile area in the southern Black Hills near the town of Edgemont (lat. 43° 22′ N, long. 103° 45′ W).

The deposits are in the nonmarine formations of the Inyan Kara group of Early Cretaceous age. This group of rocks is 500 to 600 feet thick and in ascending order consists of the Lakota sandstone, the Fuson formation, and the Fall River sandstone. These formations are composed predominantly of sandstone. Locally, however, mudstone or interbedded sandstone and siltstone predominate. The formations are lithologically very similar and therefore difficult to tell apart. The Inyan Kara group is underlain by compact clays and marls of the Morrison formation of Jurassic age and is overlain by the marine Skull Creek shale of Early Cretaceous age.

The Inyan Kara rocks form prominent hogbacks and cuestas around a central elliptical mountainous area of Precambrian igneous and metamorphic rocks and Paleozoic and Mesozoic sandstones, limestones, and shales.

The sedimentary rocks surrounding the Precambrian core have been folded into anticlines and domes. In places within the uranium-producing areas they are strongly jointed. Few faults have been observed—none with greater than 100 feet of displacement.

URANIUM DEPOSITS

Carnotite and its calcium analogue, tyuyamunite, are the most conspicuous and most important ore minerals mined from the deposits in the Inyan Kara group, but corvusite and rauvite are important constituents in some mines. Uraninite, becquerelite, hummerite, autunite, and metahewettite are also present in some deposits but have not been found in ore-grade concentrations. The uranium minerals occur as coatings on sand grains, interstitial fillings, fracture fillings, and as coatings on joint surfaces. In some deposits they comprise thin irregular concentric bands and halos. The ore forms both conformable tabular masses and irregular pod-shaped bodies that transgress textural boundaries and structures in the host rocks.

The yellow uranium vanadates, carnotite and tyuyamunite, predominate in thick noncarbonaceous sandstone deposits and are locally known as "yellow ores". Deposits that contain a high proportion of rauvite and corvusite as compared to carnotite and tyuyamunite are largely restricted to thin sandstones interbedded with highly carbonaceous siltstones and are locally known as "black ores". Deposits with a large proportion of black ore are less oxidized than deposits with only yellow ore. In general, the vanadium-uranium ratio in the black ores is greater than 1.5 and in the yellow ores is less than 1.5.

Iron oxide, iron- and manganese-rich calcium carbonate, and carbon are variously or collectively associated with the uranium deposits. A pink iron-oxide-stained sandstone forms a halo around many of the deposits. This stain is so persistently associated with the deposits that it serves as a useful guide in prospecting. Iron- and manganese-rich calcium carbonate occurs in many sandstones of the Inyan Kara group as nodules, interstitial cement, and fracture fillings. Carnotite and tyuyamunite impregnate the porous sandstone that is interstitial to the carbonate nodules and occur marginal to carbonate-filled fractures in a few deposits. Carbonaceous material is closely associated with the deposits in the Fall River sandstone in area III, Fig. 1. These deposits contain black ore and are less oxidized than the deposits in areas I and II. Carbonaceous material is sparse in the deposits of area II in which the yellow uranium vanadates predominate over corvusite and rauvite. The deposits in area I are noncarbonaceous, and their ores are completely oxidized.

With the exception of one small occurrence of uraninite, no deposits of unoxidized uranium and vanadium minerals are known in the Edgemont mining district. Uraninite suggests, however, that this mineral and some low-valence vanadium mineral—deposited, perhaps, in Cretaceous or early Tertiary time and subsequently oxidized—were the primary source of the uranium and vanadium in this district.

There is evidence that both uranium and vanadium have been moved in recent time by ground water. In

*US Geological Survey. Including work by L. R. Page, W. A. Braddock, V. R. Wilmarth, J. D. Ryan, N. P. Cuppels, W. E. Bales and R. D. Smith.

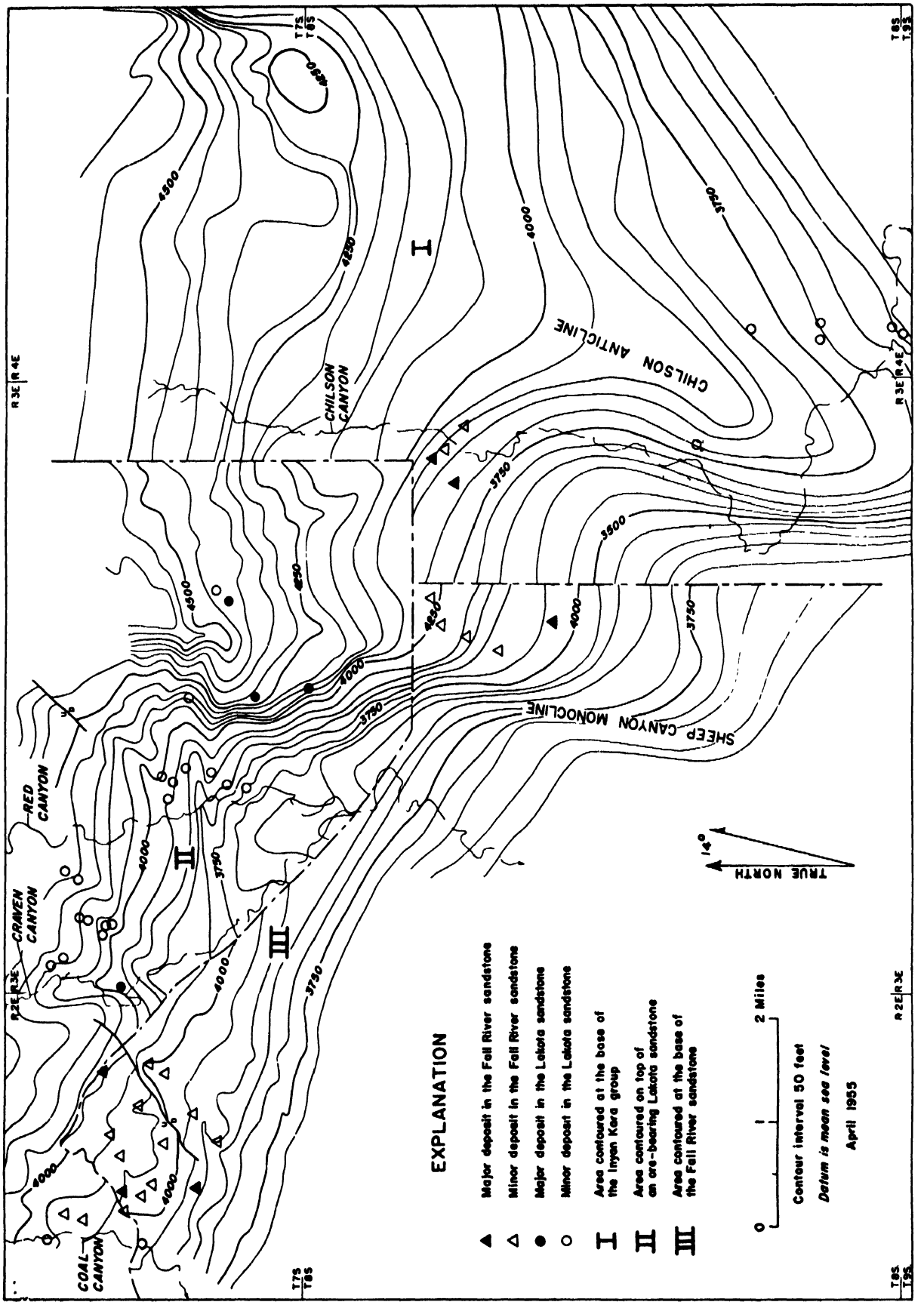


Figure 1. Structure contours and uranium deposits, Edgemont mining district, Fall River County, South Dakota

some deposits, carnotite and tyuyamunite have moved as much as 20 feet down dip from corvusite and rauvite. In other deposits, the yellow uranium vanadates are deficient in radium, thereby indicating that migration of uranium may still be in progress. This probability has been substantiated by the discovery in one of the ore deposits of a musk-ox bone partly impregnated with carnotite. A carbon-14 age determination showed the bone to be 9700 years old. In another deposit a small amount of radioactive barite coating a joint surface assayed about 7 parts per million radium. Thus, some of the radium has also migrated from the uranium during recent time. There is less evidence to show recent movement of vanadium, but hewettite has been found at several localities in fractures below deposits containing corvusite, and traces of hummerite occur on the walls of recently opened mines from which high-vanadium black ore was mined.

CONTROLS OF URANIUM DEPOSITION

Lithology and structure have influenced the localization of the uranium deposits. Also the structural attitude of the host rock and lithologic characteristics such as porosity, permeability, heterogeneous texture, continuity and thickness of the sandstone lenses, scour and fill structures, carbonaceous debris, and cementing material are important. Variations in lithology and structure probably have significantly influenced the migrant uranium-bearing solutions, and played a part in the deposition of uranium minerals. Little is known about these geochemical relationships in the Edgemont mining district.

The sandstones in the Inyan Kara group are predominantly quartzose and are cemented by variable quantities of clay, carbonate, iron oxide, and silica. They are extremely variable in texture, structure, and thickness. White detrital clay fragments, chert, and carbonaceous materials are irregularly distributed but are abundant in certain places. Thin, discontinuous beds of coal occur sporadically. Pyrite is generally rare but abundant where associated with carbonaceous material. Both iron and carbonate concretions abound locally.

The uranium deposits are restricted to three distinct types of sandstone, each having different physical characteristics. For the purpose of this discussion these sandstones are designated as types A, B, and C, which are respectively the dominant host rocks in parts of areas I, II, and III in Fig. 1. The relationship between these types of sandstone is illustrated in the diagrammatic cross section of Fig. 2.

Type A sandstone is characterized by its heterogeneity. It is fine- to coarse-grained, noncarbonaceous, poorly sorted, extremely variable in texture, and intricately cross-stratified. At certain places it contains a sedimentary breccia in which the matrix is a medium- to coarse-grained sandstone, and the fragments are white siltstone ranging in size from pellets to blocks as large as 2 feet across. The breccia fills small scours within the sandstone. This type of

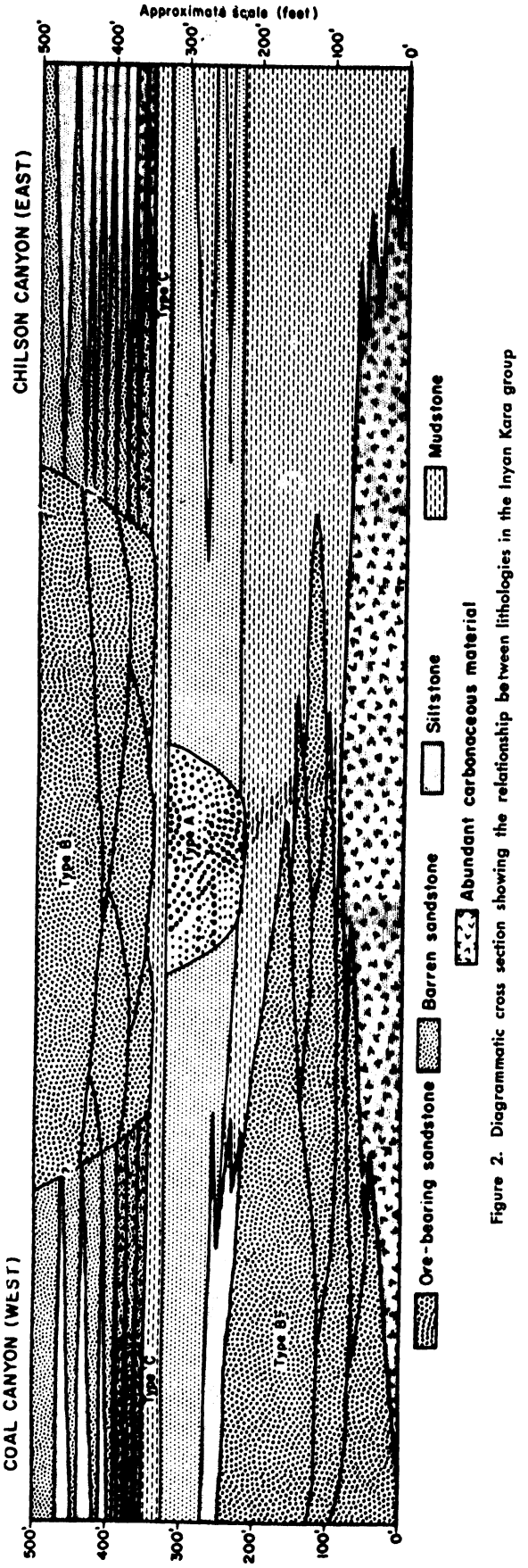


Figure 2. Diagrammatic cross section showing the relationship between lithologies in the Inyan Kara group

sandstone forms elongate bodies as much as 100 feet thick, a mile wide, and at least 3 miles long. In some places the sandstone truncates older rocks of different lithologies, but at other places this disconformable relationship is not evident. The uranium ore is concentrated mostly in medium-grained sandstone containing clay fragments. The boundaries of the deposits, however, are in tabular masses of irregular outline, generally parallel to the bedding but may locally cut across bedding and textural changes. The predominant ore minerals are carnotite and tyuyamunite, but corvusite and hewettite occur sparingly. The largest single uranium deposit in the southern Black Hills occurs in this type of sandstone.

Type B sandstone forms units as much as 250 feet thick, several miles wide, but unknown length. The units are composed of a series of lithologically similar sandstone lenses that truncate and overlap the underlying lenses. The sandstone appears to grade laterally into a facies of relatively thin sandstones interbedded with mudstones. Type B sandstone is fine to medium grained, homogeneous in texture and structure, and contains scattered pockets and streaks of carbonaceous debris parallel to the bedding. Type B sandstone is best developed in the lower part of the Lakota sandstone in area II, and in the Fall River sandstone throughout the southeastern part of area III. Many of the uranium deposits in this type of rock are associated with carbonaceous material, although some have been localized adjacent to fractures. The principal ore minerals are carnotite and tyuyamunite, but minor amounts of the high-vanadium black ores occur in some deposits. The deposits are numerous but with few exceptions small, and their total production has been of minor importance.

Type C sandstone is part of a sequence of thin, well-sorted fine-grained sandstones that alternate with thin-bedded and laminated carbonaceous siltstones. This sequence is about 25 feet thick. Macerated carbonized plant remains and disseminated crystals and nodules of pyrite are abundant, particularly in the siltstone beds. The uranium deposits are restricted to sandstones generally less than 5 feet thick. Thicker sandstones tend to be barren or to contain only small deposits.

The deposits in type C sandstone are of a magnitude of 5000 tons or less. All these deposits contain black ore having a high percentage of corvusite and rauvite, and are less oxidized than any of the deposits in the southern Black Hills. A large proportion of the ore produced in the Edgemont mining district has come from a group of deposits in this type of sandstone. These are the Fall River sandstone deposits in the western part of area III, Fig. 1.

The ore deposits in sandstone types A, B, and C are restricted to the Fall River and Lakota sandstones. Sandstones in the Fuson formation are mineralized in only a few places, and production from them has been negligible. Barren sandstones in the three formations are of several types. One is a conspicuously white noncarbonaceous fine-grained even-textured structureless sandstone that is generally cemented with clay to such an extent that its permeability appears to have been effectively reduced. Another type of barren sandstone is similar to type C described above but is interbedded with calcareous or highly argillaceous mudstones rather than with carbonaceous siltstones. Other types include sandstones in which permeability has been effectively destroyed by silicification or by carbonate cement.

The localization and relative size of uranium deposits in the Black Hills appear to be controlled by structures of various magnitudes.

The Black Hills uplift is an elongate northwest-trending dome, the east and west sides of which dip more steeply than the northwest and southwest ends. The known uranium deposits are in the areas of gently dipping rocks at the northwest and southwest ends of the uplift.

Superimposed upon the regional Black Hills uplift are several anticlines which, as they plunge northward and southward off the dome, interrupt the homoclinal dip of the beds. Figure 1 shows the relationship of one of these anticlines and smaller structural features with the ore deposits in the Edgemont mining district. This illustration shows that the west limb of the Chilson anticline is interrupted by a southward plunging structural terrace on which the dip is less than 3 degrees. This limb of the Chilson anticline continues west of the terrace as the Sheep Canyon monocline, which dips as much as 20 degrees to the west. The largest known deposits and greatest reserves in this district are located on the structural terrace between the monocline and the anticline. In addition to the ore deposits shown on Fig. 1 on this terrace, there are large low-grade deposits on the terrace that under present economic conditions cannot be mined without beneficiation. These deposits are several times larger than any ore-grade deposit in the area.

The second most important uranium-producing area within the Edgemont mining district is a group of deposits in the Fall River sandstone between Coal Canyon and Craven Canyon in the northwestern part of area III. These deposits are on another smaller structural terrace. The regional dip in this area is about 2½ or 3 degrees southwest, whereas the dip across the terrace averages about 1¼ degrees. Detailed structure-contour maps show that all these deposits occur in the area of abnormally low dip or near the margins of the terrace where the dip steepens appreciably. This group of deposits is restricted to that part of the terrace underlain by the favorable sandstones of type C. The deposits in this area are smaller than those on the terrace between the Chilson anticline and the Sheep Canyon monocline.

The deposits in the Lakota sandstone in area II west of the Sheep Canyon monocline are mostly restricted to small terraces and anticlinal noses, although a few do not appear to be related to either type of structural feature. To date the production from these deposits has been small.

Faults with displacements greater than 100 feet are uncommon in this area. With the possible exception of the fault between Coal and Craven Canyons in area III (Fig. 1), faults do not appear to be related to the deposits. In area III it is improbable, but not impossible, that the fault rather than the terrace influenced the localization of deposits.

Some of the deposits have been controlled by fractures. Fractures that cut uranium deposits are commonly filled with uranium minerals. In one of the large deposits on the terrace between the Chilson anticline and the Sheep Canyon monocline, uranium minerals have been traced discontinuously for over 4000 feet along a set closely spaced northwest-trending vertical fractures. In another mine in this same area, rich concentrations of yellow uranium minerals and considerable limonite have been found at the intersections of several variously oriented fractures. In still another mine, carnotite is concentrated in bands as much as 2 inches wide along vertical joints in a homogeneous sandstone, and isoradioactivity lines outline radioactivity anomalies enclosing and parallel to apparently unmineralized joints. In a few places, carnotite and tyuyamunite are associated with iron- and manganese-rich carbonate fracture fillings.

CONCLUSIONS

The uranium deposits in the southern Black Hills are composed of partly oxidized black ores in a highly carbonaceous environment and oxidized yellow ores in a slightly carbonaceous or noncarbonaceous environment. The restriction of the least oxidized ores to carbonaceous rocks probably has resulted from the greater stability of the original minerals in the reducing environment of carbonaceous materials. The yellow ores may have resulted from more complete oxidation because of the absence of organic material in a porous aquifer.

Carnotite and tyuyamunite occur in carbonate-cemented sandstone in a few deposits, but generally the uranium is restricted to noncalcareous rocks. It is possible that an environment of carbonate-bearing sandstone inhibits the deposition of uranium except in the transitional zones between carbonate- and noncarbonate-bearing rocks.

The greatest concentration of uranium deposits and the largest deposits in the Edgemont mining district are found where favorable lithologies and favorable structures are superimposed. The most favorable structures are the large structural terraces. Steeply dipping structures are unfavorable. Favorable structures appear to have influenced the size of the deposits. The largest deposit in both homogeneous and heterogeneous sandstone is on a large structural terrace.

On the most favorable structures, however, deposits containing black ores tend to be smaller than deposits with only carnotite and tyuyamunite.

Occurrence of Uranium in Diatremes on the Navajo and Hopi Reservations, Arizona, New Mexico, and Utah

By E. M. Shoemaker,* USA

Dikes and volcanic necks containing alkalic basaltic rocks have been known for many years to be widely distributed on the Navajo and Hopi Indian Reservations, in Arizona, New Mexico, and Utah, an area equal to about one-quarter of the state of Arizona.[1,2] Most of the exposed volcanic necks are funnel-shaped vents filled chiefly with tuff; for this kind of volcanic vent Daubrée[3] coined the name diatreme. A diatreme, as Daubrée conceived it, is a vent drilled by volcanic explosion. The primary evidence for explosive volcanism is the pyroclastic debris that fills the vent. Though the general features of many of the diatremes were long recognized, some of the details of structure, particularly in the diatremes of the Hopi Buttes, were not fully appreciated until the studies of Hack.[4] In the last few years uranium deposits have been found in or associated with diatremes in widely separated parts of the Navajo and Hopi Indian Reservations. This paper is based on a reconnaissance study which is an outgrowth of a regional investigation of the distribution of elements in the igneous rocks of the Colorado Plateau. A detailed investigation of the diatremes is in progress.

STRUCTURE OF THE DIATREMES

About 250 diatremes are located on the Navajo and Hopi Indian Reservations. In many respects they are closely similar to the typical diatremes of eastern Fife, Scotland,[5] and the Schwabian Alb.[6] A few of the Navajo-Hopi diatremes have several features in common with the diamond pipes of South Africa,[7] and, in fact, in some of them the pyroclastic material is close to kimberlite in composition. The diatremes are associated with dikes and simple basalt-filled volcanic necks, and locally with flows and tuffs interstratified with nonvolcanic sediments of middle Pliocene age.[2,8] These sediments rest upon a surface of low relief which is preserved, though deeply dissected, in parts of the Hopi Buttes area and in the Chuska Mountains, but which has been completely eroded away over most of the Navajo and Hopi Reservations (Fig. 1). Many of the diatremes flare to a width of a mile or more at the level of the Pliocene surface onto which they erupted. Where the Pliocene surface has been stripped away, the uppermost part of the diatreme is also partly removed and the exposed vent is smaller. Generally the vents range from a few hundred feet to half a mile in diameter where they are exposed at depths of 1000 to 2000 feet below this Pliocene surface.

A wide variety of material fills the diatremes; the material found at any one exposure appears to depend largely on the stage of development of the diatreme and the level at which it is exposed. A generalized description of the vertical distribution of material in a typical or ideal diatreme can be made by the study of certain diatremes which form prominent spires on the landscape, up to nearly 2000 feet in height, and on the basis of the composite features of many diatremes exposed at different levels of erosion. In its upper part, a fully developed diatreme is filled with bedded tuff and limestone, and locally with thinly laminated clay and siltstone, evaporites, and even some bedded chert. Lower in the vent these sediments give way to more massive tuff, breccia, huge blocks of country rock, agglomerate, and ultimately to solid igneous rock.

Much of the tuff filling, which in some vents is at least 2000 feet thick, is well bedded and shows many features of fluviatile deposition, such as cross-lamination, channels, and erosion surfaces. Limestone interbedded with the tuff ranges from massive to thinly laminated, and much of it is argillaceous although a few beds are composed of relatively pure calcium carbonate. The interstratification of thinly laminated limestone with bedded tuff and the content of fine-grained clastic material in the limestone suggest that the limestone was deposited in shallow ephemeral ponds within the diatremes. Hack[4] has suggested that much of the limestone in the Hopi Buttes diatremes is of thermal origin, and some of the limestone is similar to travertines formed by hot springs in nearby parts of Arizona.[11] Some of the limestone in the Hopi Buttes diatremes contains unusual concentrations of phosphate. As fresh surface and ground water generally contains extremely low amounts of phosphate, the high phosphate content of the limestone may also suggest that the carbonate was in part supplied by rising thermal solutions. The general conditions of sedimentation in the diatremes may be represented by a diatreme of recent origin at Zuni Salt Lake,[12] New Mexico, (Fig. 1).

In the upper parts of the diatremes the beds generally dip gently toward the center of the vent.

* US Geological Survey.

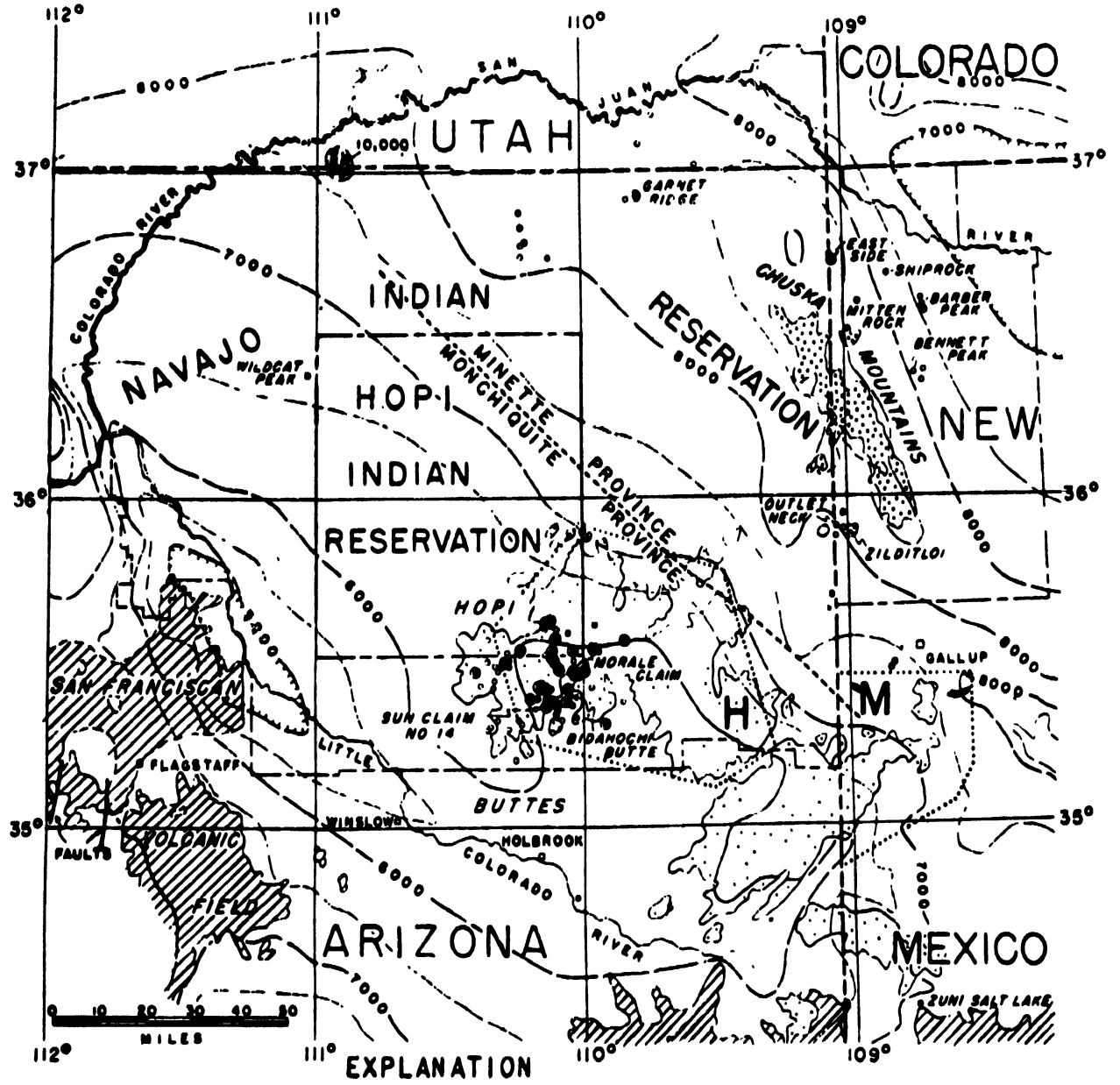


Figure 1. Map of the Navajo and Hopi Indian reservations and vicinity showing the distribution of diatremes, sedimentary and volcanic rocks of Pliocene (?) age, and contours on the Pliocene surface

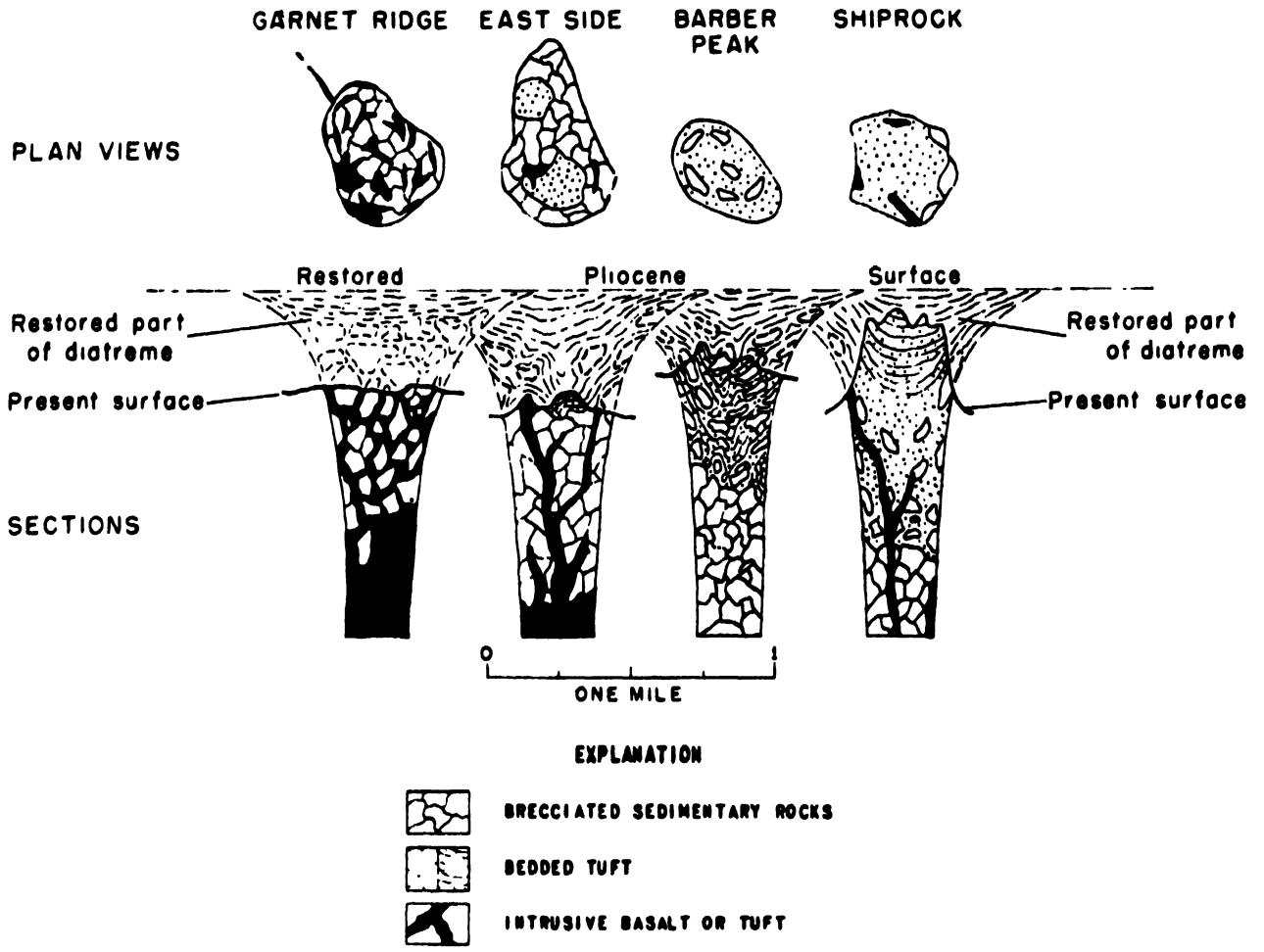


Figure 2. Diagrammatic plan views of four diatremes from the Navajo reservation illustrating successive stages of subsidence

The dips of the beds increase with depth, and the beds are commonly vertical or intensely deformed in the deeply eroded vents. In some deeply eroded vents the bedding is displaced and partly obscured by many small close-spaced thrust faults. Fragments of rocks from all parts of the sedimentary column and, in places, from the crystalline Precambrian basement are generally incorporated throughout the tuffs. The fragments range from minute grains to blocks over 100 feet long. Small fragments are derived from formations that both underlie and overlie the position at which the fragments are found, but fragments in excess of about 10 feet across are, in nearly every case, derived from above. The demonstrable downward displacement of some fragments is more than 2000 feet. The great thickness and downward increase in degree of deformation of the beds in the diatremes as well as the demonstrable downward displacement of huge blocks incorporated in well-stratified tuff are believed by the writer to indicate large-scale subsidies or collapse of the filling of most of the vents.

Successive stages of collapse are believed to be exemplified by the diatremes at Garnet Ridge, East Side mines, Barber Peak, and Shiprock (Fig. 2). These diatremes are all eroded to a comparably deep level. Incipient collapse, of a few hundred feet, is found in the diatreme of Garnet Ridge, which is filled mainly with huge blocks of down-dropped sandstone of Jurassic age enclosed in an injected pyroclastic matrix of phlogopite-bearing serpentine tuff. In a similar structure at the East Side mines, patches of stratified tuff deposited on the jumbled blocks are preserved at the level to which the diatreme has been eroded. The Barber Peak diatreme is filled with well-bedded tuff through which are scattered large blocks of sandstone of Cretaceous age forming a partial conical screen of sandstone slabs within the tuff. The beds all dip steeply toward the center of the vent. In fully developed diatremes, such as Shiprock, the bulk of the vent exposed to view is filled with tuff. Only a few large blocks of country rock are found and these are chiefly in the lower part near the walls of the vent. Near the crest of Shiprock, a tapering monolith rising about 1700 feet above the desert floor, the tuff is crudely stratified but toward the base becomes massive. The tuff probably extends to considerable depth, passing by

degrees into a tuff filled with huge blocks of country rock, such as at Barber Peak, and finally into a macro-breccia of country rock such as at Garnet Ridge and the East Side diatremes. The differences between these diatremes are probably due mainly to differences in the relative amount of subsidence that has occurred in each vent and somewhat to the differences in the depth at which each vent is exposed.

The source of the tuff filling the diatremes must have been either a cinder cone formed prior to collapse, or material ejected from nearby vents, or perhaps both. Some diatremes show unmistakable evidence of multiple explosion, such as large angular blocks of stratified or massive tuff, incorporated in a later tuff or breccia. Many diatremes are intruded by later dikes, but the dikes cannot have been the source of the tuff which they cut. Many of the diatremes probably became the locus of extrusion of lava after collapse had ceased.

In an attempt to integrate the observed relations into a coherent picture, the following generalized hypothesis of diatreme evolution is proposed. The initial phase of nearly all volcanic activity in the Navajo-Hopi region was probably the explosive drilling of a vent. Such vents commonly were of limited width and may have merged laterally or downward with dikes or may have been entirely unassociated with dikes. In general, they were filled by a quiet upwelling of lava, which in some vents reached the surface, and poured out in considerable volume. If the volcanic process ended at this stage the resulting features would be dikes, basalt-filled necks commonly jacketed with a thin layer of tuff or breccia formed in the initial vent, and flows, some of which would be traceable to the necks. These features are well represented in the Hopi Buttes and in the vicinity of the Chuska Mountains.

In general, the volcanic process progressed beyond this initial stage. At the site of a neck or a group of dikes a gradual and progressive subsidence took place. That subsidence took place more or less continuously and over a considerable period of time can be demonstrated at a number of localities by the complex sedimentary record, which includes angular unconformities between beds of tuff interstratified with thinly laminated silts and limestones. The depression created at the surface was filled with sediments chiefly of volcanic origin. The funnel-shaped orifice of the diatreme was enlarged by the inward collapse of the walls of the vent. Perhaps the funnel shape of the vent near the surface of eruption was governed to some degree by the extent of disruption of the country rock during the initial explosion. As the sediments which were deposited at the surface were sucked downward and compressed in the narrowing orifice, large blocks derived from the collapsing walls, were incorporated in the diatreme filling.

COMPOSITION OF THE VOLCANIC ROCKS

The volcanic rocks associated with the diatremes are nearly all alkaline basalts which, in their intrusive phase, would fall mainly under the classification of the two lamprophyres, monchiquite and minette.[2] Minettes are found in the northeast half at the Navajo-Hopi region and monchiquites mainly in the southwest half. A very few monchiquites are found in the same area as the minettes, but the region may be broadly divided into a monchiquite province and a minette province (Fig. 1). Serpentine tuff, some phlogopite-bearing and some similar to kimberlite, is found in the minette province at Garnet Ridge and in the Zilditloi volcanic area.[13,14]

The monchiquitic basalts are ultramafic moderately alkaline volcanic rocks. Compared with olivine basalts from the Colorado Plateau they are distinctly characterized by relatively high concentrations of water, titania, and phosphate. The monchiquites are significantly richer than Colorado Plateau olivine basalts in zirconium, barium, niobium, and the cerium group rare earths.

The minettes, highly potassic basaltic rocks, contain more water and phosphate than the olivine basalts and also relatively high concentrations of barium, strontium, beryllium, boron, cerium group rare earths, and lead.

Both the monchiquites, with an average radioactivity of 0.0012 per cent equivalent uranium (eU), and minettes with an average radioactivity of 0.0046 per cent eU are unusually radioactive compared with Colorado Plateau olivine basalts which have an

Table 1. Uranium and Thorium Content of Samples of Monchiquite and Minette from the Navajo Reservation (in parts per million)

	Olivine monchiquite, Bidahochi Butte		*Nepheline monchiquite, Wildcat Peak*		*Basic minette, Outlet Neck*		*Minette, Bennett Peak*		*Feldspathic minette, Mitten Rock*	
	U	*Th*	*U*	*Th*	*U*	*Th*	*U*	*Th*	*U*	*Th*
Total rock	2.2	6.4	4.6	17.5	11.9	28.4	12.3	31.5	10.6	50.1
Leached residue[a]	2.2	6.3	5.0	17.7	10.7	29.3	13.0	33.3	10.9	52.0
Leachate[a]	2.4	7.3	1.6	16.4	29.8	15.7	1.7	3.9	3.1	9.0
Per cent rock Leached[a]	12.51		12.33		6.34		6.31		4.45	

[a] Powdered rock leached in 0.05 molar HNO_3 in steam bath for one-half hour.

(Analyst: J. C. Antweiler, US Geological Survey; calculation: G. J. Neuerburg, US Geological Survey.

average radioactivity of 0.0005 per cent eU. The high radioactivity is due to higher concentrations of both uranium and thorium (Table I). The uranium and thorium content of the minettes is notably higher than the average uranium and thorium content in most basaltic rocks.[15] A further unusual feature of the concentration of uranium and thorium in the monchiquites and minettes is the low proportion of uranium and thorium in the acid soluble or leachable fractions of the rocks. In most igneous rocks with high content of uranium, a high proportion of the uranium is acid-soluble.[15,16] Among other factors, the low proportion of leachable uranium and thorium in the Navajo-Hopi alkaline basalts might be due to loss of leachable uranium and thorium during weathering or during the last stages of crystallization.

URANIUM DEPOSITS

Uranium deposits are localized in or adjacent to diatremes in widely separated parts of the Navajo and Hopi Indian Reservations, but the bulk of the known deposits are in the Hopi Buttes area (Fig. 1). No thorium content greater than the content of the unmineralized igneous rocks is known to be present in the uranium deposits.

In the northern part of the region, uranium-bearing rock is found at the Garnet Ridge diatreme, adjacent to the East Side diatreme, and at Shiprock. Small concretionlike deposits of uranyl and cupric vanadates and copper carbonates are localized in the Navajo sandstone of Jurassic and Jurassic(?) age. The deposits are adjacent to a discontinuous dike of mica-serpentine tuff that extends northwest of the Garnet Ridge diatreme. This occurrence has been known as a copper prospect for a long time (Reference 1, Plate II) and uranium minerals were noted in the prospect a few years ago. Malachite, chrysocolla, volborthite, and metatyuyamunite have been identified in the mineralized sandstone for the writer by M. E. Thompson, (US Geological Survey). The uranium-bearing sandstone also contains trace amounts of introduced silver, cobalt, nickel, lead and thallium. Selected samples contain as much as 2.06 per cent uranium, but the amount of exposed mineralized material is too small to be of economic importance. Spectrographic analysis of core drilled through the tuff dike shows that calcium, strontium, nickel, vanadium, copper, and lead are dispersed in the sandstone walls of the dike.

Table II. Uranium and Phosphate Analyses of Selected Samples from the Hopi Buttes

Sample and location	Per cent U	Per cent P_2O_5
Claystone, Bidahochi formation	0.001	0.18
Limestone, Sun claim No. 14	0.002	0.30
Siltstone, Sun claim No. 14	0.012	0.38
Siltstone, Morale claim	0.041	0.46
Ore, 13 tons, Morale claim	0.17	0.90

Analysts: H. Lipp and J. Such, US Geological Survey.

Blagbrough (US Atomic Energy Commission)[17] has reported the occurrence of uranium and vanadium minerals in a dike of brecciated sedimentary rocks in the Salt Wash member of the Morrison formation of Jurassic age adjacent to the East Side diatreme. It is possible that the uranium and vanadium were simply derived from nearby carnotite deposits in the sandstones of the Salt Wash member. At Shiprock the writer found slight concentrations of uranium, up to 0.002 per cent, associated with amethyst in minette agglomerate within the diatreme.

Uranium deposits were first discovered in the Hopi Buttes area in 1952 by the writer. Since then private prospecting and radiometric reconnaissance by the US Atomic Energy Commission have shown that the uranium deposits are widespread in the Hopi Buttes diatremes, and shipment of ore was begun from one deposit in 1954. Much of the limestone in the Hopi Buttes diatremes has been found to contain from 0.001 to as much as 0.02 per cent uranium, and nearly every diatreme that contains exposed limestone is conspicuously more radioactive than the surrounding rocks. Concentrations of uranium higher than 0.02 per cent are found in some limestones, but more commonly in siltstones and claystones. About 20 of the more highly mineralized diatremes are shown in Figure 1. It is expected that continued prospecting and geologic investigation may greatly increase this number.

The mineral forms in which the uranium is present in the diatreme rocks is not fully known. Gruner[18] has identified in the carnotite (calcium uranyl vanadate) from one of the diatremes, and Gross[19] (US Atomic Energy Commission) has found the liebigite (calcium uranyl carbonate) in claystone from another diatreme. Most of the more intensely mineralized rock contains no visible uranium minerals, and the material is so fine grained that microscopic identification of the minerals is difficult. Chemical analysis of a few samples reveals a strong positive correlation between the uranium and the phosphate content of the rocks (Table II at lower left of this page).

The vanadium content of the ore-grade material is less than 0.05 per cent. The amount of phosphate is considerable in excess of that required to form the known uranyl phosphates, and the fluorescent uranium phosphates, such as autunite, bassettite, or phosphuranylite, have not been detected. The bulk of the uranium may be contained in very fine-grained apatite.

The highest known concentrations of uranium in the Hopi Buttes diatreme are in laminated siltstones that unconformably overlie deformed beds of coarse tuff, tuff-breccia, and agglomerate. At the Morale claim (Fig. 1) ore-grade concentrations of uranium are also found in the coarse-grained deformed rocks beneath the unconformity. Smooth erosion surfaces bevel the deformed beds on which the fine-grained laminated rocks lie. An abrupt cessation of sedimentation followed by a renewal of sedimentation at a

very slow rate appears to be indicated by the unconformities. Concentrations of uranium approaching ore grade are also found in thick relatively massive claystone in a diatreme south of Bidahochi Butte.

Preliminary evaluation of the data on the uranium deposits has led to a tentative hypothesis on the origin of the deposits. The widespread distribution of uranium in the limestones in the diatremes suggests the uranium may be syngenetic in the limestones. It is suggested that the uranium may also be syngenetic in the fine-grained clastic sediments. One of the factors governing the concentration of uranium in the various rock types in the diatremes may simply be the rate of sedimentation. If uranium-bearing solutions were supplied more or less continuously from depth, the uranium would be concentrated in beds, such as limestone and siltstone, that were deposited at the slowest rate and would tend to be more dispersed in the coarser beds of tuff, which were deposited rapidly.

It is further suggested that the uranium was derived from the hydrous, phosphate-rich, moderately uraniferous monchiquite magma, as the magma crystallized in the depths of the diatremes or beneath the diatremes. Relatively high concentrations of phosphate in the limestones suggest the phosphate may have been supplied from depth by juvenile solutions, perhaps together with an appreciable amount of the carbonate. Spectrographic analysis of a mineralized limestone shows that it also contains low, but unusual, amounts of strontium, vanadium, cobalt, and copper—elements that are present in moderately high concentration in the monchiquites. The strong correlation of uranium with phosphate in the mineralized rocks suggests the uranium may have been carried in with the phosphate. The uranyl ion is highly soluble in carbonate solutions. The low proportion of uranium in the leachable fractions of the monchiquites may indicate that a considerable proportion of the uranium was lost in the final stages of crystallization of these rocks. It should be noted, however, that thorium is also low in the leachable fractions of the monchiquites but is not known to be concentrated in the uranium deposits.

REFERENCES

1. Gregory, H. E., *Geology of the Navajo Country, A Reconnaissance of Parts of Arizona, New Mexico, and Utah,* US Geological Survey Professional Paper 93 (See p. 83–107) (1917).
2. Williams, Howell, *Pliocene Volcanoes of the Navajo-Hopi Country,* Geological Society of America Bulletin 47: 111–172 (1936).
3. Daubrée, Auguste, *Recherches Experimentals sur la Rôle des Gas a Hautes Temperatures,* Society Geologic France Bulletin 19: 313–354 (1891).
4. Hack, J. T., *Sedimentation and Volcanism in the Hopi Buttes, Arizona,* Geological Society of America Bulletin 53: 335–372 (1942).
5. Gieke, Archibald, *Geology of Eastern Fife,* Geological Survey of Scotland Memoire (1902).
6. Branco, Wilhelm, *Schwabens 125 Vulcan-Embryonen,* Stuttgart (1894).
7. Wagner, P. A., *The Diamond Fields of Southern Africa,* Johannesburg (1914).
8. Stirton, R. A., *A New Beaver from the Pliocene of Arizona,* Journal of Mammalogy 17: 279–281 (1936).
9. Repenning, C. A. and Irwin, J. H., *Bidahochi Formation of Arizona and New Mexico,* American Association of Petroleum Geologists Bulletin 38: 1821–1826 (1954).
10. McCann, F. T., *Ancient Erosion Surface in the Gallup-Zuni Area,* New Mexico, American Journal of Science 36: 260–278 (1938).
11. Harrell, M. A. and Eckel, E. B., *Ground-Water Resources of the Holbrook Region, Arizona,* US Geological Survey Water-Supply Paper 836-B (1939).
12. Darton, N. H., *The Zuni Salt Lake,* Journal of Geology 13:185–193 (1905).
13. Malde, H. E., *Serpentine Pipes at Garnet Ridge, Arizona,* Science 119: 618 (1954).
14. Allen, J. E. and Balk, Robert, *Mineral Resources of Fort Defiance and Tohatchi Quadrangles, Arizona and New Mexico,* New Mexico Bureau of Mines and Mineral Resources Bulletin 36 (See p. 99–118) (1954).
15. Larsen, E. S., Jr. and Phair, George, *The Distribution of Uranium and Thorium in Igneous Rocks* in Faul, Henry, *Nuclear Geology,* John Wiley and Sons, Inc., New York, 75–89 (1954).
16. Hurley, P. M., *Distribution of Radioactivity in Granites and Possible Relation to Helium Age Measurements,* Geological Society of America Bulletin 61: 1–7 (1950).
17. Blagbrough, J. W., oral communication.
18. Gruner, J. W., oral communication.
19. Gross, E. B., oral communication.

The Organic Geochemistry of Uranium

By I. A. Breger and M. Deul, USA

The large number of occurrences of uranium in carbonaceous rocks precludes a purely fortuitous association. Despite this, the role of organic substances in the geochemical cycle of uranium is not well understood. It is the purpose of this paper to review information regarding several organo-uranium associations and to suggest geochemical mechanisms responsible for their formation.

Among the earliest recognized associations of uranium with organic matter were the black, carbonaceous marine shales. About the end of the nineteenth century, studies were carried out on the Swedish alum shale and on the highly carbonaceous and uraniferous kolm lenses, which occur in certain strata of the shale.[1,2,3] A summary of these studies appeared in 1923.[4] Studies of the Swedish shale and the kolm led to the conclusion that the uranium had been precipitated in the shale by means of organisms. This is apparent in studies of other radioactive shales where apparent relationships have been observed between the organic carbon and uranium.[5,6,7]

It is known that marine carbonaceous shales are usually more uraniferous than the associated marine sediments. Study of several such shales that were considered to be unusually radioactive has, however, shown them to contain less than 20 ppm of uranium.[8] This content is considerably lower than those for certain shales such as the Swedish alum and Chattanooga formations. Few marine shales contain over 50 ppm of uranium.

Although most coals are not uranium bearing, some that occur within or close to uraniferous provinces contain small but significant percentages of uranium. Study of several of these coals indicates that uranium became associated with the coal after deposition.[9] The ability of coals to adsorb uranium from solution has been shown by More[10] and Szalay;[11] Breger, Deul, and Rubinstein[12] have studied the nature of the organo-uranium association in detail. Besides the reported adsorption of uranium by bedded coals,[13] many associations of uranium with coalified logs and coalified wood fragments have also been noted on the Colorado Plateau[14] and in other areas. It has become clear within recent years that coal or materials derived from plants are avid receptors for uranium.

Uranium occurs in appreciable percentages in carbonaceous materials of unknown origin in various parts of the world. Cellular structure—which can be used to identify carbonaceous substances as of plant or animal origin—has not been recognized in these substances. One such substance, the carbonaceous gold- and uranium-bearing "carbon leader" of the Witwatersrand has been dated as Precambrian in age;[15,16] thucholite from Canada is reported to be of igneous origin.[17] Other substances, such as the carbonaceous pellets that occur in the Cretaceous sandstones in Emery County, Utah,[14] or in the dolomites and limestones of early Pennsylvanian to Permian age in the Amarillo-Wichita uplift area of Oklahoma and Texas,[18,19] also contain significant percentages of uranium. Uranium-bearing carbonaceous materials likewise occur in Australia, Russia, and on the Isle of Man.[15] The lack of information regarding the origin of these substances and their relationships to one another has resulted in the use of various names such as "uraniferous hydrocarbon," "asphaltite," "carbocer," "carbon," thucholite," etc.

THE BIOGEOCHEMISTRY OF URANIUM

Concentrations of uranium in carbonaceous material have led to speculation regarding absorption of the element by living plants and animals. To investigate the possibility that living plants might concentrate appreciable percentages of uranium, Hoffman[20,21] analyzed various woods, algae, and other materials, and obtained the data summarized in Table I. The plant samples, collected from nonuraniferous areas near Vienna, contained very small amounts of uranium, far below the range of 1 to 3 ppm, which is usually taken as the average uranium content of terrestrial sediments. Only the algae, growing in an aqueous environment subject to continuous replenishment of uranium, contained any appreciable amount of the element. It must be concluded from these data that plants absorb extremely small percentages of uranium. Even after applying maximum concentration factors due to decay and compaction of plant material, the amount of uranium absorbed is insufficient to account for the large quantities of uranium observed in some carbonaceous substances. Similar studies[22] have shown that animals absorb uranium from plants through nutritional processes and contain the element in quantities similar to those found in living plants.

Certain plants growing in uraniferous provinces, such as the Colorado Plateau, are able to absorb uranium,[23] but it is evident that neither plants nor

* US Geological Survey.

animals normally contain appreciable percentages of the element. Secondary processes must, therefore, be responsible for the introduction of uranium into carbonaceous deposits.

TRANSPORTING MEDIA

Because uranium is not genetically associated with carbonaceous substances, it is necessary to consider those media through which the element can migrate from a source to its eventual association with carbonaceous materials. The most important transporting media that are to be considered are water, petroleum, and compressed gas.

Table 1. Uranium Content of Woods, Seeds, Algae and Other Substances

Substance	*Condition*	*Ash (per cent)*	*Uranium in ash (ppm)*	*Uranium content of plant substance (ppm)*
Woods				
Apricot	Dead	1.73	7	0.12
Birch	Alive	0.65	0.059	0.0004
Plum	Alive	1.45	0.008	0.0001
Plants				
Grapevine	Alive	1.60	0.0048	0.00008
Cornstalk	Dead	0.72	0.11	0.0008
Tobacco	Dead	15.5	0.0255	0.004
Grasses	Alive	..	0.00008	..
Corn kernels	Alive	..	0.0071	..
Beans	Alive	0.58	0.014	0.00008
Algae, fresh water	Alive	..	9.1	..

Uranium, with many possible valence states and with an ability to form complexes, can be transported in aqueous solution under widely varying chemical conditions. The uranyl ion is stable even at low concentrations in solutions from which it is precipitated when present in high concentrations.[24] The uranyl ion, which is stable in acidic solution, can complex with carbonates to form alkaline or alkaline-earth uranyl carbonates stable above pH 7.0.[25,26] As the uranyl ion, the element can, therefore, travel in either alkaline or acidic medium. The ability of the uranous ion to form carbonate complexes is as yet unknown. Water is an excellent medium for the transport of uranium because of the general solubility of uranium salts in aqueous solutions.

Crude oil has been suggested as a transporting medium for uranium.[27] Although the idea of petroleum is attractive in that it is a transporting medium and also an organo-uranium association, the fact remains that crude oils from nonuraniferous provinces carry only negligible amounts of uranium.[27] Compressed carbon dioxide has recently been suggested as a medium for transporting materials under certain geologic conditions.[28] The nonpolar nature of carbon dioxide, however, renders it an unlikely carrier of the uranyl or other uranium ions.

Because of its abundance and solvent power, water is probably the most effective medium for transporting uranium from its source to its eventual concentration in carbonaceous substances.

MECHANISMS OF CONCENTRATION

Mechanisms must now be considered that can result in precipitation or concentration of uranium that has been carried in aqueous solution from its source into contact with carbonaceous substances.

There have been suggestions that organic matter reduces uranium to the insoluble uranium dioxide, UO_2, or that it adsorbs uranium as a result of surface activity such as would be expected of a clay. More recently it was found that organic matter can combine with uranium to form insoluble organo-uranium compounds. Known mechanisms as well as those considered geochemically tenable are outlined below.

Studies have shown that uranium is retained in some coals by purely chemical processes.[12] The uranyl ion on coming into contact with the coal forms an organo-uranium complex probably a uranyl humate, which is insoluble above a pH of about 2.2. Below this pH the uranium can be stripped from the coal. The organic components of the coal probably provide the acidic environment for release of the element from complexes and the chemical components for the retention of the element.

Before speculating on the association of uraninite with coalified wood fragments on the Colorado Plateau, it is necessary to know more about the reducing capacity of naturally occurring organic substances. If the uranyl ion is first adsorbed by the coal, then it is necessary to consider reduction of the uranyl ion by the carbonaceous material. No experimental work has been carried out on the adsorption of the uranous (U^{+4}) ion by coal.

Recent experimental studies of the US Geological Survey indicate physical rather than direct chemical association of uranium with the organic components of certain shales. It has been postulated that the organic matter established the chemical conditions leading to precipitation of uranium from an overlying sea perhaps slightly enriched in that element. Specifically, it has been proposed that the decomposition of the organic matter under reducing conditions leads to the formation of hydrogen sulfide, which is known to reduce the uranyl ion to the insoluble uranium dioxide.[29] The carbonaceous material, in this instance, would have only an indirect association with the uranium, but the possibility cannot be overlooked that the organic matter complexed and carried uranium down from the sea, thereby serving as a primary precipitant. If this was the mechanism of fixation, then the chemical bonds between the uranium and the organic compounds have been broken since the time the shale components were deposited.

Recent studies of coalified wood in the Chattanooga shale[30] indicate that some of the organic constituents of that shale were derived from terrestrial

plants. If that is true, then part of the uranium in the shale might be a result of the "reduction" mechanism, and part of the uranium might be in actual chemical association with humic compounds derived from terrestrial coal or coalified logs that were washed into the shale during its formation.

Limestones that contain no carbonaceous matter contain no appreciable syngenetic concentrations of uranium, but some carbonaceous limestones are known to be unusually radioactive. The black carbonaceous La Luna limestone of Venezuela,[31,32] thought to be a source bed for petroleum, is known to be the most radioactive and presumably most uraniferous formation in the region. Similar radioactive black limestones are reported from the Middle East.[33]

The absence of uranium in noncarbonaceous limestones probably has a simple explanation. Carbonates are deposited or precipitated from carbonate-saturated water. Under these conditions, the uranyl ion normally present in sea water will remain in solution as complex uranyl carbonates.[25,26] The presence of carbonaceous material in the limestone that is being deposited, however, may lead to the adsorption and retention of uranium from the sea water as a result of direct or indirect chemical activity. To illustrate such activity, it can be postulated that the acidic character of the decomposing organic sediment leads to destruction of the complex uranyl carbonate, thereby releasing the uranyl ion for retention by the organic matter, in much the same fashion as the humic material in coals retains the uranyl ion.[12] Subsequent reduction of the uranyl ion by the hydrogen sulfide in marine organic sediments could result in conversion of the sexivalent uranium to insoluble uranium dioxide.

The presence of carbonaceous matter, most of which is probably of algal origin, in vugs and cracks in limestones has frequently been reported. In one such formation, the Little Falls dolomite of New York State,[34] the carbonaceous matter is not uranium bearing (0.25 ppm uranium), thus indicating that it was deposited from a sea containing only normal or below-normal percentages of the element. The presence of uranium in carbonaceous limestones may indicate that the sea from which precipitation took place had a higher than normal uranium content. The uranium-bearing carbonaceous pellets and impregnations that occur in the dolomites and limestones of early Pennsylvanian to late Permian age of the Texas Panhandle are probably of algal origin. Paragenetic studies indicate that the carbonaceous material is later than the dolomite and limestone, but the fact that pellets fill voids left by solution of anhydrite indicates that redistribution of the algal material may have taken place within the formation. Evidence that crude oils can absorb and carry uranium during migration suggests the mechanism for transport of the uranium during redistribution of the carbonaceous material. Solidification of the original organic substances is dependent upon diagenetic processes which are yet unknown. Very old organic material, such as that from the Little Falls dolomite, is completely solid; other limestones contain organic material that is asphaltic in character.

The high uranium content of some of the pellets from Texas (10 per cent or higher) can be attributed to concentration of considerable uranium from the aqueous environment into small, discrete accumulations of organic material. The converse situation exists in other radioactive limestones where the uranium is finely distributed throughout the formation and associated with relatively large quantities of disseminated organic matter, thus resulting in relatively low concentrations of the element.

Little can be said about the processes by which uranium became associated with various unusual carbonaceous substances, because there is no definitive information regarding the origin of these substances and their interrelationships. The very old organic complexes, such as the Precambrian Babrosco "carbon" of South Africa or the Cambrian kolm of Sweden are probably of algal origin. Although it has been thought that the thucholite which occurs in Canada is of igneous origin, the possibility exists that the organic material was derived from oil that seeped downward from Paleozoic rocks.[35] With little more than morphological descriptions of the substances, little can be said regarding the mechanisms by which uranium has become associated with these carbonaceous materials.

The associations of uranium with coals, coal derivatives, or coalified fragments of wood are probably those of major economical importance. Among unclassified types of carbonaceous materials, those in South Africa are probably the only significant ones.

CONCLUSIONS

There can no longer be any question but that carbonaceous materials of various types play an important role in the secondary concentration of uranium. Some coals are avid collectors of the uranyl ion, and evidence from studies of coalified wood from the Colorado Plateau shows that the wood can also collect sufficient quantities of the uranous (U^{+4}) ion to result in the formation of uraninite. Organic material of algal origin that occurs in limestones apparently has the capacity to adsorb the uranyl ion from overlying water saturated with calcium carbonate, an environment in which that ion is normally retained in solution. Eventual reduction of the uranyl ion may result from interaction with the sulfide ion that accompanies organic material undergoing biochemical decomposition under reducing conditions.

The association of uranium with petroleum is undoubtedly a result of the ability of petroleum constituents with certain functional groups to pick up and carry the element. Although porphyrins have long been considered important in the transport of metals by crude petroleum, it seems likely that asphaltenes, which are known to have carboxyl groups, and naphthenic acids may be more important as

carriers. The association of uranium with petroleum is anomalous, and further studies may show such associations to be useful as exploration guides in search for uranium.

Uranium is not genetically associated with the carbonaceous substances, but it is collected by these substances during its migration. Thus, it is essential for an organo-uranium association that there be available not only organic matter but also a source of uranium and a medium to transport the element into contact with the organic matter. The essential character of all three requirements—organic matter, transporting medium and uranium—is demonstrated in areas of the Colorado Plateau where coalified wood fragments in close proximity are either uraniferous or nonuraniferous, a condition resulting from the localized channeling of uranium-bearing solutions. Thus, carbonaceous matter may or may not serve as a precipitant or adsorbent for uranium, even within a uraniferous province.

REFERENCES

1. Nordenskiold, A. E., *Remarks on the Native Iron of Ovifak and on the Bitumen of Crystalline Rocks of Sweden.* Comptes rendus academie science 116: 677–678 (1893).
2. Nordenskiold, A. E., *Several Comments on the Preceding Short Communication by Prof. Clemens Winkler,* Zeitschrift Krystallographie und Mineralogie 37: 286–288 (1903).
3. Landin, J., *Radium in Sweden,* Arkiv Kemi, Mineralogic, Geologie 2: 1–7 (1905).
4. Holmberg, B., *Studies of the Kolm,* IVA, Handlingar No. 16: 71–80 (1923).
5. Beers, R. F., *Radioactivity and Organic Content of Some Paleozoic Shales,* Bulletin of the American Association of Petroleum Geologists, 29: 1–22 (1945).
6. McKelvey, V. E. and Nelson, J. M., *Characteristics of Marine Uranium-bearing Sedimentary Rocks,* Economic Geology 45: 35–53 (1950).
7. Bates, T. F. et al, *An Investigation of the Mineralogy and Petrography of Uranium-bearing Shales, Third Annual Progress Report, April 1, 1953, to March 31, 1954,* Pennsylvania State University, School of Mineral Industries, State College, Pennsylvania (1954).
8. Breger, I. A., *Radioactive Equilibrium in Ancient Marine Sediments,* Geochimica et Cosmochimica Acta (in press).
9. Vine, J. D. and Moore, G. W., *Uranium-bearing Coal and Carbonaceous Rocks in the Fall Creek Area, Bonneville County, Idaho,* US Geological Survey Circular 212 (1952).
10. Moore, G. W., *Extraction of Uranium from Cold Water Solutions by Coal and Other Materials,* Economic Geology 49: 652–658 (1954).
11. Szalay, S., *The Enrichment of Uranium in Some Brown Coals in Hungary,* Acta Geologica Hungarica 2: 299–310 (1954).
12. Breger, I. A., Deul, M. and Rubinstein, S., *Geochemistry and Mineralogy of a Uraniferous Lignite,* Economic Geology 50: 206–226 (1955).
13. Miller, R. L. and Gill, J. R., *Uranium in Dakota Lignites,* Scientific American 191, No. 4, 36–39 (1954).
14. Gott, G. B. and Erickson, R. L., *Reconnaissance of Uranium and Copper Deposits in Parts of New Mexico, Colorado, Utah, Idaho, and Wyoming,* US Geological Survey Circular 219 (1952).
15. Davidson, C. F. and Bowie, S. H. U., *On Thucholite and Related Hydrocarbon-Uranium Complexes,* Bulletin of the Geological Survey of Great Britain 3: 1–19 (1951).
16. Louw, J. D., *Geological Ages of Witwatersrand Uraninites,* Nature 175: 349–350 (1955).
17. Ellsworth, H. V., *Rare-Element Minerals of Canada,* Canada Geological Survey, Economic Geology Series, No. 11: 244–247 (1952).
18. Gott, *G. B., Geologic Investigations of Radioactive Deposits, Semiannual Progress Report, June 1 to November 30, 1953,* US Geological Survey TEI–390: 256–258; US Atomic Energy Commission Technical Information Service, Oak Ridge, Tennessee (1953).
19. Gott, G. B., *Geologic Investigations of Radioactive Deposits, Semiannual Progress Report, December 1, 1953 to May 31, 1954,* US Geological Survey TEI–440: 217–219; US Atomic Energy Commission Technical Information Service, Oak Ridge, Tennessee (1954).
20. Hoffmann, J., *Determination of Uranium in Living and Dead Plants,* Bodenkunde und Pflanzenernahrung 25/26: 318–327 (1941).
21. Hoffman, J., *Experimental Determination of Uranium in Living Fresh Water Algae,* Naturwissenschaften 29: 403–404 (1941).
22. Hoffman, J., *Uranium in the Animal Organism,* Wien Tierarzliche Monatschrifte 28: 561–566 (1941).
23. Cannon, H. L., *The Effect of Uranium-Vanadium Deposits on the Vegetation of the Colorado Plateau,* American Journal of Science 250: 755–770 (1952).
24. Milkey, R. G., *Stability of Dilute Solutions of Uranium, Lead, and Thorium Ions, Analytical Chemistry* 26: 1800–1803 (1954).
25. Bachelet, M., Cheylan, E., Douis, M. and Goulette, J. C., *Preparation and Properties of Uranyl Carbonates: Uranyl Carbonates of Sodium,* Bulletin de la Societe chimique de France: 55–60 (1952).
26. Bachelet, M., Cheylan, E., Douis, M. and Goulette, J. C., *Preparation and Properties of Uranyl Carbonates, Second Note: Alkaline Earth Uranyl Carbonates,* Bulletin de la Societe chimique de France: 565–569 (1952).
27. Erickson, R. L., Myers, A. T. and Horr, C. A., *Association of Uranium and other Metals with Crude Oil, Asphalt, and Petroliferous Rock,* Bulletin of the American Association of Petroleum Geologists 38: 2200–2218 (1954).
28. Garrels, R. M. and Richter, D. H., *Is Carbon Dioxide an Ore-Forming Fluid under Shallow Earth Conditions?,* Economic Geology (in press).
29. Gruner, J. W., Rosenzweig, A. and Smith, D. K., Jr., *Annual Report for April 1, 1953 to March 31, 1954,* US Atomic Energy Commission Technical Information Service, Oak Ridge, RME–3094: 28–30 (1954).
30. Breger, I. A. and Schopf, J. M., *Germanium and Uranium in Coalified Wood from Upper Devonian Black Shale,* Geochimica et Cosmochimica Acta, (in press)
31. Smith, J. E., *The Cretaceous Limestone Producing Areas of the Mara and Maracaibo District—Venezuela,* Proceedings of the Third World Petroleum Congress, Section 1: 56–72 (1951).
32. Smith, J. E., *Discussion,* Proceedings of the Third World Petroleum Congress, Section 1: 427 (1951).
33. Ion, D. C., *Discussion,* Proceedings of the Third World Petroleum Congress, Section 1: 427 (1951).
34. Dunn, J. R. and Fisher, D. W., *Occurrence, Properties, and Paragenesis of Anthraxolite in the Mohawk Valley,* American Journal of Science 252: 489–501 (1954).
35. Quirke, T. T., *Origin of Watercourses near French River, Ontario,* Bulletin of the Geological Society of America 47: 267–288 (1936).

Uranium Deposits in Paludal Black Shales of the Dakota Formation, San Juan Basin, New Mexico

By John W. Gabelman,* USA

Non-commercial, slightly uraniferous marine black shales are common throughout the United States. Uranium deposits in paludal black carbonaceous shales and in related interbedded sandstones and coals are frequently ore-grade. Uraniferous low-rank coals are of economic importance in South Dakota.

Carbonaceous shales containing uranium ore occur at the base of the Dakota formation which crops out around the edges of the San Juan Basin of northwestern New Mexico (Fig. 1 and 1A). These deposits are so closely related to Dakota sandstone orebodies and to the structure of the San Juan Basin that all are discussed together.

STRATIGRAPHY

The San Juan basin contains sedimentary rocks of Paleozoic, Mesozoic and Cenozoic ages, which are partially exposed in concentric bands around its edges. The Dakota sandstone is the lowest Upper Cretaceous formation in the San Juan basin and in most areas it forms the resistant caprock of hogbacks. From its base upward the Dakota consists of a lower zone of interbedded and interfingering sandstones, carbonaceous shales, and low-rank coals; and an upper thick sandstone.

Overlying the gray coarse, poorly sorted Westwater sandstone or, where that is absent, the variegated Brush Basin mudstone members of the Morrison formation, the lower Dakota unit contains lenses and interfingering beds of medium to coarse-grained poorly sorted cross-bedded sandstone. The sandstones contain local strong concentrations of carbonized plant material. Interfingering carbonaceous shales are silty and contain numerous lenses of pure siltstones and gray sandstone. Local increases in carbonaceous content result in gradations to lignite.

The lower unit is most characterized by its rapid lateral lithologic variation. Minute, long, narrow lenses of silt or sand in the black shale resemble miniature filled channels.

Throughout the Colorado Plateau the Dakota sandstone marks the transition from continental paleostream deposition of the upper Jurassic to marine deposition of the upper Cretaceous. It was deposited along a migrating strand line which probably moved southward across the San Juan basin finally inundating the Jurassic land mass—the source of Morrison clastics. The sands of the Dakota migrate upward and southward across time-lines.

The lower Dakota unit represents a combined paludal and lagoonal environment retreating ahead of encroaching beaches and off-shore bars of the upper unit. Moderately active streams are suggested by poor sorting and combination of torrential and festoon cross-bedding. Sandstone beds are broad lens-like channel-fills suggesting anastomosing stream courses.

STRUCTURE

Pre-consolidation structures in the lower Dakota unit are common, and most are the result of slump. Partly consolidated sandstone beds have slid into channels along surfaces which pass into the bedding and die out in the shales. Also, thinly-layered shale and silt beds have crumpled from lateral pressure and sliding.

URANIUM MINERALIZATION

Within the basal interbedded sand and shale zone of the Dakota, uranium occurs both in black carbonaceous shale and in coarse carbonaceous sandstone, although seldom in commercial amounts in both rock types at the same deposit. The lower Dakota rocks contain intricate mixtures of bodies of sand, silt, black mud, and vegetal accumulation. Barren sand lenses occur within bodies of uraniferous shale. Uranium is restricted to one or two horizons despite the occurrence of favorable hydrocarbon trash in confining barren beds. The greatest concentrations of uranium are in carbonaceous shale, in which the host rock is mostly mascerated vegetal trash, or are in richly carbonaceous sandstone. No uranium minerals are visible in the shale and it is presumed that uranium was adsorbed by the hydrocarbon. Yellow secondary uranium minerals impregnate the carbonaceous sandstone.

DEPOSITS IN CARBONACEOUS BLACK SHALE

Hogback No. 4 Deposit

The Hogback No. 4 deposit is in McKinley County, New Mexico (Fig. 2).

Structure

In this area the Gallup hogback forms the steep western and southwestern flank of the Zuni uplift, the northwest nose of which is about 2 miles north

* US Atomic Energy Commission.

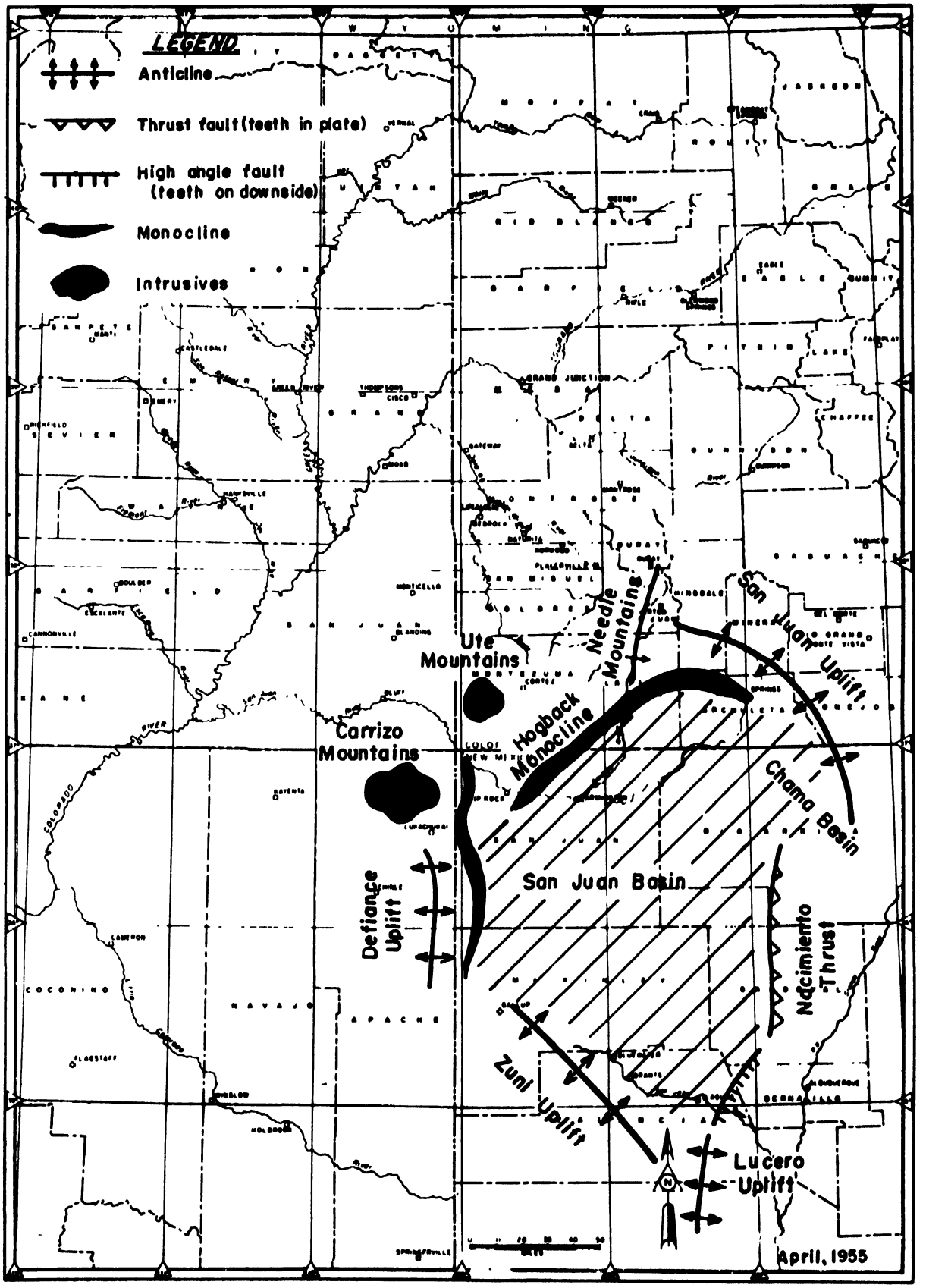


Figure 1. Index map, San Juan Basin, New Mexico

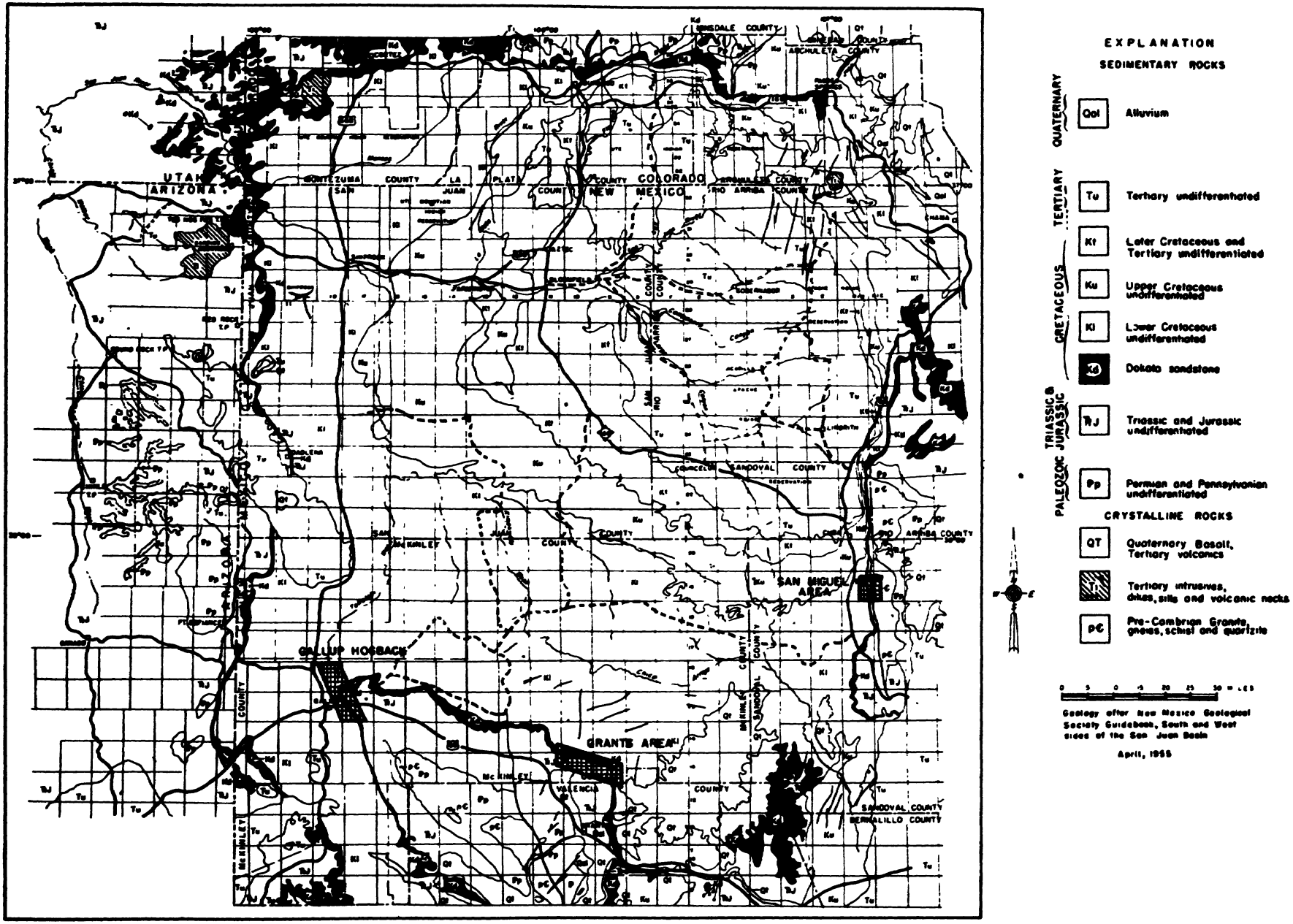


Figure 1A. Generalized geologic map showing Dakota outcrops in the San Juan Basin and areas of lower Dakota—uranium mineralization

of the Hogback 4 deposit. Both the Dakota and the Gallup sandstones, dipping 35° W and 75° W respectively, form caprocks of two hogbacks which trend north and are separated by a narrow valley in the intervening Mancos shale. A cross-fault of moderate movement is suggested by a water gap several thousand feet north of the mine, but there are no faults with more than three feet of movement near the deposit. A set of joints strike N 70° W and dip 60–70 degrees SW; a second set strikes N 15° E and dips at an equal angle SE. One to three feet of movement on joint surfaces has been occasioned by folding.

Tectonic folds apparently are absent. However, small slump folds occur in the hanging wall shale beds, and the ore shale bed is strongly wrinkled.

Stratigraphy

The ore bed is a black extremely fissile paper shale with abundant carbonized plant fragments. Locally it is very nearly a lignite. It contains numerous thin gray carbonaceous sandstone lenses of three-quarter inch average thickness and 18 inches average length marked by fluvial cross-bedding.

Mineralization

Mineralized shale has been exposed by an open pit about 500 feet in strike length, and 60 feet deep, on the crest of the hogback. There is no obvious external structural control for either the internal variation in grade or the presence of the orebody itself. The shale contains no recognizable uranium minerals. The introduced gangue minerals are limonite, gypsum, and jarosite, and the surface of the sandstone beneath the ore shale is strongly stained with limonite. The jarosite and gypsum are in thin veinlets cutting the ore bed along thin bedding seams, and as lenses.

Uranium solutions have deposited yellow secondary minerals in a sandstone bed 13 to 15 feet below the ore shale in vacated carbon trash holes, but the quantity of uranium in the lower bed is minor. Several hundred tons of black shale ore have been shipped from the mine, but the uranium cannot be very readily extracted from the shale by leaching processes.

The Butler Deposit

The Butler uranium deposit is in the Nacimiento Mountains, about 6 miles northeast of La Ventana, Sandoval County, New Mexico (Fig. 3).

Structure

The sediments have been tilted by drag resulting from the overthrusting of a granite block along the Nacimiento fault. The present Dakota hogback in the sole of the thrust strikes north and dips 45 degrees west. In San Miguel canyon less than one mile north of the deposit a tear fault offsets the hogback several hundred feet; smaller tears cut the hogback near the mine. The deposit is about three hundred feet south of a tear in which beds have been dragged through an arc of 70°. Displacement on the fault is less than 50 feet. Mineralization is confined to the arc of drag. A diagonal fault of 5 to 10 feet displacement branches from the tear fault and bounds the down dip side of the deposit.

Small crenulations, common in the shale beds, do not extend into the sandstones. It is noteworthy that these folds closely resemble those on the Gallup hogback where there is no thrusting.

Stratigraphy

Formations in the area shown in Fig. 3. The beds enclosing the mineralized horizon are, in descending order: (1) gray, fine-grained silty sandstone, stained with jarosite, 1 foot; (2) ore bed: black, lignitic, locally underlain by green mudstone, 1 foot; and (3) Westwater Canyon sandstone, gray, thick bedded, 50 feet.

The mineralized lignitic bed is a poorly bedded, porous, friable aggregate of mascerated carbonized plant fragments. It has a poorly developed nearly cubic joint pattern in which joints are oriented diagonal to the bedding strike.

Mineralization

The lignitic debris contains a maximum of 1.4 per cent U_3O_8 over outcrop and dip lengths of over 100 feet. The exact size and shape of the irregular body are unknown. The north side of the orebody is exposed, extending from the hogback crest down the dip slope of the hogback until terminated abruptly by the diagonal fault. No mineralization occurs in the fault or in any related joints.

No uranium minerals are visible but bedding and joint surfaces are coated with jarosite, gypsum and limonite, and the enclosing sandstones are impregnated with limonite. The uranium content is entirely contained in the lignite. Downward termination of mineralization against the diagonal fault suggests damming in a physiographic sump after tilting of the sediments.

Related Deposits

Low grade mineralization is prominent in the same black shale bed in Los Pinos Canyon about 2000 feet north of the Butler deposit and is possibly semi-continuous with that at the Butler. Mineralization is identical in both occurrences. Another deposit, presumably in the same shale horizon, occurs in Arroyo Dedos Gordos about 5½ miles south of the Butler deposit. Approximately three miles southwest of the Butler deposit, black shale and coal at the base of the La Ventana sandstone are similarly mineralized with low-grade uranium for several thousand feet around La Ventana Mesa.

DEPOSITS IN DAKOTA CARBONACEOUS SANDSTONE

Diamond 2 Mine

The Diamond 2 mine is in McKinley County, New Mexico, about 6 miles southeast of the town of Gallup.

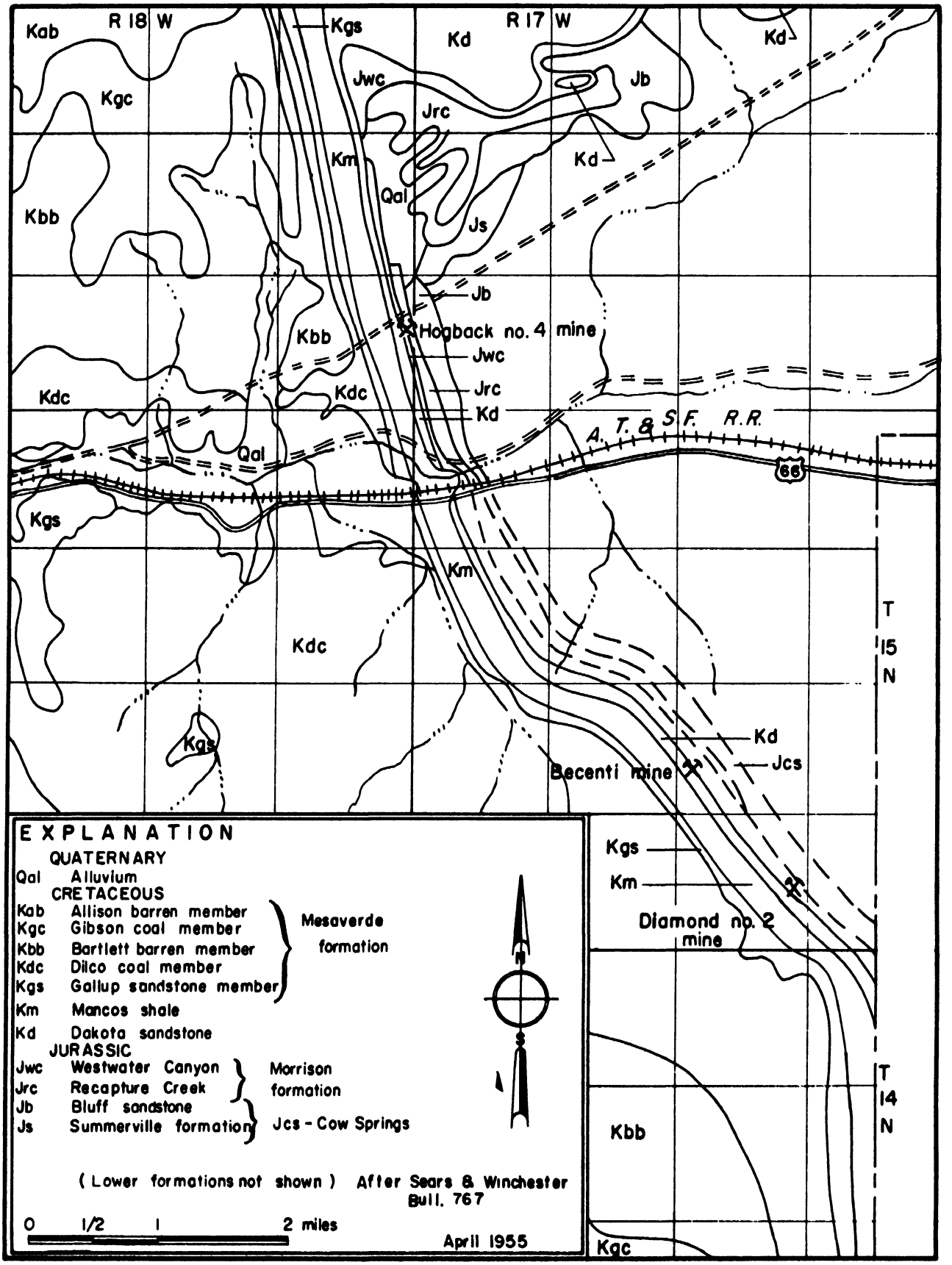


Figure 2. Geologic sketch map, Gallup Hogback area, McKinley County, Utah

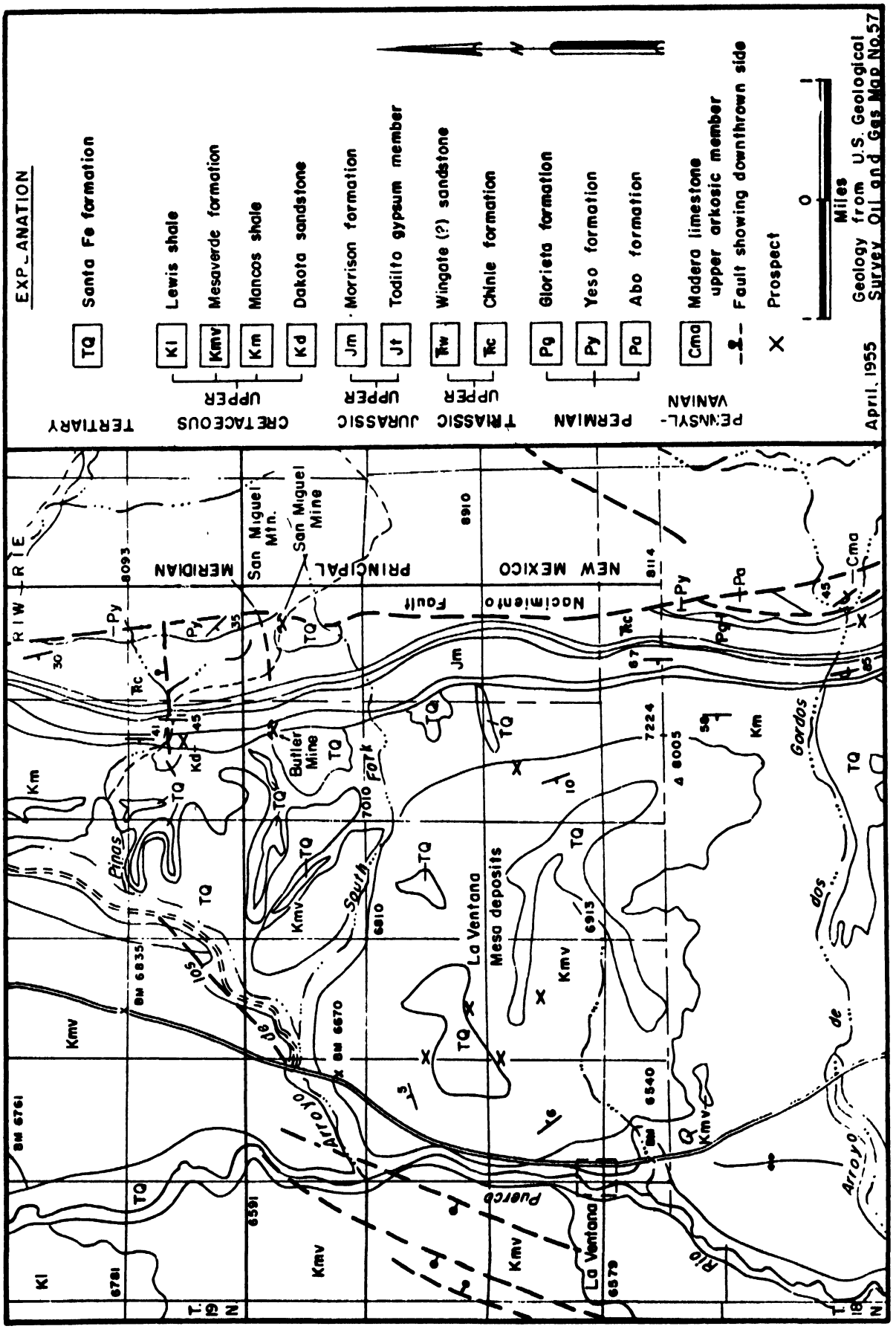


Figure 3. La Ventana area, Sandoval County, New Mexico

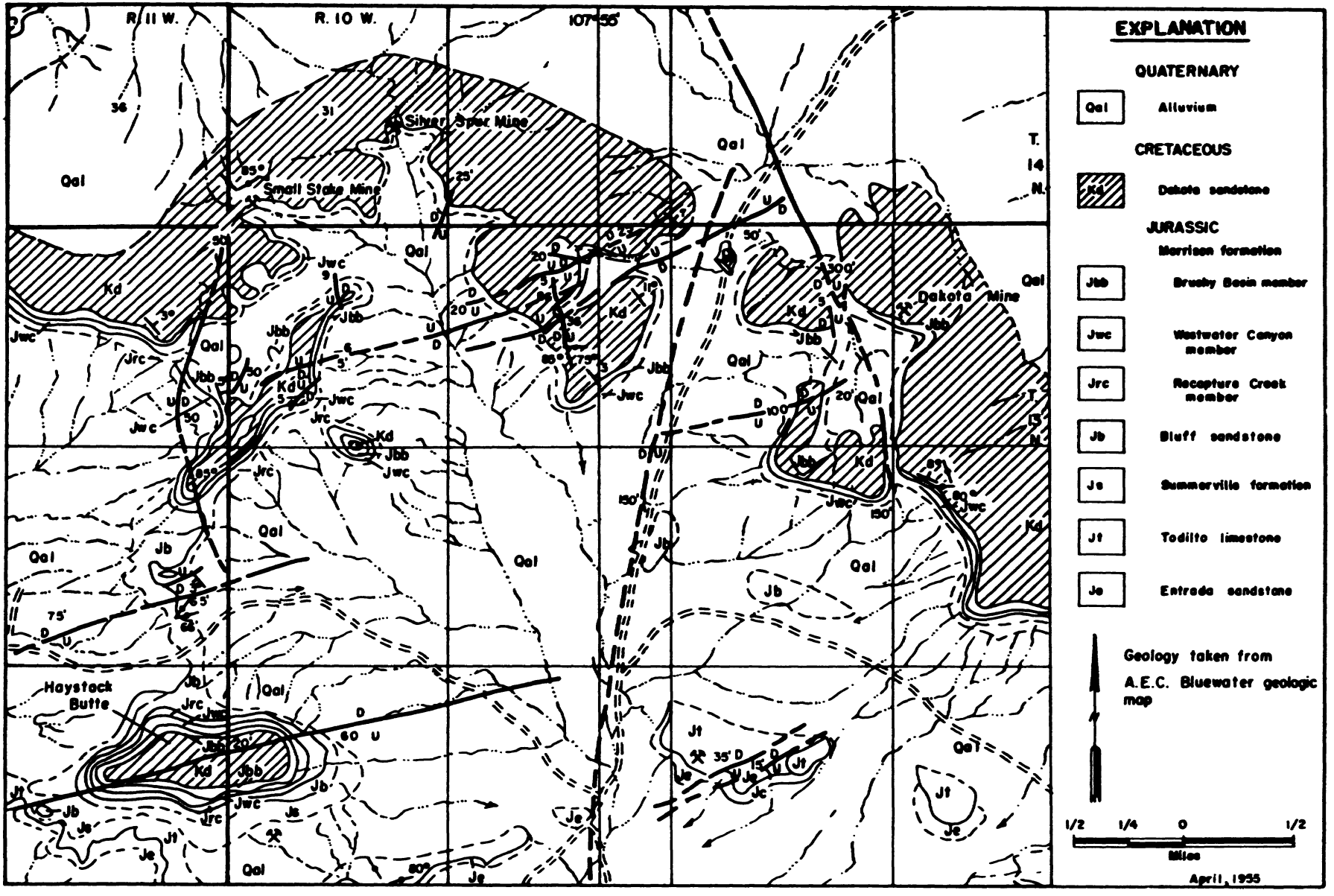


Figure 4. Geologic map, emphasizing deposits in Dakota sandstone, Haystack Butte area, McKinley County, New Mexico

Structure

The deposit is in the Gallup Hogback a part of the southwest flank of the Zuni Mts. (Fig. 2). The structure of the hogback closely resembles that at the Hogback 4 mine, several miles northwest. Here the hogback strikes N 10° W and dips 26 degrees SW. The joint pattern is nearly rectangular with the components nearly diagonally symmetrical about the strike of the hogback, and it is noteworthy that in this area the Zuni uplift probably plunges less than three degrees. Movements of less than a foot on joint surfaces are common. Many small horizontal faults displace the sandstone beds a few inches.

Large folds are absent but many small gentle cross folds from several inches to forty feet in width plunge down the dip of the beds. Small crenulations, as in the Hogback 4 and Butler deposits, are here common in the shale and to a lesser extent in the small sandstone lenses within the shale.

Stratigraphy

Formations present are the same as those at the Hogback No. 4 mine. The basal Dakota unit contains the following beds: (1) tan limonite-stained, fine-grained sandstone with fluvial cross-bedding: 8 feet; (2) black wrinkled shale with lenses of peat, mud, sand, and silt: 5 feet, hanging wall bed; (3) ore bed: gray, thin-bedded, poorly sorted sandstone; abundant lenses of mud, shale, humic hydrocarbons: 3½ feet; (4) black carbonaceous shale: 1 foot; and (5) gray, poorly sorted, cross-bedded arkosic sandstone: 4 feet. Bed No. 2, the wrinkled shale, is similar to the ore bed at the Hogback 4 mine, about 8 miles north, and may be its correlative. The bed is extremely variable with lenses and minute filled channels of sand, silt, and mud. Within 15 feet of the southeast side of the orebody this bed disappears abruptly. The coincidence of the orebody with this wedge-out is striking, although no direct controlling influence is discernible.

The ore bed is a coarse-grained, poorly sorted sandstone, strongly cross-bedded, with thin small lenses and channels of mud, shale and carbonaceous debris, and cannel coal. Some small channels contain local scours.

Mineralization

Mineralization in the sandstone occurs in irregular pods which plunge down the dip and roughly coincide with the gentle cross arches which plunge in the same direction. The average pod is about 50 feet long, 15 feet wide and 4 feet thick. Pods are confined to a lens-like area about 150 feet in outcrop length, 250 feet in dip length, and the thickness of the sandstone.

Yellow secondary uranium minerals (carnotite?) impregnate the sandstone, fill vacated carbonaceous trash holes, and fill bedding and joint fractures. The obvious ore controls are the shallow folds, the joints (many of which acted as barriers), and concentrations of carbonaceous debris. Weak mineralization locally extends into the hanging-wall shale. Gangue consists of jarosite, limonite, and calcite. Limonite is not abundant but calcite impregnation is common. Bleaching by the removal of limonite from normally tan beds may have accompanied mineralization.

The epigenetic impregnation of sandstone with uranium and the orientation of ore pods down the structural dip suggests deposition from solutions moving in that direction in thin aquifers, since tilting of beds. Impounding would have caused solutions to spread laterally. The reducing environment occasioned by hydrocarbons was a prime factor in precipitation, but why sandstone rather than adjacent peat and strongly carbonaceous shale became the host rock cannot readily be explained.

Becenti Deposit

The Becenti mine is in McKinley County, New Mexico, and is about one mile northwest of the Diamond 2 mine (Fig. 2). Stratigraphic and structural features are similar to those of the Diamond 2, even to the presence of small cross folds in the plane of the bedding. However, the Becenti folds average 6 feet wide and their axes strike about 35 degrees from the direction of bedding dip.

Yellow secondary uranium minerals impregnate the same sandstone bed beneath the black shale hanging-wall.

Silver Spur Deposit

The Silver Spur mine is in the Haystack Butte area, McKinley County, New Mexico, about 12 miles northwest of Grants (Fig. 4). The Haystack Butte area is on the Thoreau monocline which forms the gentle northeast flank of the Zuni Mountains. Sediments, outcropping in cuestas, dip 2 to 5 degrees northeast. Zones of cross faults and shallow cross folds occur at regular intervals of several miles along the monocline. The Haystack Butte area is in a zone of such faults and folds, but the nearest fault is nearly a mile from the Silver Spur mine.

As at the Diamond 2 and Becenti mines, the ore bed is a coarse-grained carbonaceous sandstone overlain by black carbonaceous shale. The footwall bed is a thin blue mudstone which overlies the Brushy Basin shale member of the Morrison formation. Maximum development of the ore bed is in a broad Paleostream channel which is traceable for some distance.

Mineralization occurs in pods, six of which are known, elongated parallel to the secondary joint direction and perpendicular to the cross bedding. Yellow secondary uranium minerals, of which tyuyamunite is the most important, impregnate the sandstone in areas of abundant carbonaceous trash, and are associated with jarosite, gypsum, calcite, and limonite.

REFERENCE

1. Bachman, G. O. and Read, C. B., Results of recent investigations of uranium in coal, black shale, and related deposits, Sandoval and Rio Arriba counties, New Mexico: US Geol. Sur., TEMR-309 (1951).

Uranium in Marine Black Shales of the United States

By Vernon E. Swanson,* USA

For the past decade black shales have been regarded as possible low-grade sources of uranium, and numerous black shale units in the United States have been tested for their uranium content. Of those tested, a few widespread shales of Paleozoic age contain on the order of 0.007 per cent uranium.

To date, the search for uraniferous shales has been mainly a broad-scale surface reconnaissance, utilizing radiation-detecting instruments. The general radioactivity of many black shales in the subsurface has been determined from gamma-ray logs of oil and gas wells,[1] and numerous well cores have been scanned radiometrically and sampled for chemical uranium determinations. Hundreds of black shale units that range in age from Precambrian to Tertiary, and from a few feet to several thousand in thickness, have been cursorily examined. Several have been studied in detail and hundreds of samples collected and chemically analyzed for uranium and other constituents; many are represented by only a few samples that have been analyzed for uranium content, or by field radioactivity measurements. The possibilities for finding black shales in the United States more uraniferous than are now known certainly have not been exhausted; and it is believed that future investigations, based on paleogeologic guide lines formulated from accumulated information, will very likely point to areas of higher grade shales.

No uranium has been produced from black shale in the United States, in part because large numbers of high-grade deposits of other types have been discovered, and in part because black shale units of sufficiently high grade and large volume have not been located. Despite the low range of uranium content in black shales, the tonnage of metallic uranium in shales is extremely large; it is possible that the amount of uranium required in the future may necessitate developing this large low-grade reserve. For example, central Tennessee and parts of adjoining states have about 85,000,000,000 tons of shale averaging slightly more than one-tenth of a pound of uranium per ton; this represents a reserve of 5,000,000 to 6,000,000 tons of uranium.[2]

Numerous references to the radioactivity of black shales exist in the literature. An extensive bibliography is listed by McKelvey and Nelson,[3] and a comprehensive review of theories on the depositional origin of black shales is given by Twenhofel.[4] The distribution of significantly uraniferous black shales is shown in Fig. 1.

LITHOLOGIC AND CHEMICAL CHARACTERISTICS

With few exceptions, the uranium content of known marine black shales of the United States does not exceed 0.02 per cent, and the contents of few shale units having a thickness of more than 2 feet exceed 0.005 per cent uranium. Black vitreous layers of coalified plant tissue, fractions of an inch thick, abundant in black shales of Devonian age, contain as much as 0.035 per cent uranium. Specially selected samples of highly phosphatic material in some black shales may exceed 0.035 per cent uranium. These and a few secondarily mineralized shales, which have sporadic uranium concentrations, are the only ones known to have more than 0.02 per cent uranium.

Several marine black shales are essentially nonradioactive, having uranium contents comparable to the average sedimentary rock. Parts of the Eagle Ford shale of Late Cretaceous age in east-central Texas, for example, contain less than 0.001 per cent, though this formation has several lithologic characteristics typical of other uraniferous shales.[4]

The total radioactivity of the more uraniferous black shales is primarily due to uranium, though thorium and the radioactive isotope of potassium are probably important constituents of other shales.

To date, laboratory experiments have failed to isolate and identify the uranium mineral or minerals in black shales. The uranium is apparently thoroughly disseminated in the shale but is associated most closely with the contained organic matter which is also finely dispersed through the rock. The rapid adsorption of uranium by carbonaceous material immersed in an uranyl solution[6,7] supports the theory that uranium in the sea water was adsorbed by the organic debris contemporaneously with the deposition of the enclosing muds.[8] The mineralogical association of the uranium and the phosphatic material common to many black shales is discussed in more detail by McKelvey.[9]

In addition to the organic matter, other common components of uraniferous shales are pyrite, in the form of lenses, nodules, and minute crystals; and phosphate, either in the form of nodules up to a foot in diameter, or as disseminated particles. Also, abnormal amounts of certain trace elements such as copper, nickel, vanadium, germanium, and molyb-

* US Geological Survey.

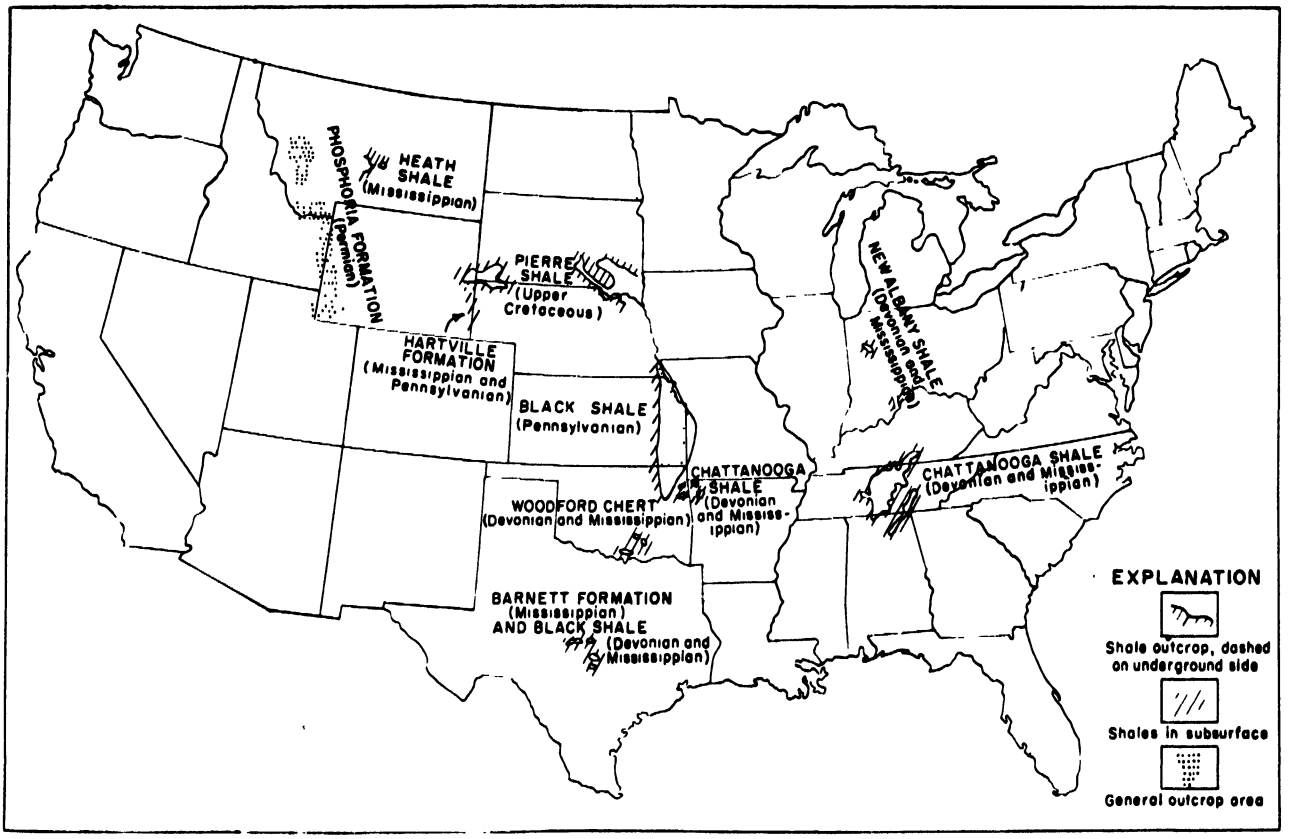


Figure 1. Distribution of significantly uraniferous black shale

denum, are common to some uraniferous black shales. The uranium content generally decreases sharply with small increases of calcium carbonate.

Many uraniferous black shales have long been known as oil shales. The marine Chattanooga shale, noted for its comparatively high radioactivity, is a low-grade oil shale, yielding on the average 5 to 10 gallons of oil per ton of shale by destructive distillation methods; further, a crude relationship can be shown between the increase of oil content and uranium content in this formation. Some oil-bearing shales, on the other hand, are not particularly uraniferous. For example, the oil shale units of the nonmarine Green River formation in Colorado and Utah contain 0.001 per cent uranium or less.

CHATTANOOGA SHALE

Among the radioactive marine black shales that have been studied in the United States, the Chattanooga shale of Late Devonian and early Mississippian age in central Tennessee is best known and is currently considered the most favorable as a future low-grade source of uranium. Other shale units in the United States locally contain more uranium but such shales are less extensive, thinner, or are deeply buried. The reader is referred to papers by Brown,[10] Conant,[8] and Hass[11] for more detailed descriptions of the Chattanooga shale.

The Chattanooga shale in Tennessee, Kentucky, and Alabama is the generally more radioactive part of a thin blanket of black shale that once covered a large part of eastern and central United States. Correlatives of the Chattanooga, all slightly radioactive, are the New Albany shale of Illinois, Indiana, and Kentucky, the Antrim shale of Michigan, the Sunbury and Ohio shales of Ohio and Kentucky, the Genessee group, Dunkirk member of the Perrysburg formation, and other thin shales of New York, the Chattanooga shale of Kansas, northern Arkansas and northern Oklahoma, and the Woodford chert of Oklahoma and Texas. Except in mountainous areas, these shales are flat-lying or locally warped into gentle folds.

The thickness of these Upper Devonian and lower Mississippian shales ranges from a feather edge to several hundred feet, but in central Tennessee, where the economic development of the shale is most feasible, the Chattanooga shale is less than 35 feet thick. They consist chiefly of black siliceous shale and gray claystone, and locally include thin sandstone beds, calcareous lenses, chert layers, and phosphatic nodules. They contain abundant plant remains (such as stems, spores, and macerated debris) as well as linguloid brachiopods, conodonts, and fish bones.

The more radioactive black shale units in central Tennessee are composed of silt-size grains of quartz (about 25 per cent); clay, feldspar, and mica (about 35 per cent); organic matter (about 20 per cent); pyrite (about 15 per cent); and minor amounts of chlorite, phosphatic material, calcite, and heavy minerals. The rock yields 3 to 15 gallons of oil per short ton by destructive distillation.

The uranium content ranges from 0.001 to 0.035 per cent and is remarkably persistent and uniform, as are the lithologic units, over large areas. In central Tennessee an upper member of predominantly black shale, about 15 feet thick, averages about 0.007 per cent uranium, and a coalified plant fragment from this area contained 0.035 per cent uranium. Parts of the Woodford chert in southeastern Oklahoma contain as much as 0.008 per cent uranium, but the average content of known units of minable thickness does not exceed 0.005 per cent uranium. In central Texas an irregularly distributed unit of black shale, correlated with and megascopically similar to the Chattanooga shale, is about 5 feet thick and contains an average of 0.008 per cent uranium. Phosphate nodules in the Chattanooga and its equivalents contain as much as 0.013 per cent uranium, but, at least in the southeastern States, their average content is less than that of the enclosing shale. In areas where gray shales are more abundant, and where sandstones, calcareous siltstones, or limestone lenses are common, the formation generally contains 0.001 to 0.003 per cent uranium. A direct relationship appears to exist between the uranium and organic content, and between the uranium and the pyrite (although the uranium is not contained in the pyrite). Uranium minerals have not been identified from these shales.

The Chattanooga shale and its correlatives accumulated in a widespread, relatively shallow, epicontinental sea that covered a vast area of the North American continent. It was deposited under conditions that resulted in extremely slow accumulations of mineral detritals and proportionately high accumulation of carbonaceous debris. Presumably uranium contributed to the sea in solution was adsorbed by the organic debris.

PENNSYLVANIAN SHALES, MIDCONTINENT

Approximately 2500 feet of gently dipping rocks of Pennsylvanian age are exposed in eastern Kansas[12] and nearby parts of Oklahoma, and Missouri. Marine black shale beds, generally only a few feet thick, are scattered throughout the sequence; many of them are units of cyclic deposition that include sandstone, coal, and limestone.

About 20 of these black shale beds are abnormally uraniferous, containing more than 0.003 per cent uranium; several contain on the order of 0.010 per cent uranium; and, locally at least, beds of black shale 0.5 to 2.0 feet thick contain as much as 0.017 per cent uranium, as in the Pleasanton group of late Pennsylvanian age. Most of the thin coal beds are essentially nonradioactive, the highest known content being 0.002 per cent uranium. Other lithologic units are essentially nonuraniferous.

Many of these Pennsylvanian black shales are characterized by irregularly distributed small phosphatic concretions or nodules, containing as much as 30 percent P_2O_5, and, at some localities, making up as much as 5 per cent of the thin shale beds. The radioactivity of the nodules is generally higher than that of the enclosing shale, their average equivalent uranium content being about 0.035 per cent and the average uranium content 0.015 to 0.020 per cent. A few samples of phosphatic nodules analyzed slightly less than 0.1 per cent uranium. Except for the general observation that the nodules are typically present in the uraniferous black shales, no correlation appears to exist between the abundance and uranium content of the nodules; nor does their content appear to be related to the thickness, lithology, and uranium content of the enclosing shales.

Of the number of Pennsylvanian black shales in the southeastern Kansas area that are abnormally uraniferous, only two are mentioned here to illustrate their geologic characteristics and distribution.

The Hushpuckney shale member of the Swope limestone (upper Pennsylvanian) of Moore[13] is composed of an upper unit of essentially nonradioactive greenish clay shale about 4 feet thick, and a lower unit of black fissile shale, devoid of phosphatic nodules, about 2 feet thick; the member is both overlain and underlain by persistent but thin limestone units. This uraniferous black shale crops out from southeastern Kansas north-northeastward into Missouri, and analyses of scattered samples suggest that it contains about 0.010 per cent uranium over most of this distance. It is present westward in the subsurface for 100 or more miles, but its radioactivity beyond the outcrop is not known.

The Cherokee formation of middle Pennsylvanian age is exposed in a belt about 25 miles wide cutting across the southeastern corner of Kansas and into adjacent parts of Missouri and Oklahoma. It is a cyclic sequence, each "cycle" crudely repeated about 14 times and generally consisting of sandstone, "underclay," coal, black shale, limestone, and claystone. Although the radioactivity of the Cherokee has not been systematically studied, most of the black shale units are uraniferous, and channel samples of a few beds as much as 2 feet thick analyzed 0.009 to 0.013 per cent uranium; adjacent units, regardless of lithology, contain less than 0.002 per cent uranium.

The thin but persistent units of black fissile shale in the Pennsylvanian indicate deposition in extremely shallow water, with too little depth for circulation and effective wave or tidal action.[13] The influx of sediment into the wide expanse of the shallow seas was apparently meager, and the reducing environment at the interface of deposition in the lower waters of the sea permitted the slow accumulation and preservation of organic debris. Available uranium in the sea water was adsorbed in this bottom sludge, with a preferential chemical exchange bonding the uranium and the phosphate during the accretionary growth of the nodules. Apparently slight, but broad scale, tectonic movements permitted oxygenation of the waters, destroying the environment favorable for the accumulation of carbonaceous material and uranium and permitting the deposition of calcium carbonate.

Several thin beds of marine black shale in the subsurface Hartville formation of Pennsylvanian age in eastern Wyoming and western Nebraska contain as much as 0.019 per cent uranium. The most radioactive shales are several thousand feet below the surface in eastern Niobrara and Goshen Counties of easternmost Wyoming and western Sioux County in westernmost Nebraska, as indicated by samples and gamma-ray logs from a limited number of wells. The subsurface distribution of these abnormally radioactive shales has not been fully defined, but they are not present in the outcrop area of the Hartville uplift 25 to 50 miles to the west in Wyoming, where their stratigraphic equivalents are dolomitic rocks.

From available data, the black shale beds less than 1 foot in thickness generally contain more than 0.01 per cent uranium, but the thicker beds, up to 10 feet thick, generally contain 0.005 per cent uranium or less. This relationship between uranium content and thickness, and the suggested lateral change from black shale into dolomitic facies probably are the significant controls for uranium distribution in these Pennsylvanian shales.

PHOSPHATIC CARBONACEOUS SHALES, PHOSPHORIA FORMATION

The rocks of the Phosphoria formation of Permian age, which are present in an area of some 100,000 square miles in Idaho, Montana, and Wyoming, are marine sediments that are significant because of their contained phosphate and uranium.[15]

Two black phosphatic shale members characterize the Phosphoria formation; chert, sandstone and limestones comprise the remainder. The lower member is about 150 to 200 feet thick and contains as much as 38 per cent P_2O_5 in southeastern Idaho, but the member pinches out in southern Montana, central Wyoming, and eastern Utah; the average uranium content is about 0.010 per cent, but some thin units contain as much as 0.033 per cent uranium. The upper member is about 75 feet thick in southwestern Montana, but thins in most directions away from this area; the P_2O_5 content of minable beds is about 30 per cent, and the uranium content is on the order of 0.010 per cent. Pyrite is an important constituent in both members.

The Phosphoria formation[16] may be roughly divided into a miogeosynclinal facies[17] on the west and a platform facies on the east. In the western facies the rocks are generally finer grained, principally dark phosphatic shales and cherts, and are thicker than in the eastern platform facies where prominent unconformities are common.

The organic and phosphatic material are apparently the constituents that contain the uranium in the Phosphoria formation;[18] and as the phosphate and carbonaceous matter increase together, the uranium content increases also.

Although concepts of the configuration and depth of the Phosphoria sea differ, the coincidence of abnormal phosphate accumulation, preservation of carbonaceous matter, limited supply of fine-grained sediment, and high uranium content unmistakably suggest a genetic similarity to the other black shales described. Presumably the sediments accumulated more rapidly than most uranium-bearing shale, but possibly an accelerated supply of the ingredients mentioned above resulted in concentrations comparable to that in other uraniferous shales.

OTHER URANIFEROUS SHALES

The Sharon Springs member of the Pierre shale of Cretaceous age—a hard, black, pyritic organic-rich shale similar to the Chattanooga shale—is slightly radioactive throughout a large part of South Dakota, Nebraska, northern Kansas, and northeastern Colorado.[19] The unit ranges in thickness from a few feet to about 500 feet. Thin beds of the shale locally contain as much as 0.01 per cent uranium, but generally the content is less than 0.003 per cent.

Several thin black shale beds in the Hermosa formation, including the Paradox member of Pennsylvanian age in western Colorado, contain on the order of 0.003 to 0.004 per cent uranium.

In the predominantly calcareous rock of Mississippian age in Montana and Utah, thin black shale beds are commonly present at the base of thick limestone units and in places contain 0.005 per cent uranium or more.[20]

In central Montana parts of the Heath shale of late Mississippian age contain as much as 0.009 per cent uranium, the most highly uraniferous shale of any thickness being at one locality in Fergus County where 4 feet of black shale near the top of the formation contain 0.006 per cent uranium.

Along an abnormally radioactive outcrop area in central Texas the Barnett formation of middle Mississippian age includes thin beds of phosphatic black shale that contain about 0.015 per cent uranium. One sample of phosphatic rock from this formation analyzed as high as 33.8 per cent P_2O_5 and 0.033 per cent uranium.

Existing sample and analytical data on the many thick dark marine shales in the states bordering the Atlantic and Pacific Oceans are very meager but, coupled with the information obtained on radiometric traverses, these shales are generally considered to have less than 0.003 per cent uranium. Those along the East Coast are mainly early Paleozoic in age, those along the West Coast chiefly late Paleozoic and Mesozoic.

GEOLOGIC SIGNIFICANCE OF ABNORMALLY RADIOACTIVE SHALES

In order to evaluate their uranium potential, marine black shales can be classified according to the tectonic and paleogeographic environment during the time of accumulation. Thus, four general categories of shale are considered, corresponding to four depositional environments: epicontinental areas, geosynclinal fringe areas, miogeosynclinal areas, and

eugeosynclinal areas. The characteristics of each depositional area are described by Kay.[21]

A number of formations composed in whole or in part of black shale can be assigned to each of the four categories of geologic environment. Those originating in epicontinental areas (or on the craton of Kay) are relatively thin formations having great horizontal persistence, as exemplified by the Chattanooga shale and the Pennsylvanian shales already described. Between the epicontinental and miogeosynclinal areas is a belt where formations change rapidly in thickness and rock type; shales in the Hamilton and Marcellus formations of Devonian age in the eastern States can be considered typical of the geosynclinal-fringe deposits. Within the thick predominantly clastic sequence of miogeosynclinal deposits, laid down in a belt lacking volcanism, the graptolitic Ordovician shales of the Deepkill and Normanskill formations are examples. And, lastly, representative of the eugeosynclinal deposits, which typically are rapidly deposited sediments measured in thousands of feet that were laid down in belts of active volcanism, are the Mariposa slate and other dark argillites and siltstones common in the Mesozoic sequence in the West Coast region.

The general tectonic and paleogeographic category into which most uraniferous shales fall is that of the epicontinental area. This environment was common to much of the interior of the United States during several intervals of the Paleozoic. The long-term inundation of a broad expanse of a relatively flat surface, and the lack of a source of a large amount of clastic sediment made possible the development of specific geochemical conditions that controlled the accumulation and preservation of uraniferous carbonaceous muds.

REFERENCES

1. Gott, G. B. and Hill, J. W., *Radioactivity in Some Oil Fields of Southeastern Kansas,* US Geological Survey Bulletin 988-e (1953).
2. Johnson, J. C., *Uranium Resources for Industrial Power,* US Atomic Energy Commission Press Release (5 April 1955).
3. McKelvey, V. E. and Nelson, J. M., *Characteristics of Marine Uranium-bearing Sedimentary Rocks,* Society of Economic Geologists Bulletin 45: 35–53 (1950).
4. Twenhofel, W. H., *Environments of Origin of Black Shales,* American Association of Petroleum Geologists Bulletin 23: 1178–1198 (1939).
5. Eargle, D. H., written communication (1955).
6. Szalay, S., *The Enrichment of Uranium in Some Brown Coals in Hungary,* Acta Geologica Academiae Scientiarium Hungaricae, Magyar Tudomanyos Akademia II: 299–310 (1854).
7. Moore, G. W., *Extraction of Uranium from Aqueous Solutions by Coal and Some Other Materials,* Society of Economic Geologists Bulletin 49: 652–658 (1954).
8. Conant, L. C., P/52, *Environment of Accumulation of the Chattanooga Shale,* Vol. 6, Session 6B, these Proceedings.
9. McKelvey, V. E., P/290, *Uranium in Phosphate Rock,* Vol. 6, Session 6B, these Proceedings.
10. Brown, Andrew, P/53, *Uranium in the Chattanooga Shale of Eastern Tennessee,* Vol. 6, Session 6B, these Proceedings.
11. Hass, W. H., *Age of the Chattanooga Shale and Maury Formation,* US Geological Survey Professional Paper, in press (1955).
12. Moore, R. C. et al., *The Kansas Rock Column,* State Geological Survey of Kansas Bulletin 89: 53–103 (1951).
13. Moore, R. C., *A Reclassification of the Pennsylvanian in the Northern Midcontinent Region,* Kansas Geological Society 6th Annual Field Conference Guidebook: 79–98 (1933).
14. Moore, R. C., *Environment of Pennsylvanian Life in North America,* American Association of Petroleum Geologists Bulletin 13: 459–487 (1929).
15. McKelvey, V. E. and Carswell, L. D., P/291, *Uranium in the Phosphoria Formation,* Vol. 6, Session 6B, these Proceedings.
16. Swanson, R. W., McKelvey, V. E. and Sheldon, R. P., *Progress Report on Investigations of Western Phosphate Deposits,* US Geological Survey Circular 297 (1953).
17. Kay, Marshall, *Geosynclinal Nomenclature and the Craton,* American Association of Petroleum Geologists Bulletin 21: 1289–1293 (1947).
18. Thompson, M. E., *Distribution of Uranium in Rich Phosphate Beds in the Phosphoria Formation,* US Geological Survey Bulletin 988-d (1953).
19. Tourtelot, H. A., written communication.
20. Mapel, W. J., P/54, *Uraniferous Black Shales in the Northern Rocky Mountains and Great Plains Regions,* Vol. 6, Session 6B, these Proceedings.
21. Kay, Marshall, *North American Geosynclines,* Geological Society of America Memoir 48 (1951).

Environment of Accumulation of the Chattanooga Shale

By Louis C. Conant,* USA

The black Chattanooga shale of the southeastern United States is clearly of marine origin, but for many years geologists have argued whether it is of Devonian or Mississippian age, and whether it accumulated in a shallow or deep sea. Recent studies of the conodonts by Hass[1] have apparently settled the age in central Tennessee and nearby areas as Late Devonian, but the question of depth of water is still debated. This paper presents evidence that the sea was shallow.

This discussion concerns only that part of the Chattanooga shale in the southeastern United States in and near Tennessee (Fig. 1), where the shale underlies about 40,000 square miles (about 100,000 square km). The shale is unusual because of its lithologic and stratigraphic uniformity, its thinness, and its uranium content. Also notable is the remarkably smooth peneplain on which the shale was deposited. Before deposition of the shale, the Nashville arch, which dominates the regional structure, had already undergone some of its many uplifts and had been peneplained. This erosion surface beveled gently dipping limestones, shales, and sandstones ranging in age from Middle Ordovician to Early Devonian, yet rarely does an outcrop 100 feet long show even a few inches of irregularity.

To the northeast an ancient Appalachian upland was supplying sediments to a submerging trough on its western side. To the west was the upland of Ozarkia. The peneplain lay between these two widely separated uplands.

DESCRIPTION OF THE CHATTANOOGA SHALE

The Chattanooga shale consists essentially of fine-grained black shale, but throughout large areas the upper part is more massive and is separated from the lower part by an apparent minor diastem. The lower part is the Dowelltown member, the upper the Gassaway member. This terminology is adapted from Campbell.[2] In the Eastern Highland Rim area of Tennessee two intervals are present in which gray claystone is interbedded with black shale. This makes it possible to divide the Chattanooga further into five traceable units, two in the Dowelltown, three in the Gassaway. Recognition of these units permits easy regional correlation of the shale and aids in interpreting the depositional history. A bentonite bed, about an inch thick, near the top of the Dowelltown member is an especially valuable marker.[3]

A few scour channels as much as a foot deep and a few tens of feet wide have been found in the Chattanooga shale, but such evidence of contemporary erosion of the beds is not common.

The lower parts of the Chattanooga shale, especially the Dowelltown member, are absent at many places, notably to the south, but no place is known where the Gassaway member is absent and the lower part is present. The topmost beds of the Gassaway, however, which are marked by scattered phosphate nodules and by a different conodont fauna, are not present in part of Tennessee and in the area farther south. This may indicate an inconspicuous hiatus at the top of the Chattanooga. Everywhere the shale is overlain abruptly by a greenish-gray claystone unit only about 1 to 6 feet thick, and this unit by chert, gray shales, and limestones, all of early Mississippian age (Kinderhook and Osage).

The conodont faunas[1] indicate that the Chattanooga shale, thin as it is, represents most of the Upper Devonian series. Dunkle[4] has identified bones of *Dinichthys terreli* and scales of the ray-fin fishes *Rhadanichthys devonicus* and *R. antiquus* from a rare bone assemblage at one place near the top of the formation. These vertebrates indicate a Late Devonian age. Other marine organisms include radiolaria,[5] *Lingula,* and *Orbiculoidea.* It is apparent that the Chattanooga sea was connected with the open ocean, presumably continuously and perhaps at a considerable distance.

The identifiable plant matter[6] includes marine spores, macerated particles of *Foerstia, Protosalvinia,* and *Prototaxites,* and the land spores *Tasmanites.* Logs of *Callixylon* have been found that are several feet long, a foot or more wide, and a fraction of an inch thick. The large plant remains, which have the appearance of films of bitumen, are high-volatile bituminous coal and have a uranium content as high as 0.02 per cent.

The conodonts, bones, plants, and other fossils have a tendency to be more abundant in certain layers, though all types are not necessarily associated in a fossil-rich layer.

The mineral composition of the black shale has been extremely difficult to determine because of the fine grain size and the masking effect of the abundant organic matter. Detailed studies conducted at Pennsylvania State University under the supervision of Bates[7,8,9] have employed chemical analyses, light

* US Geological Survey.

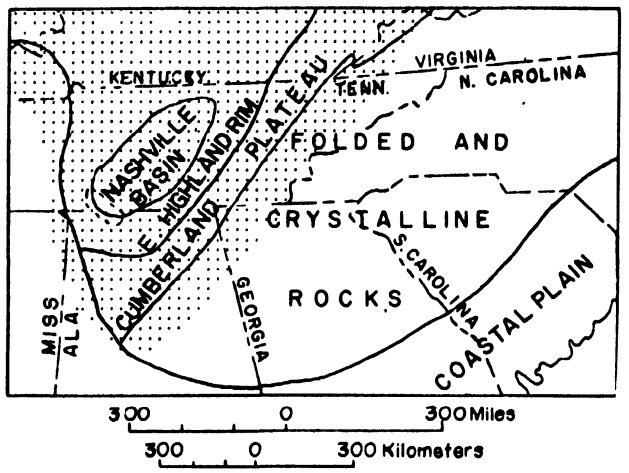


Figure 1. Setting of the Chattanooga shale. Shading shows the supposed approximate area of shale accumulation

and electron microscopes, electron and X-ray diffraction equipment, and various other techniques. These studies have shown that the denser and darkest parts of the shale, which have the most uranium, contain about 10 to 15 per cent pyrite, 20 to 25 per cent quartz, 10 per cent feldspar, 25 to 30 per cent clay and mica, 15 to 20 per cent organic matter, and about 5 per cent chlorite, free ferric oxides, and miscellaneous minerals. Zircon constitutes about 90 per cent of the nonmetallic heavy minerals. These studies have also shown that most of the minerals range downward in size to particles considerably below the resolving power of the light microscopes. The larger quartz grains are near the upper limit of silt in size, about 0.06 mm in diameter, but most of the mineral grains are very much smaller.

Sandstone is a minor part of the formation except at a few places that are believed to have been near shore. A basal sandstone, present at most places, is commonly only a fraction of an inch thick, though at some places it is absent, and locally it is several inches thick. At most places it is nearly black. The sandstone consists chiefly of insoluble detritus from the underlying formations, chiefly quartz and chert sand, fragments of phosphatized shells, and such phosphatic objects as conodonts and teeth. At some places the sandstone is underlain by a few millimeters of black shale, and at some other places it has a thin parting of black shale. The significance of this sandstone is referred to later. Locally another sandstone bed is at the base of the Gassaway member and still another is at the base of the upper unit of gray beds. Other beds of sandstone are present in some areas, especially in the lower part of the formation.

One of the most striking charcteristics of the shale, even in thin section, is the perfection of its paper-thin laminae. These are, for the most part, alterations of films of quartz grains and layers of mixed organic and mineral detritus. Many of the quartz layers are hardly more than films of dust three of four grains in thickness. No laminae are interpreted as varves. Some of the thinnest quartz laminae recognizable on an outcrop can be traced for several hundred feet and apparently continue to outcrops a mile or more away. Other laminae pinch and swell markedly, even within the length of a thin section.

The full thickness of shale is only about 30 to 35 feet (about 9–11 meters) in most of the area. At many places it is much thinner because the lower units are absent. The entire formation is absent in a few places, which apparently were islands in the Chattanooga sea. Northward, through Kentucky, the Chattanooga shale merges into the essentially identical Ohio and Sunbury shales and New Albany shale, which are considerably thicker. To the northeast, in Kentucky, Virginia, and West Virginia, it merges into a sequence of Middle and Upper Devonian sedimentary rocks, several thousand feet thick, which formed in the exogeosynclinal area between the interior platform and the Appalachian highlands.

It is clear that the sea spread slowly over the vast peneplain, perhaps from the direction of the geosyncline to the northeast. Parts of Kentucky and northern Tennessee were inundated early in the Late Devonian and sediments of the Dowelltown member were deposited. In most of southern Tennessee and in the northern parts of Alabama and Georgia, the area was not submerged until later and only the Gassaway member is present. Some relatively small areas (one of them of about 1,500 square miles) seem to have been low island areas throughout Late Devonian time, for the Chattanooga is absent, and lower Mississippian rocks of Kinderhook age lie on the pre-Chattanooga strata. It is not thought that the Chattanooga shale is missing because of erosion at the end of the Devonian, because no place is known where the Chattanooga thins toward those areas by progressive loss of its upper beds. Instead, there is everywhere a progressive loss of the older beds towards those areas, indicating an onlapping condition.

If the age interpretations are correct, and sedimentation was as nearly continuous as it appears to have been, 30 feet of shale seems to represent fully 10 million years—a phenomenally slow rate of sedimentation.

INFERENCES REGARDING ENVIRONMENT OF ACCUMULATION

The following inferences regarding the conditions under which the shale accumulated are based on the foregoing facts of composition and on regional, stratigraphic, and structural relations. Various considerations have required alternative possibilities to be abandoned.

A reducing environment at the bottom of the sea is indicated beyond reasonable doubt by the abundance of pyrite and undecomposed plant matter, and by the almost total absence of calcareous fossils and minerals. An oxygenated upper layer of water seems

necessary to have supported planktonic marine plant life and is strongly suggested by the conodonts, fish, and other animal remains. As will be seen later, the strata must have been thin, yet the waters of the two layers were apparently mixed only occasionally.

Any hypothesis that the shale accumulated in relatively deep water, as expressed by several earlier workers, and more recently by Rich[10,11,12] appears untenable in the Tennessee area. Any deep-water explanation seems to create more serious problems than it solves.

If one maintains that the black shale required deep water for its formation, he must assume that until the water reached the required depth any sediments reaching the sea were swept away. But no accumulation of coarse material is known that could reasonably be interpreted as those sweepings. It is highly improbable that all shallow-water sediments would have escaped preservation and yet that the first sediment to accumulate when the water became deep was a near-shore type of detritus.

It is entirely unreasonable to assume that the area sank so rapidly that only a thin basal sandstone could form, because the area of the Nashville dome has been a notably stable and positive area since early Paleozoic time.

At the close of Devonian time the sea spread over considerably larger areas, including the islands of the Chattanooga sea. Seemingly this Mississippian sea would have been at least as deep as the Chattanooga sea, yet the abundant and diverse fossils of those rocks are commonly thought to indicate a shallow epi-continental sea.

At nearly all places in the Chattanooga sea, regardless of the apparent time of inundation, the first sediment to accumulate was the basal sandstone, which is commonly less than an inch thick, and which is composed of detritus that was lying on the old land surface. It seems especially significant that at some places this sandstone bed has one or more partings of black shale, is underlain by a few millimeters of black shale, or is missing. Apparently a reducing environment existed close to the shore where the first sediments accumulated. It is probable that the first of these sediments accumulated close to shore, in water only a few feet deep. This concept should not be difficult to accept, for similar muds have been reported in shallow water of the Baltic Sea,[13] the Norwegian fjords,[14] and in a few other places. The slight erosion interval at the top of the Dowelltown member suggests either withdrawal of the sea or marine planation. In one area of about 100 square miles the bentonite bed and its associated beds are missing. In the surrounding area the 1 or 2 feet of Dowelltown strata that normally are above the bentonite are gently beveled toward the central region. Clearly the muds were removed, probably by marine planation, as a result of a slight upwarp of the sea bottom. This condition suggests a delicate balance between deposition and erosion in a shallow and quiet sea.

The perfection of the lamination and the sorting of the fine sediments suggest frequent mild disturbance of the muds. Associated with this is evidence that the muds moved appreciable distances along the bottom and filled local areas that were subsiding. It is believed that gentle movements of the water frequently worked over the muds, shifted them to lower places, and sorted them. The extremely thin laminae, which do not commonly grade upward or downward into one another, are not suggestive of gravitational sorting of large amounts of mud that have been stirred up or washed into the sea.

The fineness of the muds and the slowness of accumulation seem to result from the extensive surrounding peneplain, which was developed chiefly on limestone. From such a source only a small amount of sediment could be expected, and it would be mostly fine mud. Most of the sediments from the Appalachian upland were trapped by the geosyncline, and only the finest or most buoyant of the particles would have reached the Chattanooga sea. Windblown dust from greater distances may also have contributed materially to the sediments.

The perfection and continuity of the stratification and the general lack of storm waves in a shallow sea require either the absence of storms or the existence of conditions unfavorable to the generation of large waves. It is unreasonable to assume that during all of Late Devonian time an extensive sea was not exposed to storms. More likely, conditions in the Chattanooga sea did not favor the frequent generation of large waves and strong currents. Scattered islands and an irregular shoreline also doubtless interfered with the formation of storm waves.

A well-graded sea bottom may have been an important factor in preventing the generation of strong waves. Keulegan and Krumbein[15] have shown that in a sea having a sufficiently gently sloping bottom storm waves will lose their energy so gradually in their approach to shore that breakers do not form. Under these conditions, which must have existed in the Chattanooga sea, much of the bottom may have been protected from any strong wave action.

An additional obstacle to the development of large waves, and perhaps an important one, may have been an abundant growth of seaweeds and other types of floating plants.

Some of the conditions here set forth are almost certain to have existed, and the others apparently could have existed. The combination may well have brought about the environment thought to have existed in the Chattanooga sea. Strong wave action would have been uncommon, and the waves that did exist would have supplied the gentle agitation that appears to have reworked the muds so frequently.

Occasional storm waves probably did disturb the waters enough to poison the upper layer and kill the large numbers of animals or plants that are found in some beds.

As stated, it seems highly probable that the first sediments at any given place accumulated in water close to shore, probably only a few feet deep. These sediments include interbedded black sandstone and black shale. Other evidence, not cited here, suggests that the sea floor was well graded and had slopes of only a few inches per mile. Projections of those slopes between probable land areas indicate that the depth of water at most places was not more than a few tens of feet.

URANIUM CONTENT

The uranium content is highest in the Gassaway member, which contains slightly more than 0.005 per cent uranium. The uranium was probably brought to the sea by streams from the surrounding land areas in normal quantities, and any inflow of sea water would have brought more. The abundant organic matter that was exposed on the bottom, or that was in suspension, is believed to have extracted the uranium in some unknown manner. The form and association of the uranium have so far defied exact determination, but much of the metal is probably associated with the plant matter in an ionic form. Moore[16] has shown that low-rank coals have a strong affinity for uranium, and the same is undoubtedly true for plant matter in earlier stages of coal formation.

Significant in this respect is the much higher uranium content of the coalified logs that have been isolated and analyzed. This higher uranium content of the logs probably results from the absence of mineral matter, and perhaps from longer exposure to the water.

The relatively high uranium content of the Chattanooga shale probably results from the extremely slow accumulation of mineral matter in an environment favorable to the removal of the uranium from the water. If even less mineral matter were present, or if the surrounding land masses had supplied more uranium to the sea, the shale would have been even richer.

REFERENCES

1. Hass, W. H., *Age of the Chattanooga Shale and the Maury Formation [Abstract]*, Geological Survey of America Bulletin 64: 1532 (1953).
2. Campbell, Guy, *New Albany Shale*, Geological Society of America Bulletin 57: 829–908 (1946).
3. Hass, W. H., *Upper Devonian Bentonite in Tennessee*, American Association of Petroleum Geologists Bulletin 32: 816–819 (1948).
4. Dunkle, D. H., personal communication.
5. Henblest, personal communication.
6. Schopf, personal communication.
7. Bates, T. F., *Mineralogy of the Chattanooga Shale [Abstract]*, Geological Society of America Bulletin 64: 1529 (1953).
8. Bates, T. F. *et al.*, *An Investigation of the Mineralogy, Petrography and Paleobotany of Uranium-Bearing Shales and Lignite (Scope A—Lignite)*, Atomic Energy Commission NYO-3363 (1953).
9. Strahl, E. O. *et al.*, *An Investigation of the Mineralogy, Petrography and Paleobotany of Uranium-Bearing Shales and Lignites (Scope A—Lignite)*, Atomic Energy Commission NYO-6068 (1955).
10. Rich, J. L., *Probable Deep-Water Origin of the Marcellus-Ohio-New Albany-Chattanooga Shale [Abstract]*, Geological Society of America Bulletin 59: 1346–1347 (1948).
11. Rich, J. L., *Probable Fondo Origin of Marcellus-Ohio-New Albany-Chattanooga Bituminous Shales*, American Association of Petroleum Geologists Bulletin 35: 2017–2040 (1951).
12. Rich, J. L., *Paleogeographic Implications of Evidences Pointing to Fondo Origin of the Chattanooga-New Albany-Ohio Bituminous Shales [Abstract]*, Geological Society of America Bulletin 64: 1535–1536 (1953).
13. Twenhofel, W. H., *Notes on Black Shale in the Making*, American Journal of Science 4th Ser. 40: 272–280 (1915).
14. Strøm, K. M., *A Concentration of Uranium in Black Muds*, Nature 162: 922 (1948).
15. Keulegan, G. H. and Krumbein, W. C., *Stable Configuration of Bottom Slope in a Shallow Sea and its Bearing on Geological Processes*, American Geophysical Union Transactions 30: 855–861 (1949).
16. Moore, G. W., *Extraction of Uranium from Aqueous Solution by Coal and Some Other Materials*, Economic Geology 49: 652–658 (1954).

Uranium in the Chattanooga Shale of Eastern Tennessee

By A. Brown,* USA

The uraniferous Chattanooga shale is part of a widespread blanket of bituminous shales of Late Devonian and early Mississippian age which were deposited over much of central United States from New York to Texas. In this region the shale sequence varies widely in lithology and thickness, and is known by several formational names. The name Chattanooga, however, is used for this bituminous shale sequence in a large area including Arkansas, Tennessee, and adjoining states.

In 1942 reconnaissance of the Chattannoga shale around the Nashville dome, Tennessee, showed that the shale is much more radioactive than other rocks in the area. Investigations in 1947 and later indicated that the most uraniferous part of the shale is in the Eastern Highland Rim and in Walden Ridge north and west of the city of Chattanooga, Tennessee; the favorable area also may extend southward into Alabama. This report is concerned, therefore, with a roughly triangular region bounded on the southeast by the folded Appalachians of Tennessee and Alabama, and on the west by the axis of the Nashville dome. The northern boundary is defined roughly by a west-east line extending from Smithville through Crossville to the Cumberland escarpment south of Rockwood (Fig. 1). South of that line, the Chattanooga shale is generally less than 35 feet thick; to the north it thickens rapidly.

GEOGRAPHY AND TOPOGRAPHY

The Nashville Basin extends across the state of Tennessee in a northeasterly direction and is about 125 miles long and 60 miles wide (Fig. 1). Structurally it is a subsidiary dome on the Cincinnati arch.[1] The general surface of the Basin is about 500 feet above sea level and is underlain by beveled limestones of Ordovician age. A topographic terrace east of the Basin, known as the Eastern Highland Rim, is about 25 miles wide and rises 500 to 600 feet above the Basin floor. The edge of the Eastern Highland Rim is highly dissected, and many good outcrops of the Chattanooga shale are exposed. East of the Rim, the topography rises 900 to 1,000 feet to the Cumberland Plateau, which extends eastward to the folded rocks of the Tennessee River valley. About 25 miles west of the edge of the Cumberland Plateau the Sequatchie River valley has been cut parallel to the axis of an anticline (Fig. 1). Walden Ridge, structurally a shallow syncline, is east of the valley and is about the same height as the Plateau. The Chattanooga shale is well exposed on the western side of Walden Ridge.

The Chattanooga shale underlies the Eastern Highland Rim, the Cumberland Plateau proper, and Walden Ridge and apparently has much the same composition and thickness throughout the entire region.

STRATIGRAPHY

The Chattanooga shale rests on the Liepers limestone of Late Ordovician age in the Eastern Highland Rim, and on Silurian rocks in Walden Ridge. This erosion surface on which the shale was deposited is very flat; the maximum relief is a few tens of feet.[1]

In this area the Chattanooga shale is of Late Devonian age and consists of two members, the Dowelltown and the overlying Gassaway; each contains several units.[2] The Dowelltown member consists, in ascending order, of the basal sandstone, the lower black unit, and the middle gray unit. The basal sandstone is a fine-grained conglomerate commonly 2 inches or less in thickness. The lower black unit is a tough, black, relatively thin-bedded bituminous shale. It underlies part of the Eastern Highland Rim and is absent south of Tullahoma and north of a line about 20 miles south of the Kentucky-Tennessee state boundary (Fig. 1). The eastern and western limits of the lower black unit are undetermined. In the central part of its depositional area, the lower black unit is commonly 6 to 7 feet thick, though thicknesses of 4 and 12 feet are known.

The middle gray unit, a series of interbedded gray and black shales, forms the top of the Dowelltown member. Gray beds constitute about three-fourths of the unit; black beds, generally 2 inches or less thick, are abundant in the lower and upper thirds. A persistent 0.1-foot bed of bentonite near the top of the unit is a useful stratigraphic marker.[3] The thickest measured sections of the middle gray unit in the Eastern Highland Rim are about 12 feet thick and in Walden Ridge about 5 to 6 feet thick. Like the lower black unit, the middle gray unit thins to both the north and south and is absent not far beyond the limits of the lower black unit.

The Gassaway member comprises, in ascending order, the middle black unit, the upper siltstone, the top black unit, and the phosphatic zone. The middle

* US Geological Survey. Including work by L. C. Conant, W. H. Hass, R. C. Robeck and R. E. Smith.

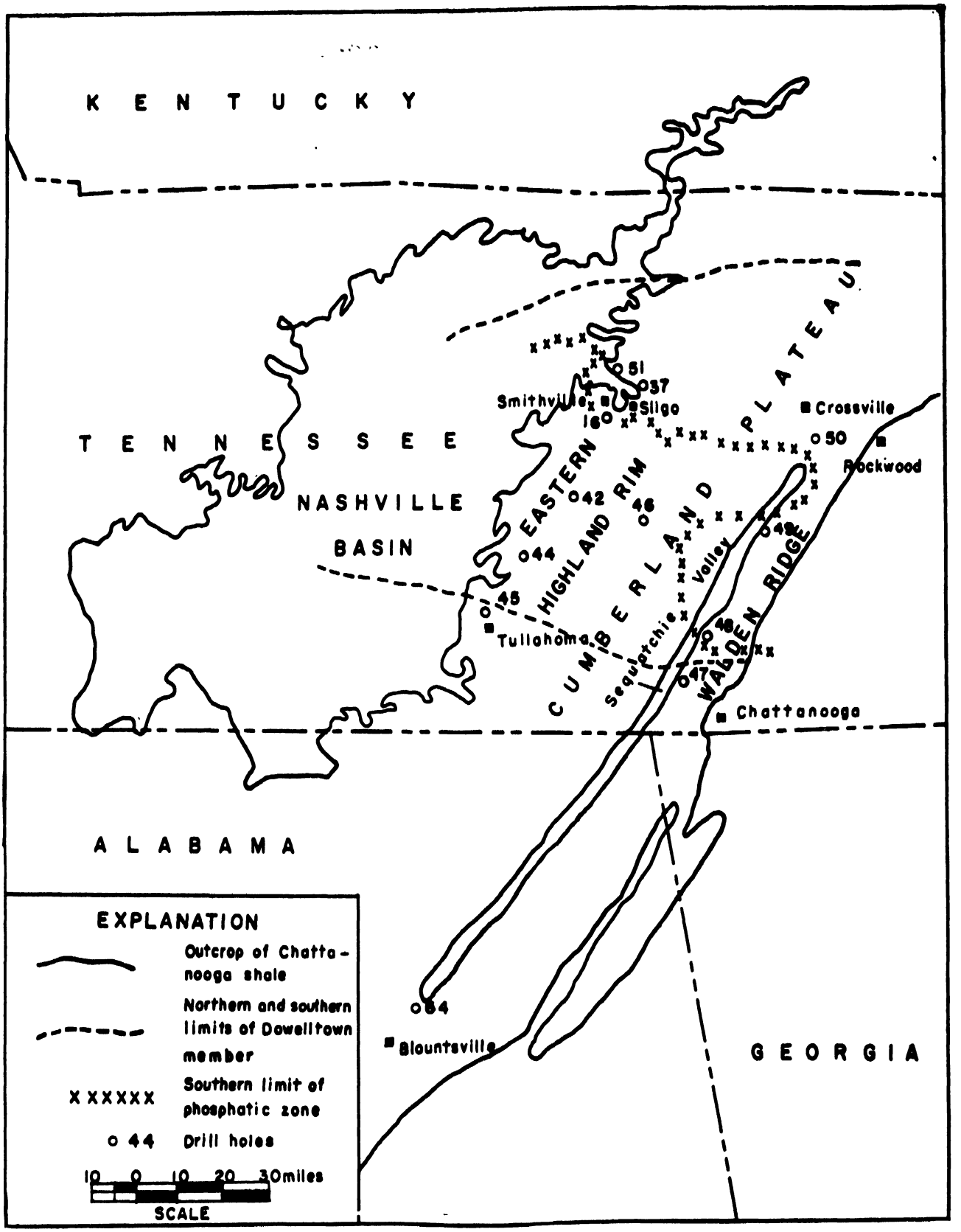


Figure 1. Sketch map showing distribution of the most uraniferous portion of the Chattanooga shale

black unit is a black bituminous shale similar to the lower black unit of the Dowelltown member but somewhat thicker bedded. It is 7 to 8 feet thick near Smithville but thins to the north, south, and possibly east.

The upper siltstone is a black shale sequence that contains a number of thin beds of gray shale or siltstone. It is 2 to 3 feet thick in the vicinity of Smithville but thins to the east, south, and north. It has not been recognized south of Tullahoma (Fig. 1). In Walden Ridge the gray beds, though recognizable in some drill cores, are hard to detect in outcrops.

The top black unit of the Gassaway member is the most widespread and most uraniferous unit of the Chattanooga shale. It is darker in color than the other "black" units, and its outcrops are commonly massive. It is 4 to 10 feet thick in Tennessee, somewhat thicker in Alabama. Small differences in thickness are interpreted as the result of local erosion of the top of the unit. This variation in thickness, coupled with paleontologic data,[4] indicates a minor unconformity at the top of the Gassaway member south of Smithville and in Walden Ridge.

North of the Smithville-Rockwood line, at a few localities to the south, and in parts of Walden Ridge, the top black unit is overlain by the phosphatic zone which consists of black shales that contain scattered phosphatic nodules. The nodules are commonly 1 inch or more in diameter. The contact between the top black unit and the phosphatic zone is not sharp and can be detected only by the presence or absence of the nodules, and by a different assemblage of conodonts.

In summary, the Chattanooga shale in the Eastern Highland Rim and Walden Ridge areas has a maximum thickness of about 35 feet. The Dowelltown member reaches a maximum thickness of about 18 feet; the Gassaway member ranges from 7 feet near Tullahoma to 18 feet near Smithville and from 11 to 21 feet in Walden Ridge.

The Chattanooga shale is directly overlain by the soft, light-green Maury formation which weathers to yellow or brown. At the base of the Maury in the northern part of the area is a 4-inch to 2-foot bed of black shale that contains large flattened phosphatic nodules; this shale Hass,[5] on the basis of its conodont fauna, considered to be of latest Devonian age. The Maury, from similar evidence, is assigned to lowest Mississippian.

In the Eastern Highland Rim and Walden Ridge the Maury formation is from 1 to 3 feet thick. It is overlain by the Fort Payne chert, which forms cliffs along the Eastern Highland Rim and Walden Ridge.

STRUCTURE

The Chattanooga shale dips eastward from the axis of the Nashville dome to the Sequatchie Valley at the rate of about 30 feet to the mile. Folds in the monocline trend northeast and are of minor importance. The highest observed local dips are about 15 degrees. The one fault observed in the Eastern Highland Rim has cut out all but 3 feet of the Chattanooga shale by horizontal thrusting.

The monoclinal structure is broken along the west side of the Sequatchie Valley by the Sequatchie fault, overthrust from the southeast. The fault brings the Chattanooga shale, which is under about 2,000 feet of cover west of the valley to the surface in its eastern escarpment, Walden Ridge. In the ridge the Chattanooga shale dips southeast at an average rate of about 8 degrees, the maximum observed dip being 15 degrees. All outcrops in Walden Ridge are fractures but cores from drill holes not far behind the outcrops show less disturbance of the rocks than the exposures would indicate.

COMPOSITION OF THE CHATTANOOGA SHALE

The predominant components of all units of the Chattanooga shale are fine silt and clay particles, most of which could have been transported by either wind or water. The black units contain abundant pyrite and organic material,[6,7] some in the form of plant debris but most as a translucent, yellow or brown material. The gray units contain much smaller quantities of carbonaceous matter and pyrite than do the black beds.

Analyses of two cores from drill holes about 5 miles apart between Smithville and Sligo (Fig. 1) show that silicates make up the bulk of all units of the Chattanooga shale, and that pyrite and carbon are next in abundance. The relationship between these constituents is shown below:[7]

Unit	*Silicates (per cent)*	*Pyrite (per cent)*	*Carbon (per cent)*	*Total silicates, pyrite, carbon (per cent)*
Gassaway member				
Top black unit	62	15	13	90
Upper siltstone	78	6	8	92
Middle black unit	69	8	13	90
Dowelltown member				
Middle gray unit	80	4	4	88
Lower black unit	70	6	9	85

The inverse relationship between silica on the one hand and pyrite and carbon on the other is noticeable in all units but particularly those of the Gassaway member. The pyrite and carbon content of the upper siltstone in these cores probably is lower than that for the Eastern Highland Rim as a whole, as the gray beds of the unit are best developed in the Smithville area.

The organic material in the shale is derived largely from spores. In the lower part of the shale *Foerstia*, a planktonic marine alga, is common, and a large algoid plant, *Prototaxites*, is rare. The most common woody material, occurring in silicified form and as bituminous coaly streaks, is drift wood of *Callixylon*. Most of the uranium-rich stringers formerly identified as asphaltite are now known to be *Callixylon* fragments.[8]

Semi-quantitative spectrographic analyses of three cores of the total thickness of the Chattanooga shale and 15 cores across the Gassaway member show that the chemical composition of the shale is fairly constant, both vertically and laterally, from northeast of Smithville (holes 37 and 51, Fig. 1) to the vicinity of Blountsville, Alabama (hole 64) and in Walden Ridge (holes 48 to 50). The percentage range of the following elements in these cores is:

0.0001–0.001 %	0.001–0.01 %	0.01–0.1 %	0.1–1.0 %	1.0–10.0 %	10+ %
Be Yb	Zr Ga Y	Cu B	Ti	Fe	Si

The abundance of the following elements showed greater percentage range:

0.0001–0.01 %	0.001–0.1 %	0.01–1.0 %	0.1–10 %	1.0–10+ %
Sc Ag	Pb Cr Co	Ba	Mg Na	Al
	V Sr Mn		Ca K	
	Ni La Sn			

The abundance of cobalt, molybdenum, and nickel in the middle gray unit is one order of magnitude below the average—0.01–0.1 per cent—of the other units. The vertical distribution of elements in the Gassaway is uniform except that aluminum is less than 10 per cent in most samples of the top black unit and is more than 10 per cent in the other units. The barium content is more than 0.1 per cent in the top black unit and less than 0.1 per cent in the lower units. Strontium is most abundant—0.001–0.01 per cent—in the top black unit. The percentage of calcium in about half of the samples is more than 1.0 per cent and apparently is never as much as 2 per cent.

The lateral variations in the content of minor constituents are greater than the vertical variations in the Gassaway member. Lead, cobalt, and sodium in samples from the Eastern Highland Rim are more than .01 per cent in some cores, less in others; increases in these elements are accompanied by decreases in vanadium and vice-versa. Magnesium, sodium, lead, manganese, and strontium are more abundant in rocks from hole 49 in Walden Ridge than in hole 48 to the south and hole 50 to the north.

Lanthanum was found only in holes 48 and 50 in Walden Ridge and in hole 42 in the Eastern Highland Rim; silver only in holes 48, 49, and 50 in Walden Ridge and holes 44, 45, 64, and 51 in the southern part of the Eastern Highland Rim; and tin in all holes in the Eastern Highland Rim and in hole 49 in Walden Ridge. No correlations can be made between uranium and minor metal content.

URANIUM IN THE CHATTANOOGA SHALE

All units of the Chattanooga shale contain more uranium than most marine shales, but the content varies from unit to unit as shown at top of next column.

	Range of uranium content in per cent
Gassaway member	
Phosphatic zone	0.0016–0.0036
Top black unit	0.0060–0.0086
Upper siltstone	0.0028–0.0058
Middle black unit	0.0039–0.0066
Dowelltown member	
Middle gray unit	0.0011–0.0020
Lower black unit	0.0024–0.0052

The wide range of uranium content in the upper siltstone unit reflects the relative abundance of interbedded gray, slightly uraniferous shale in that unit. The presence of the thick, almost barren middle gray unit above the relatively thin lower black unit rules out the Dowelltown member as a source of uranium, and only the Gassaway member can be considered a potential source under present conditions.

Throughout most of the Eastern Highland Rim area the highest uranium content of the Gassaway member is in the upper part of the top black unit. At the northernmost and southernmost holes in Walden Ridge (holes 47 and 50) the vertical distribution of uranium is the same as in the Eastern Highland Rim. In the central area (holes 48 and 49) the high uranium zone parallels the bottom of a tongue of the phosphatic zone. That part of the Gassaway member beneath the phosphatic zone in Walden Ridge contains about 20 per cent more uranium than the part in the Eastern Highland Rim.

No uranium minerals have been identified in the shale. The element is present as a separate colloidal phase disseminated through the organic matrix and is not chemically combined with the organic matter.[9] Autoradiographic studies by Bates[10] demonstrate that the alpha-particle source material is localized around concentrations of organic matter and pyrite.

Uraniferous black shales are generally characterized by relative thinness of the formations; fairly high phosphate content or the presence of phosphatic nodules; high oil yield; and low calcium content.[11] The Chattanooga shale is very thin and has a low calcium content. The phosphate content and oil yield of the rock, however, are relatively low, and in that respect the Chattanooga differs from the "typical" uraniferous black shale as described by McKelvey, Everhart, and Garrels[11] and other writers.

The relationship between the thinness of the Chattanooga shale and its uranium content seems obvious; the 35-foot thickness of the formation represents all of Late Devonian time and is equivalent to 10,000 feet or more of sediments in other areas.[6] Thinness, however, is only one factor, as the distribution of uranium in the Chattanooga shale itself shows. The formation is of about the same thickness on all sides of the Nashville dome; yet the uranium content is much higher on the eastern side of the dome than elsewhere.

The most uraniferous portion of the Chattanooga shale contains only 0.2 to 0.3 per cent phosphate and does not contain visible phosphatic nodules. West of Nashville, where phosphate occurs near the base of the formation, the uranium content is low. The phosphatic zone on the Northern and Eastern Highland Rims and in Walden Ridge also contains less uranium than do the other black units of the formation.

The oil yield of the most uraniferous portion of the Chattanooga shale, the top black unit of the Gassaway member, appears from scattered analyses to be no greater, and perhaps somewhat less, than the average for the Gassaway member or for the lower black unit of the Dowelltown member.[12]

A rough correlation between the relative blackness of the shale and its uranium content was noted in the field; in general, the darker the color, the higher the uranium content. Reflectance studies by Flanagan[13] and Bates[10] confirm this relationship.

The color of the shale is a function of its carbon and sulfide content. One of the first correlations noted by students of uraniferous black shales was that between uranium and carbonaceous material.[14] Analyses of 24 samples taken in 1948 from various localities and different units of the Chattanooga shale showed a direct relationship between the contents of total sulfur and uranium. Recent studies by Bates[10] show positive correlations of the uranium with total carbon, pyrite, and sulfur, and low correlations with other components of the shale. It thus seems clear that the concentration of uranium in the Chattanooga is associated with pyrite and carbonaceous materials and not with other constituents of the rock.

The hypothesis that uranium in black shales was concentrated by means of upwelling of currents from oceanic depths upon a continental shelf[11] can hardly be applicable to the Chattanooga shale. Although the southeastern limit of the Chattanooga sea connot be determined because of later structural changes, the preponderance of evidence points to deposition of the shall in a sea that was for the most part landlocked and comparatively shallow. The uraniferous Eastern Highland Rim-Walden Ridge area was apparently in the central and deepest part of this sea, because the area contains only a small amount of coarse clastic material and the shale is noticeably sandier toward the west[15] and north.[16] Lack of circulation on the bottom of such a sea would provide anaerobic conditions and permit carbonaceous material, which has a strong affinity for uranium, to accumulate.

The relatively nonuraniferous gray beds in the upper siltstone are best developed near Smithville and thin in all directions from that central area. They may thus represent periods during which the reducing conditions within the sea were less severe. This change of conditions could have been accomplished by periods of storm which would have introduced oxygen into the water; influx of water into the epicontinental sea which would have provided more bottom circulation; or conditions unfavorable for plant life in the sea and on the surrounding land. The same hypothesis may, to a certain extent, be applicable to the middle gray unit of the Dowelltown member.

Phosphate is formed in shallower better aerated water than the nonphosphatic black shales.[11] Thus the extreme reducing conditions which permitted concentration of uranium in the Eastern Highland Rim-Walden Ridge area probably did not prevail west of the Nashville dome when the phosphatic part of the Chattanooga shale was deposited there or in the northeast when the phosphatic zone was laid down. This change in environment could account for the lower uranium content of those units as compared to the blacker shales.

The suggestion[11] that the high uranium content of certain black shales represents concentration of only normal quantities of the element in sea water over tremendously long periods of geologic time, and that no particularly uraniferous source material is necessary, may not apply to the Chattanooga shale. It has been suggested that the land mass of crystalline rocks east of the Chattanooga sea could have provided more than average amounts of uranium; another possible source is volcanic ash. The bentonite bed in the Chattanooga shale is evidence of volcanic activity, and Rich[6] has noted that some of the clastic material throughout the Chattanooga shale is of possible volcanic origin. It is altogether likely that small quantities of ash fell into the sea almost continuously during Chattanooga time and increased the amount of uranium available for concentration. Streams also could have brought in ash from the surrounding land.

REFERENCES

1. Wilson, C. W., Jr., *Pre-Chattanooga Stratigraphy in Central Tennessee,* Tennessee Department of Conservation, Division of Geology, Bulletin 56 (1949).
2. Campbell, Guy, *New Albany Shale,* Geological Society of America Bulletin 57: 829–908 (1946).
3. Hass, W. H., *Upper Devonian Bentonite in Tennessee,* American Association of Petroleum Geologists Bulletin 32: 816–819 (1948).
4. Hass, W. H., oral communication.
5. Hass, W. H., *Age of the Chattanooga Shale and Maury Formation* (abstract), Geological Society of America Bulletin 64: 1532 (1953).
6. Rich, J. L., *Probable Fondo Origin of Marcellus, New Albany, Chattanooga Bituminous Shales,* American Association of Petroleum Geologists Bulletin 35: 2017–2040 (1951).
7. Strahl, E. O., Silverman, E. N., O'Neill, R. L., Dewey, H. D., Griffiths, J. C., Wright, H. D. and Bates, T. F., *An Investigation of the Mineralogy and Petrology of Uranium-Bearing Shales,* 4th Annual Progress Report to US Atomic Energy Commission (April 1955).
8. Schopf, J. M., *Organic Matter of the Chattanooga Shale,* US Geological Survey TEI–330, US Atomic Energy Commission Technical Information Service, Oak Ridge, 146–152 (1953).
9. Deul, Maurice and Breger, Irving, *Uranium in Black Shales,* US Geological Survey TEI–440, US Atomic Energy Commission Technical Information Service, Oak Ridge, 178–182 (1954).
10. Bates, T. F., Strahl, E. O., Short, N. M., Silverman, E. N. and Camilli, E., *Mineralogy and Petrology of the Chattanooga Shale* (abstract), Geological Society of America Bulletin 65: 1230 (1954).
11. McKelvey, V. E., Everhart, D. L. and Garrels, R. M., P/300, *Summary of Hypotheses of Genesis of Uranium Deposits,* Vol. 6, Session 6B, these Proceedings.

12. Cuttitta, Frank, *A Photometric Method for the Estimation of Oil Yield of Oil Shale*, US Geological Survey TEI-152, US Atomic Energy Commission Technical Information Service, Oak Ridge (1951).

13. Flanagan, F. J., *Relationship of Color of Shales to Uranium Control*, US Geological Survey TEI-440, US Atomic Energy Commission Technical Information Service, Oak Ridge, 163-164 (1953).

14. McKelvey, V. E. and Nelson, J. M., *Characteristics of Marine Uranium-Bearing Sedimentary Rocks*, Economic Geology 45: 35-53 (1953).

15. Mellen, F. F., *Black Warrior Basin, Alabama and Mississippi*, American Association of Petroleum Geologists Bulletin 31: 1801-1816 (1947).

16. Maher, S. W., *Sandy Zones in the Chattanooga of the Eastern Highland Rim, Tennessee* (abstract), Geological Society of America Bulletin 65: 1363 (1954).

Uraniferous Black Shales in the Northern Rocky Mountains and Great Plains Regions

By W. J. Mapel,* USA

Deposits of black shale that range in age from Precambrian to late Cretaceous crop out or are penetrated in test wells drilled for oil and gas at many places in the northern Rocky Mountain and Great Plains regions of the United States and southern Canada. A reconnaissance search for uranium in black shale in this region was carried out during the summer of 1953 at many localities in southwestern and central Montana, central and southeastern Idaho, and northwestern Utah.

Previous reconnaissance in the western States had indicated that the Heath shale of late Mississippian age, a thin black shale sequence known locally as the Bakken formation, the Kinderhook shale, or the Exshaw formation of early Mississippian age, and a black shale at the base of the Brazer limestone of middle and late Mississippian age, at some places contain 0.005 per cent or more uranium. These and 17 other formations (Fig. 1 and Table 1) that contain black shale were examined at one or more places at their outcrop or by means of drill cuttings and cores, and more than 100 commercial gamma-ray logs of oil and gas wells—mostly in Montana and North Dakota—were scanned for highly radioactive zones.

The work reported here is a continuation of previous reconnaissance studies conducted at various times since 1951 in the western States by D. C. Duncan, W. J. Hail, Jr., J. R. Gill, G. W. Moore, and J. D. Vine.[1] D. C. Duncan, R. J. Ross, J. E. Smedley, R. P. Kunkel, P. W. Richards, Roy Kepferle, and H. D. Hadley supplied samples of black shale or guided the writer to exposures of shale in Utah, Montana, and North Dakota. W. J. Hail, Jr. compiled information from the gamma-ray logs and assisted in interpreting the results of this work.

BLACK SHALE AT THE BASE OF THE MADISON LIMESTONE AND EQUIVALENTS

A black-shale sequence of early Mississippian (Kinderhook) age, a few inches to 100 feet thick, occurs locally at the base of the Madison limestone or its equivalents in southwestern and central Montana, and in the Williston Basin of Saskatchewan, Manitoba, Montana, and the Dakotas. The term Bakken formation has been used to identify this unit in the subsurface in the Williston Basin, where it is described by Nordquist[3] as ". . . two thin highly radioactive black shales separated by a gray calcareous sandstone, siltstone, or dolomite". According to Nordquist, the upper shale unit may be correlative with a bed of black shale a few inches to 30 feet thick at the base of the Madison or Lodgepole limestone in various parts of southwestern Montana and northeastern Utah. The lower shale and medial sandstone-dolomite units may correlate with the Sappington sandstone member, a shale and sandstone sequence as much as 60 feet thick that occurs below the Madison limestone in parts of southwestern Montana. In most parts of the northern Rocky Mountain region, the Bakken formation and its equivalents unconformably overlie the Three Forks or Jefferson formations of late Devonian age.

The black shale sequence at the base of the Madison limestone was sampled at 17 localities in the mountainous parts of southwestern and central Montana and northwestern Utah. The maximum observed uranium content of the sequence is 0.005 per cent in the lower half of a 2½-foot thick bed of black shale near Three Forks, Montana (locality 43, Fig. 2), and 0.005 per cent in the basal part of a 10-foot thick bed of brownish-black shale nearby (locality 44).

The Bakken formation of Nordquist[3] was sampled in 2 wells in northeastern Montana, and in 2 wells in northwestern North Dakota. The lithology, radioactivity, and uranium content of the formation in 3 of these wells are shown by Fig. 3. The samples from the Carter no. 1 Danielson well are anomalous in that they are decidedly out of balance in favor of equivalent uranium as indicated in Table 2. J. N. Rosholt, Jr. (US Geological Survey Trace Elements Laboratory) investigated the source of the high radioactivity in sample 204067 (Table 2). The sample contained 0.003 per cent thorium-232, 0.009 per cent thorium-230, and 0.006 per cent radium. His data indicate that Th^{230} and radium, both daughter products of uranium, are the principal contributors of excess radioactivity. The relatively high concentrations of these elements in comparison to uranium suggest that leaching of uranium or addition of Th^{230} and radium has occurred in this deeply buried shale in comparatively recent time.

The thickness and areal distribution of radioactivity in the Bakken formation as determined from published sample descriptions and gamma-ray logs is shown by Fig. 3. These maps suggest that black shale

* US Geological Survey.

in the Bakken formation of Nordquist[3] is thickest in northwestern North Dakota and that the formation is most radioactive slightly east of this area near the northeastern corner of Montana. Perhaps no convincing conclusions can be drawn from the data presented, but it seems evident that radioactivity in the Bakken formation varies appreciably and with a definite pattern from place to place. Recognition of the pattern doubtless will help in outlying areas in which maximum concentrations of uranium in the formation might be expected.

BLACK SHALE AT THE BASE OF THE BRAZER LIMESTONE

In parts of Utah and Idaho the Brazer limestone of middle and late Mississippian age includes at its base a black phosphatic shale sequence a few inches to about 75 feet thick. Exposures of this black-shale sequence were tested at two places in southeastern Idaho (localities 21 and 22, Fig. 1) and at one place in northwestern Utah (locality 30, Fig. 1). Beds of black shale in sequence at the two Idaho localities are essentially nonuraniferous, but in sec. 32, T. 13 N., R. 6 E., Rich County, Utah, a bed of phosphatic shale 14 feet thick in the upper part of the sequence contains as much as 0.006 per cent uranium, and one 8 feet thick in the lower part contains as much as 0.009 per cent uranium.

Duncan (Ref. 1, p. 68) reported that at Ogden Canyon, Weber County, Utah, about 45 miles southwest of the Rich County locality, phosphatic shale about 1 foot thick contains as much as 0.005 per cent uranium, 0.18 per cent vanadium oxide, and 17.3 per cent phosphate.

HEATH SHALE

The Heath shale of late Mississippian age crops out along the margins of the Little Belt and Big Snowy Mountains in central Montana, and it has been penetrated in drill holes throughout a large area in eastern Montana and western North Dakota (Fig. 4). The formation consists largely of marine black shale with subordinate amounts of gray limestone and fine- to coarse-grained sandstone. The

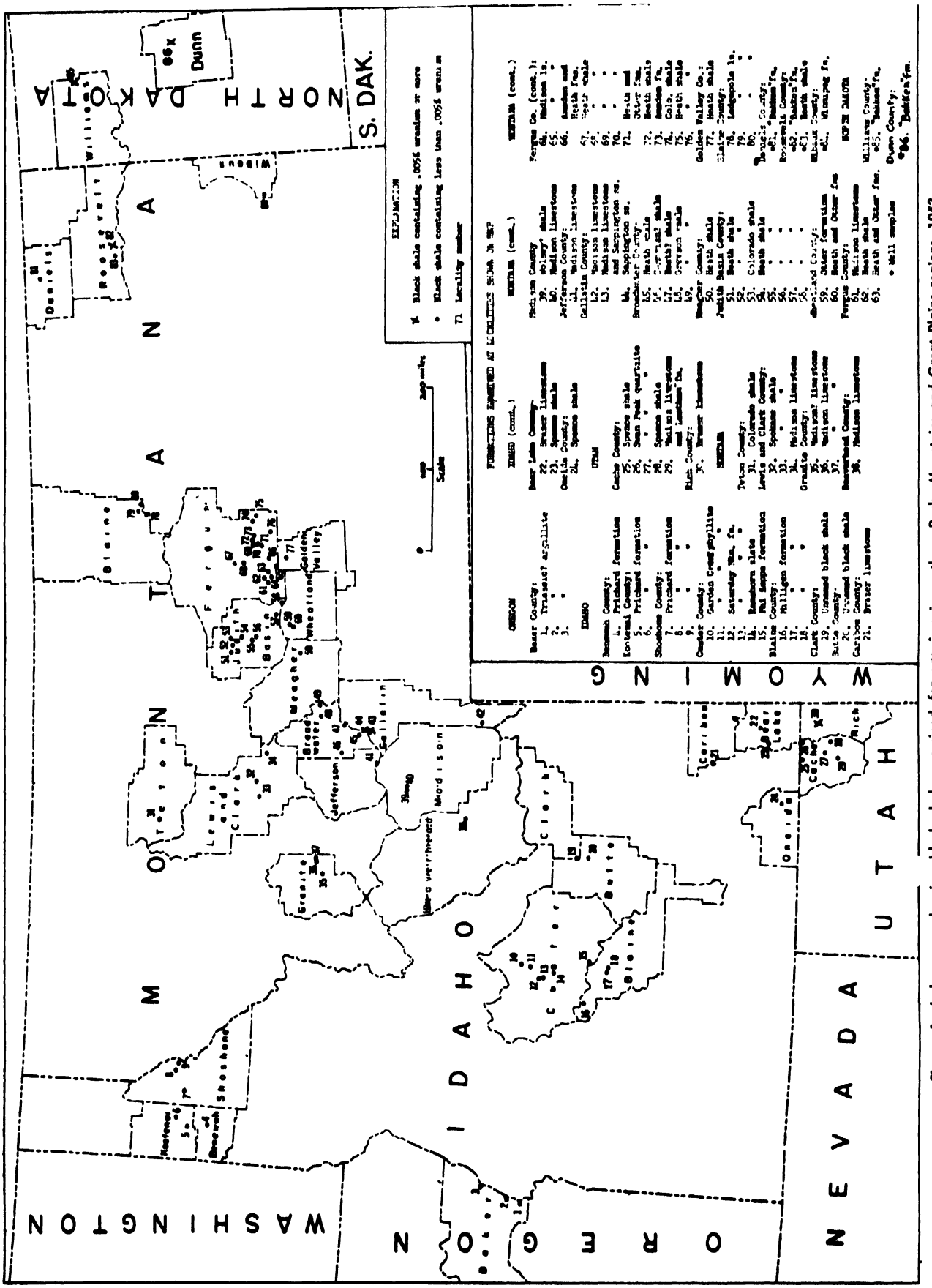
Table I. Chart Showing the Relative Stratigraphic Positions and Maximum Known Uranium Content (in per cent) of Formations Examined. (Localities at which the formations were sampled shown by Fig. 1)

Age		*Central and northern Idaho, eastern Oregon*	*Southeastern Idaho*	*Northwestern Utah*	*Central and southwestern Montana*	*Eastern Montana*
Cretaceous					Colorado shale (0.002)	
Triassic		Unnamed argillite*				
Carboniferous / Mississippian	upper	Unnamed shale*	Brazer limestone*	Brazer limestone (0.009)	Amsden formation (lower part) (0.003)	Heath shale*†
					Heath shale (0.006)	
					Otter formation (0.003)	
		Milligen formation*		Madison limestone (0.003)	Madison limestone (0.005)‡	Lodgepole limestone (0.002)
	lower			Leatham formation (0.003)		Bakken formation of Nordquist[3] (0.007)†
Ordovician		Saturday Mountain formation* Ramshorn slate* Phi Kappa formation*		Swan Peak formation (0.003)		Winnipeg formation† (0.001)
Cambrian		Garden Creek phyllite*	Spence shale member*	Spence shale member (0.003)	Wolsey shale (0.001)	
Precambrian		Pritchard formation*			Spokane shale* Greyson shale (0.003)	

* Samples contain 0.003 per cent or less equivalent uranium; not analyzed chemically.

† Not exposed; drill cuttings or cores examined.

‡ Underlain by Sappington sandstone member of Three Forks shale in this area. The age of the Sappington is considered to be Mississippian by some geologists and Devonian by others.


NORTH DAKOTA
S. DAK.
MONTANA
WYOMING
IDAHO
NEVADA
UTAH
OREGON
WASHINGTON
EXPLANATION
Black shale containing .005% uranium or more
Black shale containing less than .005% uranium
Locality number
Scale
Dunn
Williston
Bowman
Glendive
Sidney
Plentywood
Wolf Point
Havre
Malta
Glasgow
Harlem
Fort Peck
Chinook
Zortman
Lewistown
Harlowton
Roundup
Billings
Hardin
Broadus
Miles City
Forsyth
Baker
Ekalaka
Belle Fourche
Sturgis
Rapid City
Custer
Hot Springs
Edgemont
Buffalo
Gillette
Sheridan
Kaycee
Casper
Douglas
Lusk
Torrington
Lingle
Guernsey
Wheatland
Laramie
Rawlins
Saratoga
Encampment
Rock Springs
Green River
Kemmerer
Evanston
Lovell
Cowley
Basin
Thermopolis
Worland
Greybull
Shell
Cody
Meeteetse
Powell
Lovell
Frannie
Cody
Yellowstone Park
Gardiner
Livingston
Bozeman
Three Forks
Whitehall
Dillon
Virginia City
Ennis
Big Timber
Reed Point
Columbus
Red Lodge
Joliet
Roberts
Fromberg
Belfry
Bridger
Fishtail
Absarokee
Nye
Boulder
Jefferson
Broadwater
Meagher
Golden Valley
Wheatland
Sweet Grass
Stillwater
Park
Madison
Gallatin
Beaverhead
Big Horn
Treasure
Rosebud
Powder River
Carter
Fallon
Wibaux
Dawson
Richland
Roosevelt
Sheridan
Daniels
Valley
Phillips
Blaine
Hill
Liberty
Toole
Pondera
Teton
Chouteau
Cascade
Judith Basin
Fergus
Petroleum
Golden Valley
Musselshell
Yellowstone
Carbon
Stillwater
Sweet Grass
Park
Gallatin
Madison

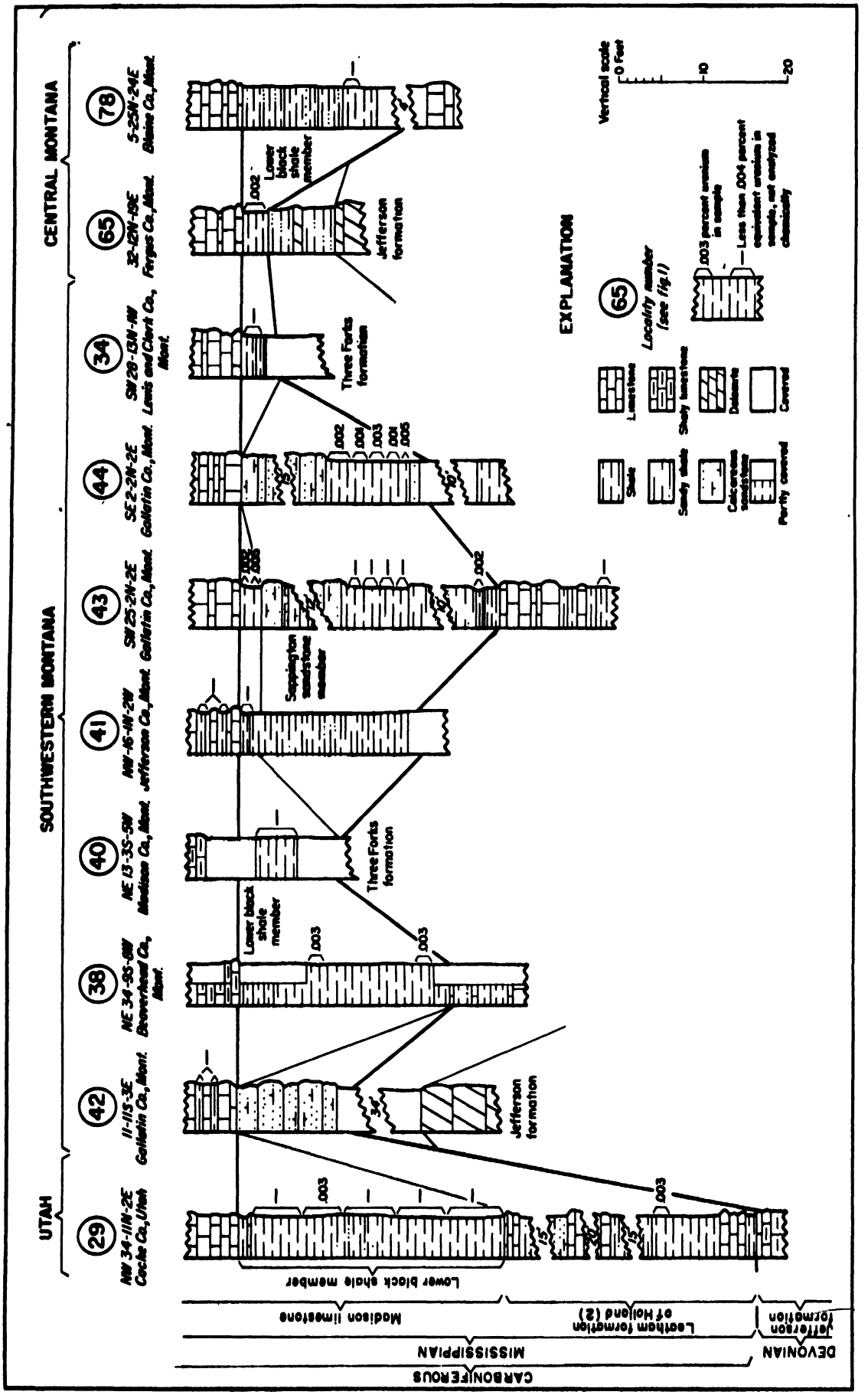


Figure 2. Graphic sections showing uranium content of Basal Mississipian black shale at outcrops in the northern Rocky Mountain region

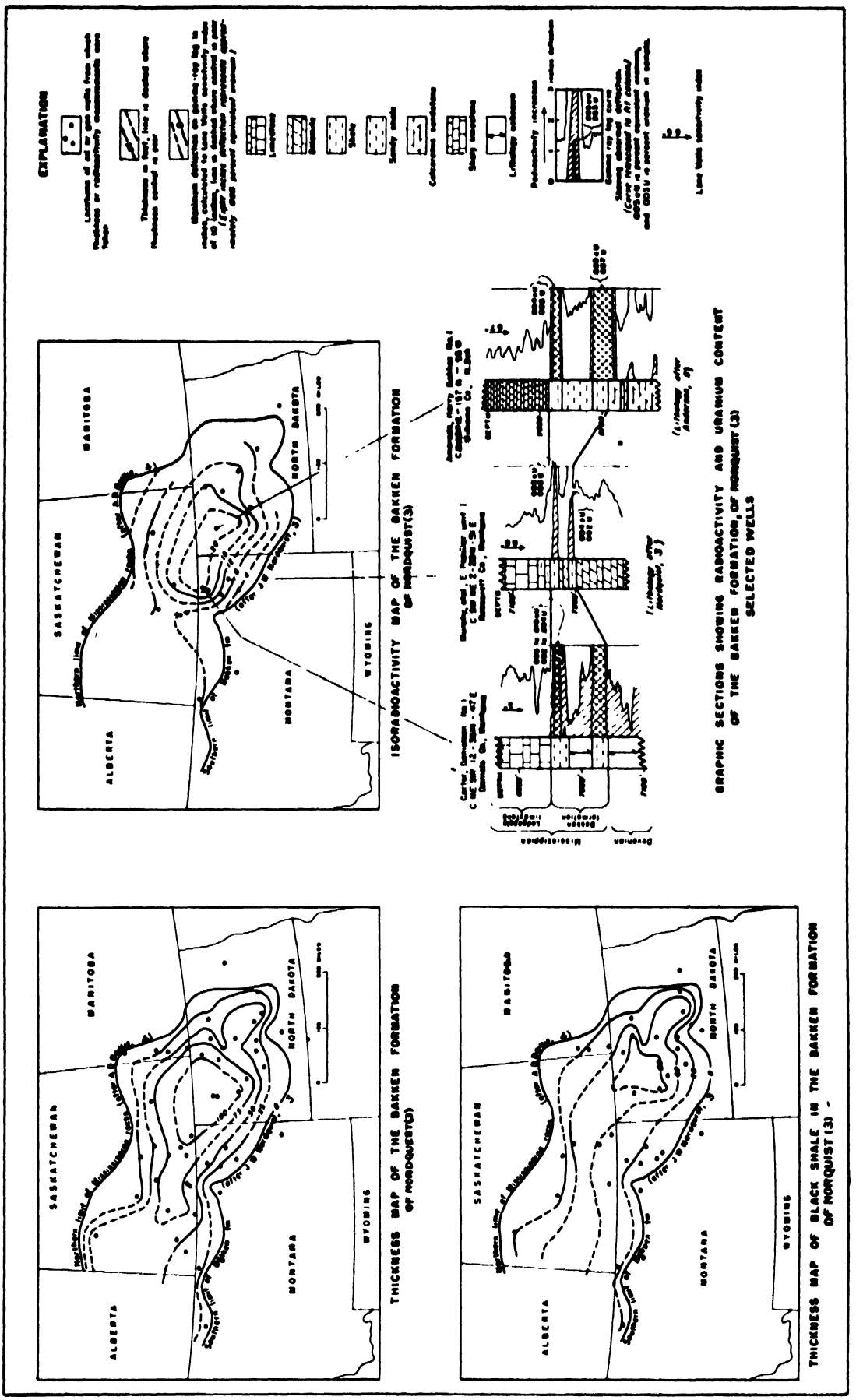


Figure 3. Maps and sections showing thickness and radioactivity of the Bakken formation of Nordquist[3] northern Great Plains

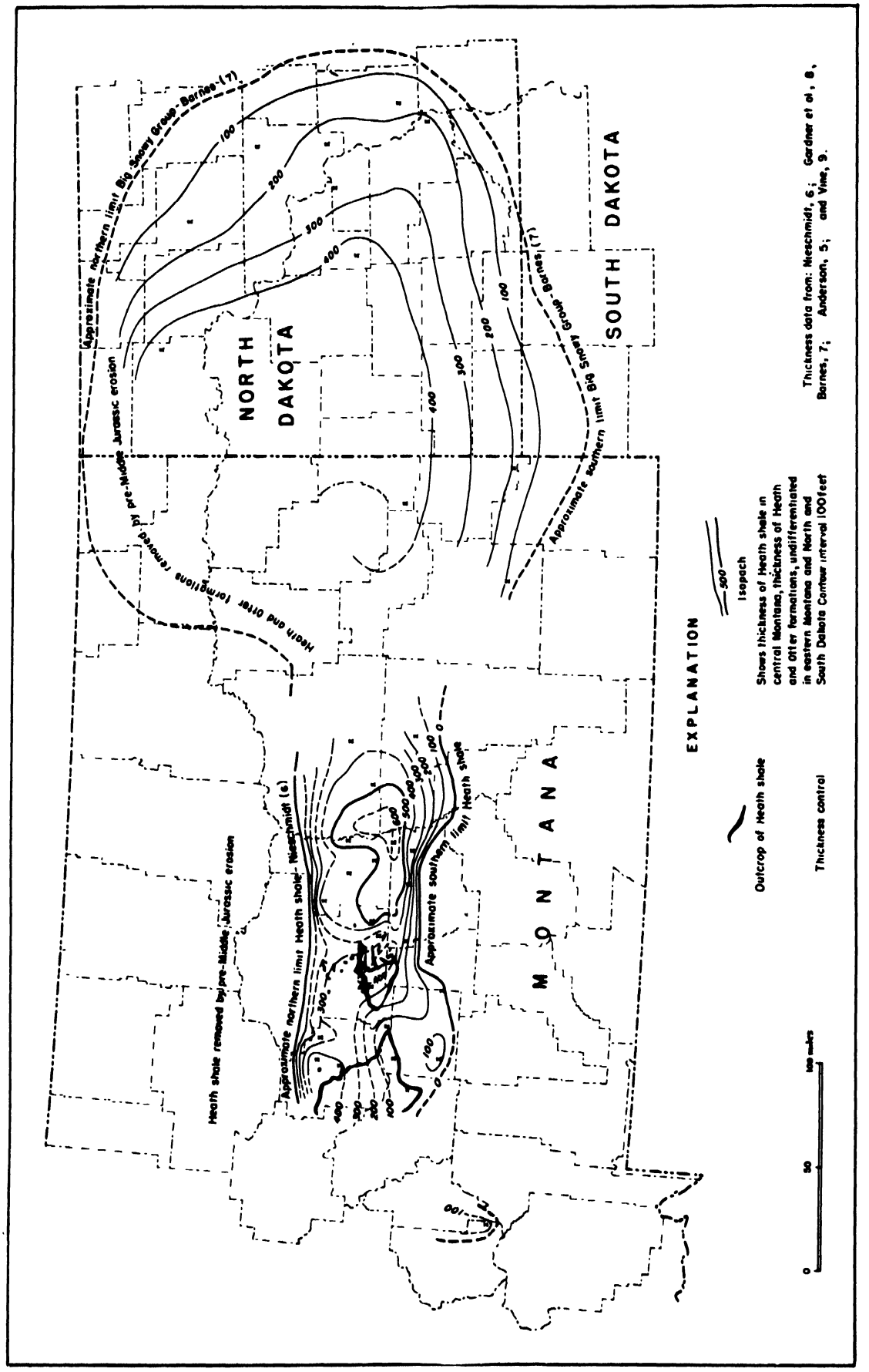


Figure 4. Map showing thickness and distribution of the heath shale in central Montana and the heath and other formations in eastern Montana and adjacent parts of North and South Dakota

Table 2. Description of Samples from the Carter No. 1 Danielson Well, Danielson County, Montana

Sample no.	Depth (feet)	Lithology	(Equivalent U) per cent	U per cent
204065	6964	Core chip, noncalcareous black shale	0.006	0.002
204066	6966	Core chip, noncalcareous black shale	0.005	0.002
204067	6968	Core chip, noncalcareous black shale	0.010	0.003
204068	6970	Same as above, some disseminated pyrite	0.007	0.004
204069	6971	Same as above, some disseminated pyrite	0.008	0.004
204070	6974	Core chip, dark-gray shale with light-gray calcareous laminae	0.003	0.002

Heath shale is underlain by green and black shale and gray limestone of the Otter formation of late Mississippian age, and it is overlain by red shale and sandstone and minor interbedded gray limestone and dolomite of the Amsden formation of late Mississippian and Pennsylvanian age.

The most highly uraniferous black shale thus far found in the formation was discovered by Hail and Gill (Ref. 1, p. 42–43) 3 miles southeast of Forestgrove, Fergus County, Montana. At this locality, the upper 4 feet of a 6-foot thick bed of black shale near the top of the formation contains 0.006 per cent uranium. Samples of black shale from the Heath shale elsewhere in central Montana contain a maximum of 0.003 per cent uranium.

Gamma-ray log data for oil and gas wells suggest that a bed 10 feet thick in the Heath shale penetrated by a well in McCone County, Montana, may contain more than 0.01 per cent equivalent uranium, and that parts of the formation in Musselshell County, Montana, may be nearly as radioactive.

OTHER RADIOACTIVE BLACK SHALES

Examination of commercial gamma-ray logs of oil and gas wells in Montana and North and South Dakota indicate that certain black-shale bearing formations other than the ones discussed above are appreciably radioactive locally and may contain significant amounts of uranium. One of these formations is the Minnelusa sandstone of Pennsylvanian age, which crops out in the Black Hills in northeastern Wyoming and northwestern South Dakota. Beds of black shale as much as 6 feet thick were sampled by Love[10] in two oil and gas wells in southeastern Wyoming and found to contain from 0.005 to 0.019 per cent uranium.

Gamma-ray logs of the Colorado shale of Cretaceous age in central Montana indicate that its radioactivity at most places ranges from 0.002 to 0.005 per cent equivalent uranium; in Musselshell County, Montana, a thin zone of shale near the middle of the formation may contain as much as 0.008 per cent equivalent uranium.

Gamma-ray logs of wells in northeastern South Dakota indicate that a thin zone of black shale in the lower part of the Pierre shale of Cretaceous age is more highly radioactive than average and may contain 0.008 per cent equivalent uranium. Tourtelot[11] has observed that a black organic-rich shale known as the Sharon Springs member of the Pierre shale may contain as much as 0.01 per cent equivalent uranium in southwestern Nebraska and along the Missouri River valley in central South Dakota.

REFERENCES

1. Duncan, D. C., compiled by, *Reconnaissance investigation for uranium in black shale deposits of the western States during 1951 and 1952*, US Geological Survey TEI-381, US Atomic Energy Commission, Technical Information Service, Oak Ridge (1953).
2. Holland, F. D., Jr., *Stratigraphic details of lower Mississippian rocks of northeastern Utah and southwestern Montana*, American Association of Petroleum Geologists Bulletin, vol. 36, no. 9, p. 1697–1735 (1952).
3. Nordquist, J. W., *Mississippian stratigraphy of northern Montana*, Billings Geological Society Guidebook, 4th annual field conference, Little Rocky Mountains, Montana, southwestern Saskatchewan, p. 68–82 (1953).
4. Baillie, A. D., *Devonian system of the Williston Basin area*, Mines Branch Province of Manitoba, publ. 52-55 (1953).
5. Anderson, S. B., *Stratigraphic sections of the Mississippian system in North Dakota*, North Dakota Geological Survey, Report of Investigations no. 16 (1954).
6. Neischmidt, C. L., *Subsurface stratigraphy of the Heath shale and Amsden formation in central Montana*, US Geological Survey Oil and Gas Investigations Chart OC 50 (1953).
7. Barnes, T. R., *The Williston Basin—a new province for oil exploration*, Billings Geological Society Guidebook, 3rd annual field conference, Williston Basin—Black Hills, p. 97–117 (1952).
8. Gardner, L. S., Hendrichs, T. A., Hadley, H. D. and Rogers, C. P., Jr., *Stratigraphic sections of upper Paleozoic and Mesozoic rocks in south central Montana*, Montana Bureau of Mines and Geology Memoir no. 24 (1946).
9. Vine, J. D., *Geology of the Stanford-Hobson area, Judith Basin and Fergus Counties, Montana*, US Geological Survey Bulletin, in preparation.
10. Love, (unpublished data).
11. Tourtelot, (written communication).

Uranium-Bearing Coal in the United States

By James D. Vine,* USA

Unusually high concentrations of uranium in coal have been reported from many parts of the world[1,2] even though coal is commonly considered to be one of the least radioactive rocks.[3] Uranium-bearing coal was first reported in the United States in 1875 in a description by Berthoud[4] of the Leyden coal mine northwest of Denver, Colorado. However, recent interest results from the discovery of uranium-bearing coal in the Red Desert area of central Wyoming in 1946 by Slaughter and Nelson[5] and the discovery two years later of uranium-bearing lignite in the northern Great Plains by Wyant and Beroni.[6] Since then many coal-bearing strata in the United States have been examined and numerous uranium-bearing coal, lignite, and carbonaceous shale localities have been reported. (See Fig. 1 on following page and Table I below.)

* US Geological Survey.

A large potential low-grade reserve of uranium is contained in coal. Because uranium is concentrated in the ash when coal is burned as a fuel there is a possibility that some of the uraniferous coal may be utilized as a commercial fuel and the uranium extracted from the ash as a by-product. Recent discoveries of ore-grade uranium in coal in the northern Great Plains[7] may have immediate commercial importance as a source of uranium.

GEOGRAPHIC AND GEOLOGIC DISTRIBUTION

The principal deposits of uranium-bearing coal, lignite, and carbonaceous shale in the United States are in Cretaceous and Tertiary rocks of the northern Great Plains and Rocky Mountain regions (Fig. 1 and Table I).

Uranium-bearing lignite occurs sporadically on or adjacent to high buttes and mesas throughout a vast area in the northern Great Plains, including parts

Table I. Principal Deposits of Uranium-Bearing Coal, Lignite, and Carbonaceous Shale in the United States

Name and location of area	*Age and name of formation or group*	*Lithology*
Northern Great Plains region:		
1. Sentinel Butte, Golden Valley Co., North Dakota	Paleocene Fort Union (Sentinel Butte shale member)	Lignite
2. Bullion Butte, Billings Co., North Dakota	Paleocene Fort Union (Sentinel Butte shale member)	Lignite
3. Chalky Buttes, Slope Co., North Dakota	Paleocene Fort Union (Sentinel Butte shale member)	Lignite
4. Medicine Pole Hills, Bowman Co., North Dakota	Paleocene Fort Union (Tongue River member)	Lignite
5. Ekalaka Hills, Carter Co., Montana	Paleocene Fort Union (Tongue River member)	Lignite
6. Cave Hills, Harding Co., South Dakota	Paleocene Fort Union (Ludlow and Tongue River members)	Lignite
7. Lodgepole district, Perkins Co., South Dakota	Paleocene Fort Union (Tongue River member)	Lignite
8. Slim Buttes, Harding Co., South Dakota	Paleocene Fort Union (Ludlow member)	Lignite
Red Desert area, central Wyoming	Eocene Wasatch	Coal
Fall Creek area, southeastern Idaho	Cretaceous Bear River	Coaly shale
Goose Creek area, southern Idaho	Pliocene Salt Lake	Lignite and lignitic shale
Gamma Property, Churchill Co., Nevada	Tertiary (Unknown)	Lignitic shale
Old Leyden Coal Mine, Jefferson Co., Colorado	Cretaceous Laramie	Coal, partially silicified
La Ventana Mesa, Sandoval Co., New Mexico	Cretaceous Mesaverde	Coal and coaly shale
Hogback No. 4, McKinley Co., New Mexico	Cretaceous Dakota	Carbonaceous shale

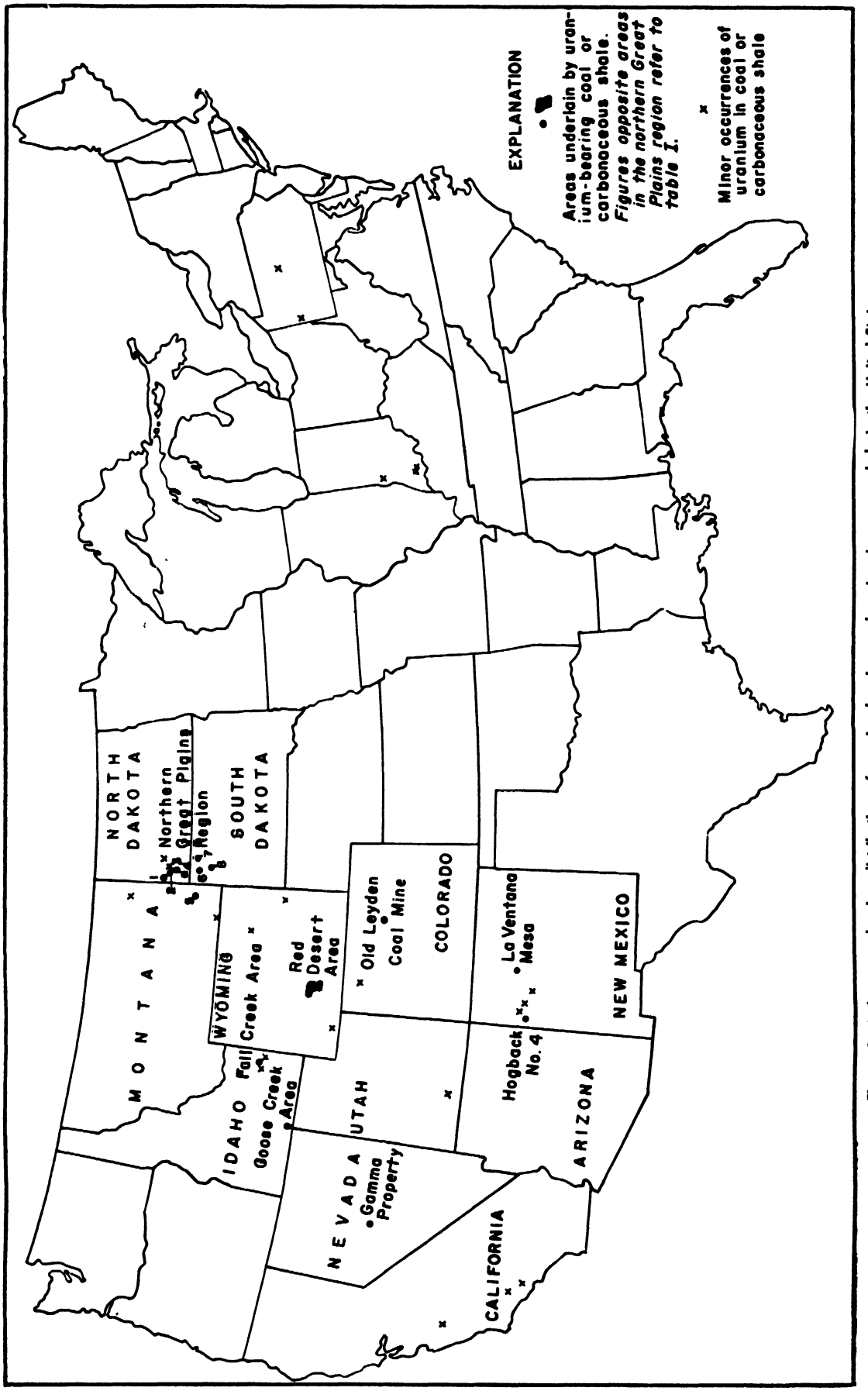


Figure 1. Index map showing distribution of uranium-bearing coal and carbonaceous shale in the United States

of northwestern South Dakota, southwestern North Dakota, and eastern Montana.[8,9] It is within a sequence of lignite-bearing strata, more than 1500 feet thick, belonging to the Hell Creek formation of Cretaceous age and the Fort Union formation of Paleocene age. The coal-bearing members of the Fort Union formation, from oldest to youngest, include the Ludlow, Tongue River, and Sentinel Butte shale members. These strata dip about 10 to 40 feet per mile to the northeast and are truncated unconformably by overlying tuffaceous sediments of Oligocene and Miocene age, erosional remnants of which form the cap rock 200 to 300 feet thick on many of the high buttes and mesas. The uranium content of the lignite ranges from less than 0.001 per cent to more than 10 per cent, but the average content of uraniferous lignite is about 0.008 per cent.

Uranium-bearing sub-bituminous coal is present in the generally flat-lying Wasatch formation of Eocene age in the Red Desert area of the Great Divide Basin, Sweetwater County, Wyoming.[10,11] Eocene sediments with an exposed thickness of about 3400 feet in this area range from coarse fluvial conglomerate in the Battle Spring formation on the north and east sides of the Red Desert area to lacustrine and paludal shale, siltstone, sandstone, and marl in the Green River and Wasatch formations on the south and west sides of the Red Desert area. Coal and carbonaceous shale beds were laid down in a northwest trending zone where the lacustrine and fluvial facies of the Eocene intertongue. Coal beds are thickest near the center of this zone and pinch out both to the northeast and southwest. The uranium content of the coal ranges from about 0.001 to 0.05 per cent, the average for the entire area is about 0.003 per cent.

Carbonaceous rocks of the Bear River formation of Early Cretaceous age contain uranium in the Fall Creek area, Bonneville County, Idaho.[12] The area is in the Caribou Mountains, which are characterized by complex structural features including closely spaced parallel folds, overturned at many places and broken by both normal and thrust faults. Uranium occurs in a bed of sheared coaly shale and the directly overlying bed of carbonaceous limestone. Locally, the coal contains as much as 0.1 per cent uranium; the average for the uraniferous zone is about 0.02 per cent uranium.

In the Goose Creek intermontane basin of southern Cassia County, Idaho, and adjacent parts of Utah and Nevada as much as 0.1 per cent uranium is contained locally in lignite and carbonaceous shale in the Salt Lake formation of Pliocene age.[13] The carbonaceous beds occur in a sequence nearly 2300 feet thick consisting chiefly of volcanic ash and welded tuff.

Uranium-bearing coal and carbonaceous shale occur in the Mesaverde and Dakota formations of Cretaceous age in the La Ventana area, Sandoval County, in north-central New Mexico.[14] The area is situated on the east flank of the San Juan Basin adjacent to the Sierra Nacimiento and the Jemez volcanic plateau. As much as 0.6 per cent uranium is contained in coal and carbonaceous shale in the stratigraphically highest carbonaceous zone in the Mesaverde formation on La Ventana Mesa.

Uranium-bearing coal and silicified coal are present in nearly vertical beds in a hogback of the Laramie formation of Late Cretaceous age northwest of Denver, Jefferson County, Colorado.[15] Individual samples of coal with fracture fillings of carnotite contain as much as 3 per cent uranium.

Tertiary sediments at least 300 feet thick contain uranium-bearing impure lignite at the Gamma Property on the west side of the Desatoya Range in Churchill County, Nevada.[16] As much as 0.05 per cent uranium is contained in the top of a 3-foot bed of impure lignite.

Other localities of uraniferous coal in the western United States, shown on Fig. 1, include: uranium-bearing coal in the Wasatch formation of Eocene age in the Pumpkin Buttes district in the Powder River Basin, northeastern Wyoming;[17] uranium in carbonaceous shale and coal in the Dakota and Mesaverde formations of Cretaceous age along the south flank of the San Juan Basin in McKinley County, New Mexico;[18,19] and uranium-bearing lignite and carbonaceous shale in Los Angeles and San Benito Counties, California.[20]

Most coal of Mississippian, Pennsylvanian, and Permian age in the coal fields of central and eastern United States contain less than 0.001 per cent uranium, though some of the shales and underclays associated with these coals contain from 0.002 to 0.005 per cent uranium.[21-25] Patterson[26] reports coal from Illinois as containing up to 0.008 per cent and black shales above coal as much as 0.017 per cent uranium. Coal in Indiana locally contains as much as 0.002 per cent uranium[27] whereas that in western Pennsylvania contains as much as 0.007 per cent uranium[28] and that in central Pennsylvania contains as much as 0.019 per cent uranium.[29]

GEOLOGIC SETTING

Although there is stratigraphic control for the distribution of uranium in coal, emplacement is quite unlike the widespread uniformly disseminated uranium in some beds of marine black shale and phosphorite.[30]

In the northern Great Plains, Denson, Bachman, and Zeller[31] have shown that uranium-bearing lignite is found throughout the 1500 feet of coal-bearing strata, but always within 150 feet of the pre-Oligocene unconformity. The highest concentration of uranium is commonly contained in the stratigraphically highest bed of lignite below the unconformity. Lignite beds more than 3 feet thick generally contain more uranium at the top of the bed than at the bottom. Locally, where the stratigraphically highest lignite is overlain by shale, it may be nonuraniferous. A similar emplacement of uranium in the stratigraphically highest beds was noted at La Ventana Mesa in New Mexico[14] and in the Goose Creek area of southern Idaho.[13] A similar preferential enrichment of urani-

um in a given thick bed was recorded in the Fall Creek area of southeastern Idaho[12] and at the Gamma Property in Nevada.[16]

The concentration of uranium in coal beds of the Wasatch formation in the Red Desert area is related to the permeability of the enclosing sediments.[10,11] The greater concentrations of uranium are contained in coal beds adjacent to permeable sandstone beds regardless of the stratigraphic position. Locally, where coal of Wasatch age has been truncated and is unconformably overlain by younger Tertiary sediments there is a preferential distribution of uranium in the top of the stratigraphically highest bed of coal.[10]

Uranium-bearing coal beds range from nearly flat in the northern Great Plains, the Red Desert, and La Ventana Mesa to vertical in the Old Leyden coal mine, but structural control during mineralization is evident in some of the deposits. The highest concentration of uranium in the Goose Creek area[13] is along the trough and flanks of a broad syncline. Similar observations were made at La Ventana Mesa[14] and in the Red Desert area.[11] Locally, in the northern Great Plains and at La Ventana Mesa, there is an increase in uranium content of lignite and coal adjacent to joints.[31,14]

Uranium-bearing coal is associated with other types of uranium deposits in several districts. Schroeckingerite forms a surficial evaporite-type deposit that Wyant, Beroni, and Granger[32] have postulated overlies uraniferous coal at Lost Creek in the northern Red Desert area. Carnotite, uranophane, and uraninite deposits in sandstone are interbedded with uraniferous coal in the Pumpkin Buttes area near the center of the Powder River Basin in northeastern Wyoming.[17] Uranophane, carnotite, and tyuyamunite occur in sandstone beds of the Fort Union formation of Paleocene age and the White River formation of Oligocene age in the northern Great Plains.[7]

MODE OF OCCURRENCE

Uranium is found chiefly in low-rank and impure coal, including lignite, sub-bituminous coal and carbonaceous shale. High-rank, low-ash coals of the type most desired for fuel are rarely uraniferous, and no significant concentration of uranium has been found in a producing coal mine. Bituminous coal and anthracite occur principally in Paleozoic rocks of the central and eastern United States, whereas lignite and sub-bituminous coal are most abundant in Cretaceous and Tertiary rocks of the Rocky Mountain and western states. Therefore, it is not readily apparent whether the lack of significantly uraniferous coal in the central and eastern United States is due to age, rank, or geologic setting. One line of evidence is afforded by the results of an experimental study by Moore[33] who demonstrated that peat, lignite, and sub-bituminous coal extract 98 per cent or more of the uranium from an aqueous solution, whereas bituminous coal and anthracite extract only 17 and 34 per cent respectively.

Uranium minerals have not been recognized in coal that contains less than about 0.1 per cent uranium. Fracture fillings of carnotite in silicified coal at the Old Leyden coal mine near Denver, Colorado, have been described,[15] but the visible mineral is not sufficiently abundant to account for all the uranium present. Autunite, torbernite, and zeunerite are disseminated in highly uraniferous lignite in the Cave Hills area in the northern Great Plains,[7] but it is doubtful if the visible mineral is sufficient to account for all the uranium present. Coffinite has been reported by Gruner[34] in highly uraniferous coal from La Ventana Mesa in New Mexico.

Petrologic studies of uraniferous coal by Schopf and Gray[35] show that no quantitative correlation exists between uranium content and the petrologic constituents of coal. However, relatively large amounts of humic attrital matter, which results from decomposition and microbial decay, were recognized in samples containing the most uranium. Because of this observation, they conclude that plant material that has been most subjected to decay is probably the most receptive to uranium emplacement. Mineralogical studies of low-grade uraniferous lignite from the northern Great Plains by Breger, Deul, and Rubinstein[36] show that more than 90 per cent of the uranium is associated with organic material in the lignite rather than with the extraneous mineral matter, which includes jarosite, quartz, gypsum, calcite, and clay minerals. They infer that uranium in coal is present in the form of organo-uranium complexes that are insoluble in the pH range of 3 to 6 encountered in coal.

The inorganic constituents of coal have been classified according to their source, age, and properties,[37] as follows: (I) the inherent mineral matter derived from the inorganic constituents of the parent plants, (II) the fixed adventitious inorganic matter which consists of chemically combined inorganic constituents added to the organic matter after the death of the plants, and (III) the free adventitious inorganic matter or extraneous minerals added to the deposit in an uncombined state. The adventitious constituents are further subdivided into: (*A*) the syngenetic mineral matter, which is added during the formation of coal, and (*B*) the epigenetic mineral matter, which is added after coalification. Uranium could be added to a deposit of coal by any one or a combination of several of these methods. An interpretation of factors that control the distribution of uranium in coal depends on what type of constituent the uranium is considered to be.

At the time of the discovery of uranium in lignite in the northern Great Plains, it was considered by Gott, Wyant, and Beroni[38] that the even distribution of radioactivity in a sample of lignite, as revealed by an autoradiograph, indicated that the uranium was an inherent or fixed adventitious constituent present in the coal at the time of coalification. Petrologic and mineralogic studies of uraniferous coal confirm the uniform distribution of uranium in individual samples and the association of the uranium with the

organic constituents of the coal. However, the cross-cutting relation of uranium to the regional dip of beds, especially in the northern Great Plains region, the common top preferential distribution of uranium in thick beds, and the concentration of uranium in the stratigraphically highest beds or in beds adjacent to zones of high permeability indicate an epigenetic origin for the uranium. Thus, it would seem that uranium is contained in coal as fixed adventitious inorganic matter of epigenetic origin. When more uranium is available to the coal than can be held by the organic matter, various minerals including carnotite, autunite, torbernite, zeunerite, and coffinite may be formed.

Slightly impure coal generally contains more uranium than carbonaceous shale or very pure coal. Carbonaceous shale probably contains less uranium because the uranium-fixing organic matter is diluted with extraneous mineral matter, whereas the very pure coal may be too impervious to solutions that introduce the uranium.

FACTORS CONTROLLING THE DISTRIBUTION OF URANIUM IN COAL

The mode of occurrence of uranium in coal indicates that ground water was probably the principal agent for transportation and deposition of uranium from solution. The time of mineralization varies with each deposit. The close association of uranium-bearing lignite of Paleocene age in the northern Great Plains region to the pre-Oligocene unconformity implies a period of uranium mineralization during or after the time of erosion that produced the unconformity. Elsewhere, uranium-bearing solutions had access to coal soon after the accumulation of plant debris in the coal swamp. For example, in the Goose Creek area, the uranium-bearing lignite is interbedded with volcanic ash beds of Pliocene age that are themselves slightly uraniferous. Redistribution of uranium from the volcanic ash and concentration in the lignite have probably been continuous since Pliocene time. In some areas of uraniferous lignite and coal, present day ground water is enriched in uranium, according to Denson and others.[39]

Regardless of the source for the uranium contained in the ground-water solutions, the factors that control the distribution of uranium in coal are the variations in permeability and attitude of the enclosing strata, as these largely control the volume and direction of flow of ground water. The physical and chemical characteristics of the coal such as the rank, ash content, permeability, and degree of decay, probably determine the ability of the coal to hold uranium.

SOURCE OF URANIUM

There is no general agreement among geologists regarding the origin of uranium in coal. While investigating the uraniferous lignite in the northern Great Plains, Beroni and Bauer[40] noted the large percentage of minerals of volcanic origin in the lignite-bearing strata of the Fort Union formation. This observation prompted the suggestion that uranium in lignite was derived from the redistribution of uranium originally disseminated throughout the volcanic material during or shortly after the deposition of the lignite. As a result of later regional and detailed studies, Denson, Bachman, and Zeller[31] noted the close association of uraniferous lignite to the pre-Oligocene unconformity as well as other epigenetic features and proposed that uranium was derived from downward percolating meteoric water that leached uranium from the White River formation of Oligocene age and the Arikaree formation of Miocene age. The interbedded uraniferous lignite and volcanic ash in the Goose Creek area tend to confirm the origin of uranium from volcanic sediments. Evidence in many of the other areas is not as clear, though a similar origin is possible for nearly all the principal deposits. Uranium mineralization at the Old Leyden coal mine, only a few miles from uraniferous vein deposits of hydrothermal origin in the Colorado Front Range, suggests this might be an exception to the origin of uranium in coal leached from volcanic sediments.

The generally low uranium content of coal beds of Paleozoic age in the coal fields of the central and eastern United States may be due to the absence of widespread volcanic activity in this region as compared with Tertiary volcanic activity in the western states. It is possible that the slight amount of uranium contained in the coals of Paleozoic age is of syngenetic origin, similar to deposits of marine black shale as described by Swanson.[30]

CONCLUSIONS

Uranium-bearing coal occurs in widely scattered localities in the United States. The principal deposits of uranium-bearing coal are in low-rank coals of Cretaceous and Tertiary age in the northern Great Plains and Rocky Mountain regions. In most deposits uranium is thought to have been introduced into the coal by ground-water solutions and fixed by the organic matter of the coal. Visible uranium minerals form in coal only when the amount of uranium available is in excess of that which can be held by the organic matter. The association of uranium-bearing coal with rocks of volcanic origin in some areas indicates that volcanic rocks may be one source for uranium.

REFERENCES

1. Davidson, C. F. and Ponsford, D. R. A., *On the Occurrence of Uranium in Coals*, The Mining Magazine (London) 91: 265–273 (1954).
2. Szalay, S., *The Enrichment of Uranium in Some Brown Coals in Hungary*, Acta Geologica Academiae Scientiarum Hungaricae, Magyar Tudomanyos Akademia 2: 299–310 (1954).
3. Russell, W. L., *Relation of Radioactivity, Organic Content, and Sedimentation*, American Association of Petroleum Geologists Bulletin 29: 1470–1494 (1945).
4. Berthoud, E. L., *On the Occurrence of Uranium, Silver, Iron, etc., in the Tertiary Formation of Colorado Territory*, Academy of Natural Sciences of Philadelphia; Proceedings 27: 363–365 (1875).
5. Slaughter, A. L. and Nelson, J. M., written communication.
6. Wyant, D. G. and Beroni, E. P., written communication.

7. Gill, J. R., *Northwestern South Dakota, Southwestern North Dakota and Eastern Montana, in Geologic Investigations of Radioactive Deposits, Semiannual Progress Report, June 1 to November 30, 1954,* US Geological Survey Trace Elements Investigations Report 490, US Atomic Energy Commission Technical Information Service, 149–155 (1954).
8. Denson, N. M. and Gill, J. R., P/57, *Uranium-Bearing Lignite and its Relation to Volcanic Tuffs in Eastern Montana and the Dakotas,* Vol. 6, Session 6B, these Proceedings.
9. King, J. W., P/286, *High Grade Uraniferous Lignites in Harding County, South Dakota,* Vol. 6, Session 6B, these Proceedings.
10. Masursky, Harold, P/56, *Trace Elements in Coal in the Red Desert, Wyoming,* Vol. 6, Session 6B, these Proceedings.
11. Pipiringos, G. N., P/287, *Uranium-Bearing Coal in the Central Part of the Great Divide Basin, Sweetwater County, Wyoming,* Vol. 6, Session 6B, these Proceedings.
12. Vine, J. D., *Geology and Uranium Deposits in Carbonaceous Rocks of the Fall Creek Area, Bonneville County, Idaho,* US Geological Survey Bulletin, in preparation.
13. Mapel, W. J. and Hail, W. J., Jr., *Tertiary Geology of the Goose Creek District, Cassia County, Idaho, Boxelder County, Utah, and Elko County, Nevada,* US Geological Survey Bulletin, in preparation.
14. Bachman, G. O., Vine, J. D, Read, C. B. and Moore, G. W., *Uranium-Bearing Coal and Carbonaceous Shale in La Ventana Mesa Area, Sandoval County, New Mexico,* US Geological Survey Bulletin, in preparation.
15. Gude, A. J., 3rd and McKeown, F. A., written communication.
16. Staatz, M. H. and Bauer, H. L., *Gamma Property,* in Lovering, T. G., *Radioactive Deposits of Nevada,* US Geological Survey Bulletin 1009–C, 76–77 (1954).
17. Troyer, M. L., McKay, E. J., Soister, P. W. and Wallace, S. R., *Summary of Investigations of Uranium Deposits in the Pumpkin Buttes Area, Johnson and Campbell Counties, Wyoming,* US Geological Survey Circular 338 (1954).
18. Gableman, J. W., P/50, *Uranium Deposits in Paludal Black Shales, Dakota Formation,* Vol. 6, Session 6B, these Proceedings.
19. Bachman, G. O., Baltz, E. H. and O'Sullivan, R. B., written communication.
20. Moore, G. W. and Stephens, J. G., *Reconnaissance for Uranium-Bearing Carbonaceous Rocks in California and Adjacent Parts of Oregon and Nevada,* US Geological Survey Circular 313 (1954).
21. Snider, J. L., *Radioactivity of Some Coal and Shale of Pennsylvanian age in Ohio,* US Geological Survey Trace Elements Investigations Report 404, US Atomic Energy Commission Technical Information Service (1954).
22. Snider, J. L., *Reconnaissance for Uranium in Coal and Shale in Southern West Virginia and Southwestern Virginia,* US Geological Survey Trace Elements Investigations Report 409, US Atomic Energy Commission Technical Information Service (1954).
23. Welch, S. W., *Radioactivity of Coal and Associated Rocks in the Anthracite Fields of Eastern Pennsylvania,* US Geological Survey Trace Elements Investigations Report 348, US Atomic Energy Commission Technical Information Service (1954).
24. Welch, S. W., *Radioactivity of Coal and Associated Rock in the Coal Fields of Eastern Kentucky,* US Geological Survey Trace Elements Investigations Report 347, US Atomic Energy Commission Technical Information Service (1954).
25. Patterson, E. D., *Radioactive Coal and Shale of Pennsylvania and Permian Age in Northern West Virginia,* US Geological Survey Trace Elements Investigations Report 494, US Atomic Energy Commission, Technical Information Service (1955).
26. Patterson, E. D., written communication.
27. Snider, J. L., *Reconnaissance for Uranium in the Indiana Coal Field,* US Geological Survey Trace Elements Memorandum Report 784, US Atomic Energy Commission Technical Information Service (1954).
28. Ferm, J. C., *Radioactivity of Coals and Associated Rocks in Beaver, Clearfield, and Jefferson Counties, Pennsylvania,* US Geological Survey Trace Elements Investigations Report 468, US Atomic Energy Commission Technical Information Service (1955).
29. Patterson, E. D., *Radioactivity of Part of the Bituminous Coal Region of Pennsylvania,* US Geological Survey Trace Elements Investigations Report 479, US Atomic Energy Commission Technical Information Service (1955).
30. Swanson, V. E., P/51, *Uranium in Marine Black Shales of the United States,* Vol. 6, Session 6B, these Proceedings.
31. Denson, N. M., Bachman, G. O. and Zeller, H. D., *Uranium-Bearing Lignite and its Relation to the White River and Arikaree Formations in Northwestern South Dakota and Adjacent States,* US Geological Survey Bulletin, in preparation.
32. Wyant, D. G., Beroni, E. P. and Granger, H. C., *Some Uranium Deposits in Sandstones, in Selected Papers on Uranium Deposits in the United States,* US Geological Survey Circular 220, 26–29 (1952).
33. Moore, G. W., *Extraction of Uranium from Aqueous Solution by Coal and Some Other Materials,* Economic Geology 49: 652–658 (1954).
34. Gruner, J. W., oral communication.
35. Schopf, J. M. and Gray, R. J., *Microscopic Studies of Uraniferous Coal Deposits,* US Geological Survey Circular 343 (1954).
36. Breger, I. A., Deul, Maurice and Rubinstein, Samuel, *Geochemistry and Mineralogy of a Uraniferous Lignite,* Economic Geology 50: 206–226 (1955).
37. Francis, Wilfrid. *Coal, its Formation and Composition,* Edward Arnold (Publishers) Ltd., London, 483–509 (1954).
38. Gott, G. B., Wyant, D. G. and Beroni, E. P., *Uranium in Black Shales, Lignites, and Limestones in the United States,* in *Selected Papers on Uranium Deposits in the United States,* US Geological Survey Circular 220, 31–35 (1952).
39. Denson, N. M. *et al., Summary of Uranium-Bearing Coal, Lignite, and Carbonaceous Shale Investigations in the Rocky Mountain Region During 1951,* US Geological Survey Trace Elements Memorandum Report 341 A, US Atomic Energy Commission Technical Information Service (1954).
40. Beroni, E. P. and Bauer, H. L., Jr., written communication.

Trace Elements in Coal in the Red Desert, Wyoming

By Harold Masursky,* USA

Geological mapping and exploratory core drilling from 1951 to 1953 to determine the areal distribution, thickness, and uranium content of coal in the eastern part of the Red Desert area, Sweetwater County, Wyoming resulted in much data concerning the distribution of uranium and other trace metals and their origin and mode of emplacement in coal.

The area investigated includes about 300 square miles in the east-central part of the Great Divide Basin, a region of internal drainage along the continental divide, with an altitude ranging from 6500 to 7200 feet. Sixty core holes, 140 power-auger holes, and 80 surface sections were dug during the course of the field work. Chemical uranium analyses were made of 1,700 core samples and 500 surface samples, and semiquantitative spectrographic analyses were made of about 100 samples.

Detailed investigations of uranium-bearing coal in the region were begun by the writer and G. N. Pipiringos in 1951. The writer was assisted by J. R. Pierson, Jr., H. D. Gower, and G. W. Moore during part of 1952. J. G. Stephens, R. F. Gantnier, R. L. Sutton, and J. H. Sindelar assisted in the field in 1953; Stephens and Gantnier assisted in compilation of the drilling data during the winter of 1953-54. J. M. Schopf processed coal cores and provided detailed description of the coal from 16 drill holes. Chemical spectrographic and permeability determinations are by the US Geological Survey. Wayne Montjoy performed the experimental work on the adsorption of uranium.

Reports by Smith[1] and Bradley[2] described the geology, coal, and oil-shale deposits of the area; more recent investigations of the uranium occurrences were made by Slaughter and Nelson,[3] and by Wyant, Sharp, and Sheridan.[4]

STRATIGRAPHY

The Wasatch and Green River formations of Eocene age are the principal stratigraphic units in the area studied. About 1200 feet of the upper part of the main body of the Wasatch formation is exposed. In the northeast corner of the mapped area the sandstone facies of the Wasatch formation comprises fluviatile, cream to buff, coarse-grained, massive, and cross-laminated arkose that is variegated in places, green to gray sandy claystone, and a few thin beds of carbonaceous shale. The rocks change facies markedly to the southwest, becoming finer grained and even bedded, having been deposited under alternating paludal and lacustrine conditions. This coal-bearing facies consists of gray siltstone, carbonaceous shale, coal, brown organic paper shale, and fossiliferous, calcareous sandstone. The Tipton tongue of the Green River formation is exposed at the northwest corner of the area and comprises about 300 feet of lacustrine organic paper shale and fossiliferous sandstone.

The locus of maximum coal deposition was along the transition zone between the fluviatile "Wasatch type" arkose and the lacustrine "Green River type" organic shale and sandstone. The transition zone is about 15 miles wide and trends northwest. Each coal bed is lenticular in cross section and grades into shale to the northeast and southwest. The coal beds range from a few inches to 42 feet in thickness and average about 7 feet. The coal is black, vitreous, banded, dominantly attrital, and is subbituminous B in rank. Deposition of the "coal measures" was cyclic; the usual sequence in each cyclothem[5] in ascending order, is sandstone, coal, and organic shale. Extensive terrace surfaces are covered with gravel tentatively correlated with the Browns Park formation of Miocene(?) age. Pleistocene and Recent playa lake deposits, alluvium, and sand dunes mantle the bedrock over large areas.

Sedimentary rocks of Oligocene, Miocene, and Pliocene age, consisting principally of volcanic material, are well exposed in the surrounding area, and remnants of these younger rocks overlie the Eocene strata in places within the area (Fig. 1).

DISTRIBUTION OF URANIUM

The highest known concentrations of uranium in coal occur locally in the topographically highest coal at Creston Ridge (Fig. 1–1) where a coal bed in the Wasatch formation is directly overlain by a conglomerate of possible Miocene age. This coal bed contains as much as 0.051 per cent uranium, whereas a bed 40 feet lower contains less than 0.001 per cent uranium. Similar relations were observed at Bison Basin north of the mapped area where a coal bed in the Fort Union formation of Paleocene age has a higher concentration of uranium where it is overlain by conglomerate of Miocene(?) age. More extensive, lower concentrations of uranium in the coal and thin claystone are related to the permeability of the adjacent rocks. In vertical section the uranium

* US Geological Survey.

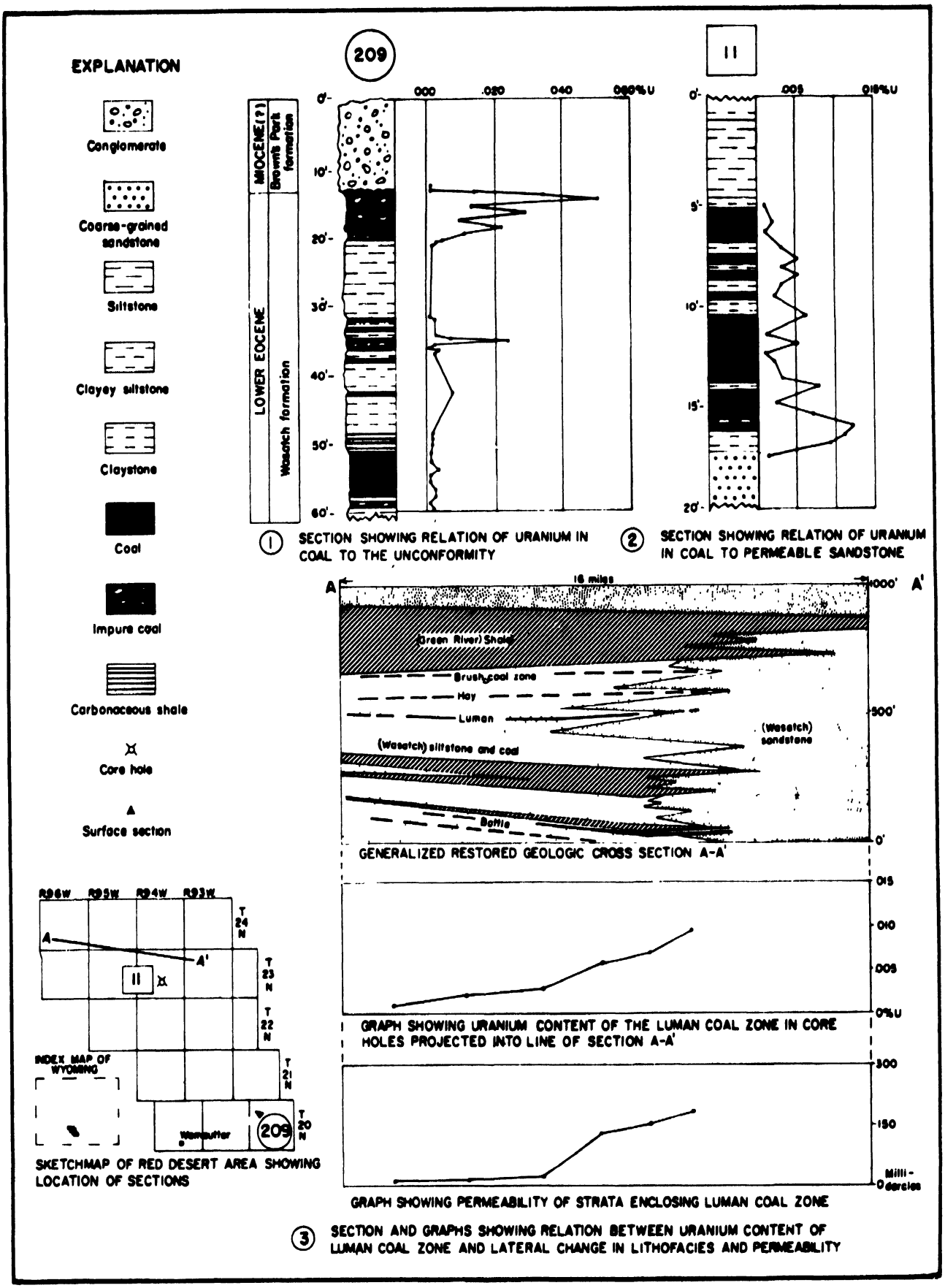


Figure 1. Diagram showing three controls for epigenetic emplacement of uranium in the coal of the Red Desert, Sweetwater County, Wyoming

content of a coal bed or thin claystone is high, adjacent to the interbedded permeable sandstone. As sandstone usually underlies the coal in the cyclic deposits, the coal commonly contains more uranium at the bottom of the bed (Fig. 1–2). Each coal bed in the several repetitions of the cyclic sequence is enriched in uranium. Determinations show that the underlying sandstone has an aqueous permeability of about 270 millidarcies whereas the overlying shale has a permeability of less than 0.1 millidarcy. Detailed sampling of the coal shows that the highest uranium content within a coal bed is adjacent to clay or carbonaceous shale partings, whereas the lowest uranium concentration is in the central part of the impermeable (0.02 to 0.5 millidarcy) pure coal layers. The relationship of the uranium content of a coal bed to the change in lithofacies is shown in Fig. 1–3. Data from six core holes show that the uranium content of the Luman coal zone and the weighted average permeability of the 20 feet of strata enclosing the coal rises to the east as the rocks become coarser grained.

Lanthanum, molybdenum, neodymium, lead, scandium, and yttrium have distribution patterns similar to uranium in the coal at Creston Ridge (Fig. 2) and may have been similarly emplaced. The content of uranium and other selected elements in organic paper shale interbedded with coarse-grained permeable sandstone exposed at Eagles Nest is shown in Fig. 3.

The widespread concentration of uranium and some other trace elements in beds of coal, organic shale, and claystone adjacent to permeable coarse-grained sandstone suggests that these constituents have been epigenetically emplaced, perhaps by ground water circulating through the sandstone.

LEACHING AND ADSORPTION OF URANIUM

Previous work[6–9] has shown that uranium is readily adsorbed by coal and is held irreversably as a disseminated adsorbed constituent, probably forming an organo-metal compound. Experiments were carried out to determine whether coal would adsorb uranium from aqueous solution at the concentration and pH expected in Red Desert ground water.

Several drill holes in the northwestern part of the area encountered strong artesian flow of water containing as much as 47 parts per billion uranium. Surface water in Lost Creek seven miles north of the area contains as much as 60 parts per billion uranium near the schroeckingerite $(NaCa_3)(UO_2)(CO_3)_3(SO_4)F{\cdot}10H_2O$ deposit. Schroeckingerite is a secondary uranium mineral, which occurs in caliche-like masses near the surface along the Cyclone Rim fault zone. It probably forms by the evaporation of ground water escaping and rising to the surface along the fault zone from a small artesian basin. Water with the same mineral content and pH as that from Lost Creek was mixed with schroeckingerite-bearing rock and the filtrate passed over Red Desert coal. The water dissolved 87 per cent of the uranium from the schroeckingerite-bearing rock and the coal adsorbed 95 per cent of the uranium from the leachate. The coal also effectively adsorbed uranium from water containing 47 parts per billion. Coal immersed in a uranyl nitrate solution adsorbed up to 8.6 per cent uranium; X-ray analysis of this sample showed that no crystalline uranium mineral had formed.

Investigation showed that the pH of ground and surface water is about 7.9 to 8.6, whereas the pH of a slurry of crushed fresh coal from core samples is 6.0 and that of weathered coal from surface sections is 3.2 to 3.5. The redox potential[10] of the carbonaceous rocks is very different from that of the clastic sediments. The "Eh" of siltstone from Eagles Nest is plus 0.391 volts at pH 8.2, the "Eh" of organic shale from the same section is plus 0.066 at pH 7.8.

Results of the experiments indicate: (1) coal can adsorb uranium from the ground water passing through it at the present time; (2) water from Lost Creek will leach uranium from schroeckingerite and deposit it on coal; (3) coal not only removes uranium from solution by formation of an organo-metallic compound, but can markedly depress the pH and "Eh" of solutions in its vicinity.

SOURCES OF URANIUM

Although the epigenetic emplacement of uranium in the coal by means of circulating ground water seems probable, the ultimate source of the uranium is equivocal. Field and laboratory evidence partially supports all three of the following hypotheses:

1. Hydrothermal solutions—uranium mineralization along the thrust fault north of Crooks Gap and along the Cyclone Rim fault zone could mean that uraniferous hydrothermal solutions have risen along these faults and spread laterally into the ground water system.

2. Granite leach—Piggott,[11] Hurley,[12] and Brown and others[13] have shown that most of the uranium in granite is held interstitially and is removed easily by leaching. The granite of Sweetwater Mountains, the source of the coarse fractions of Wasatch sediments of the Red Desert area, and boulders derived from the granite contain from 0.002 to 0.003 per cent uranium. The arkose (sand-size material) contains about 0.0005 per cent uranium in the resistant heavy minerals which are in about the same proportions in the granite and arkose. The other 75 to 85 per cent of the uranium in the intergranular films is released during weathering and erosion. As the Wasatch sediments are 2000 to 4000 feet in thickness, large amounts of uranium would have been released during their formation.

3. Volcanic ash leach—Denson, Bachman, and Zeller[14] proposed that uranium leached from overlying volcanic ash by ground water was adsorbed by the coal in the Dakotas. Similar tuffaceous rocks of the Browns Park formation are preserved north, east, and south of the Red Desert and undoubtedly

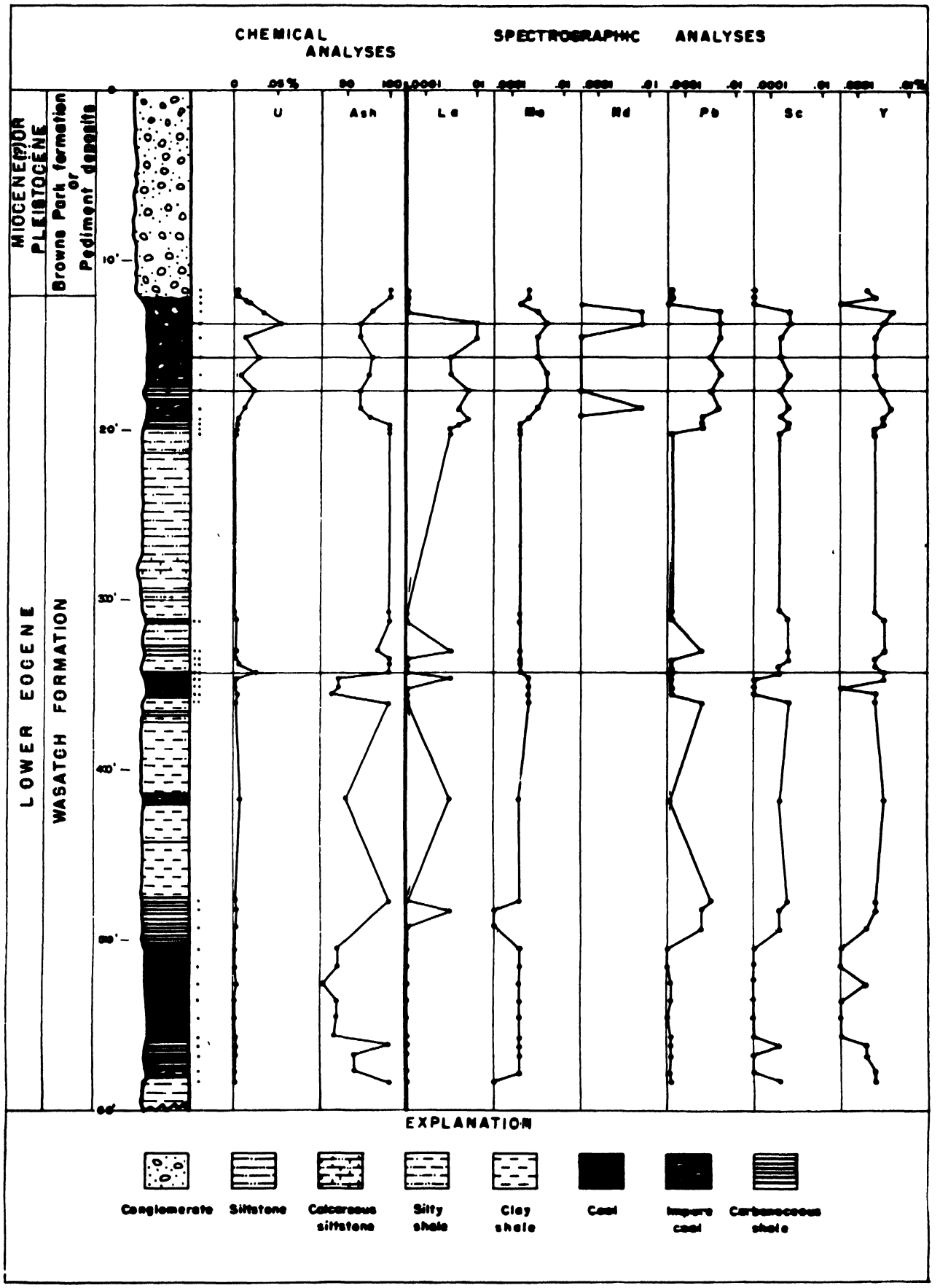


Figure 2. Diagram showing distribution of uranium and selected trace elements in the Creston coal zone at Creston Ridge, eastern Red Desert area, Sweetwater County, Wyoming

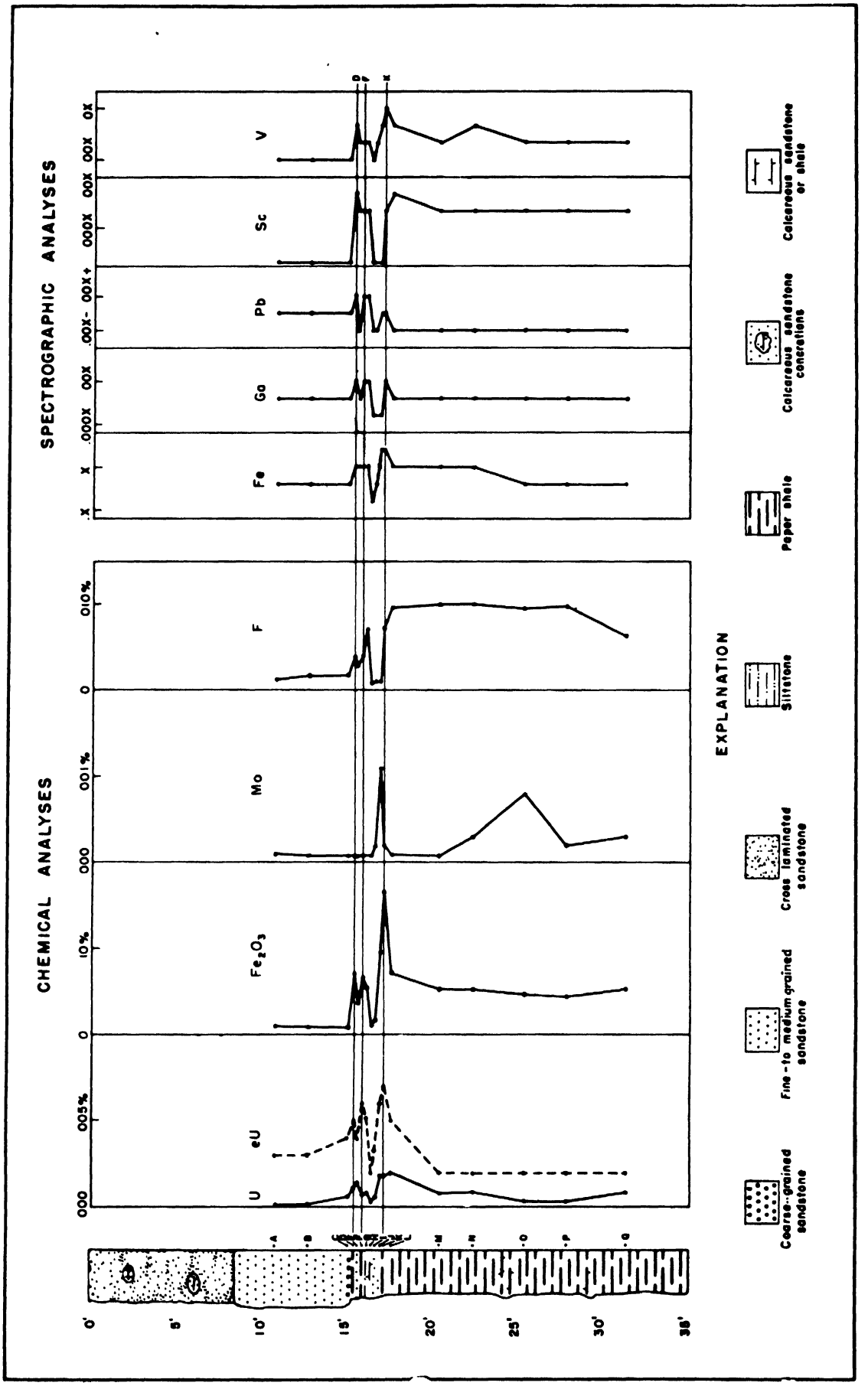


Figure 3. Diagram showing distribution of selected elements in interbedded sandstone and paper shale in the Wasatch formation, exposed at Eagle's Nest along Lost Creek, Red Desert area, Wyoming

once blanketed the area. Water from wells in the Browns Park formation contains from 39 to 50 parts per billion uranium indicating mobility of its contained uranium. Coal directly overlain by the tuffaceous rocks at Creston Ridge and Bison Basin has a high uranium content. In other places where the tuffaceous rocks overlie the sandstone facies of the Wasatch formation, the uraniferous water from the tuffaceous rocks might travel downward and laterally, reaching and mineralizing a coal bed.

Results of the investigation indicate that the large reserves of coal in the Red Desert are of interest primarily as a fuel resource and that uranium can only be produced as a by-product. However, thin carbonaceous shales in the coarse-grained clastic facies to the northeast of the principal coal area may be the sites of localization of higher grade uranium deposits.

REFERENCES

1. Smith, E. E., *The Eastern Part of the Great Divide Basin Coal Field, Wyoming,* US Geological Survey Bulletin 341; 220–242 (1909).
2. Bradley, W. H., *Geology of the Washakie Basin, Sweetwater and Carbon Counties, Wyoming and Moffat County, Colorado,* US Geological Survey Oil and Gas Investigations Preliminary Map 32 (1945).
3. Slaughter, A. L. and Nelson, J. M., written communication (1946).
4. Wyant, D. G., Sharp, W. N. and Sheridan, D. M., written communication (1951).
5. Moore, R. C., *Stratigraphic Classification of the Pennsylvanian Rocks of Kansas,* Bulletin of the University of Kansas 36, no. 22; 1–256 (1926).
6. Tolmachev, I. M., *Adsorption of Uranyl Salts on Solid Adsorbents,* USSR Academy Science Bulletin 1; 28–34 (1943).
7. Moore, G. W., *Extraction of Uranium from Aqueous Solution by Coal and Some Other Materials,* Economic Geology 49: 652–658 (1954).
8. Szalay, S., *The Enrichment of Uranium in Some Brown Coals in Hungary,* Acta Geologica, Magyar Tudomanyos Akademia 2, nos. 3–4; 299–310 (1954).
9. Breger, I. A., Deul, Maurice and Rubinstein, Samuel, *Geochemistry and Mineralogy of a Uraniferous Lignite,* Economic Geology 50; 206–226 (1955).
10. ZoBell, C. E., *Studies on Redox Potential of Marine Sediments,* American Association of Petroleum Geologists Bulletin 30; 477–511 (1946).
11. Piggott, C. S., *The Radium Content of Some Representative Granites of the Eastern Seaboard of the United States,* American Journal of Science, ser. 5, 17; 13–34 (1929).
12. Hurley, P. M., *Distribution of Radioactivity in Granites and Possible Relation to Helium Age Measurements,* Bulletin of the Geological Society of America 61; 1–8 (1950).
13. Brown, Harrison *et al., Leaching Studies of Interstitial Material in Igneous Rocks,* Bulletin of the Geological Society of America 64; 1400 (1953).
14. Denson, N. M., Bachman, G. O. and Zeller, H. D., written communication (1950).

Uranium-Bearing Lignite and its Relation to Volcanic Tuffs in Eastern Montana and the Dakotas

By N. M. Denson and J. R. Gill,* USA

Uranium-bearing lignite in the Williston Basin of North Dakota and South Dakota was discovered by Wyant and Beroni in 1948.[1] Detailed investigations were conducted from 1950 to 1954 by N. M. Denson, G. O. Bachman, J. R. Gill, H. D. Zeller, and others to evaluate economic possibilities of the radioactive lignite and to determine the geologic factors controlling the accumulation of uranium.

Geiger counters, scintillometers, and car-borne scintillation equipment guided the field work and sampling program. A jeep-powered auger and core drills were used to obtain unweathered samples of lignite to determine correlation and areal extent of radioactive beds in selected areas. Approximately 900 surface and 1000 core samples of lignite were analyzed for uranium. Chemical and semiquantitative spectrographic analyses for other trace elements and petrologic examination of a few samples were made in conjunction with routine uranium determinations.

GEOGRAPHY

Uranium-bearing lignite deposits of eastern Montana and the Dakotas occur in an area of about 13,000 square miles near the eastern margin of the Great Plains province, about 100 miles north of the Black Hills (Fig. 1). The region is a rolling prairie, broken by small areas of badlands or by buttes and ridges which are rugged and precipitous. Most of the buttes and hills stand 300 to 500 feet above the surrounding country. Rock strata are well exposed in the cliffs around the buttes.

The eastward flowing Grand River and the northward flowing Little Missouri River and their tributaries drain most of the region. Low sandy hills and broad sandy flats adjoin the rivers, whereas away from the streams the divides in many places are capped by small rock buttes or by red baked rock and clinker resulting from the burning of lignite beds. The altitude of the region ranges from 2100 feet above sea level along the east border to about 4000 feet on the Short Pine Hills. Numerous county roads and prairie trails, in addition to State and Federal highways, make most places in the region fairly accessible.

GEOLOGY

The stratigraphic section exposed in eastern Montana and adjacent parts of the Dakotas includes rocks of Cretaceous, Tertiary, and Quaternary age, which have a combined thickness of approximately 3800 feet. Drill tests for oil and gas indicate that about 7600 feet of Paleozoic and Mesozoic rocks occur between the oldest exposed rocks and the top of the Precambrian granite.

Radioactive lignite occurs sporadically at many horizons in the Hell Creek formation of Late Cretaceous age, in the Ludlow, Tongue River, and Sentinel Butte shale members of the Fort Union formation of Paleocene age and in the overlying Golden Valley formation of Eocene age. These formations total 2210 feet or more in thickness and consist predominantly of fluviatile deposits of somber-colored, soft, sandy clay-shale and massive thick-bedded tan and gray-brown sandstone.

Overlapping the lignite-bearing sequence with marked regional unconformity is 300 feet or more of ash-gray, mildly radioactive tuffaceous sandstone and bentonitic clay of the Chadron, Brule, and Arikaree formations of Oligocene and Miocene age. Erosional remnants unconformably capping many of the high buttes and escarpments indicate that these formations once extended over most if not all of the lignite-bearing rocks of the region.

The lignite-bearing formations herein described occupy the southwestern flank of the Williston Basin, the axis of which trends northwest and lies along the eastern edge of the area. In general, the strike of the rocks is northwest and the regional dip is 10 to 40 feet per mile to the northeast. The dominant structural feature affecting the regional dip is the plunging north end of the Black Hills uplift, the axis of which trends north-northwest and passes to the west of the Short Pine Hills in western Harding County, South Dakota. All of the lignite-bearing rocks are about equally deformed with the younger rocks of the White River group and the Arikaree formation resting almost horizontally on the truncated edges of the older formations. Few faults or folds extend to great depth in the region, but at numerous places landslides of Recent and Miocene(?) age produced surficial faults and folds.

URANIUM-BEARING LIGNITE

Megascopically visible uranium minerals (zeunerite, autunite, and torbernite) have recently been discovered in lignite and associated rocks in the Cave Hills area of northwestern South Dakota. There the

* US Geological Survey.

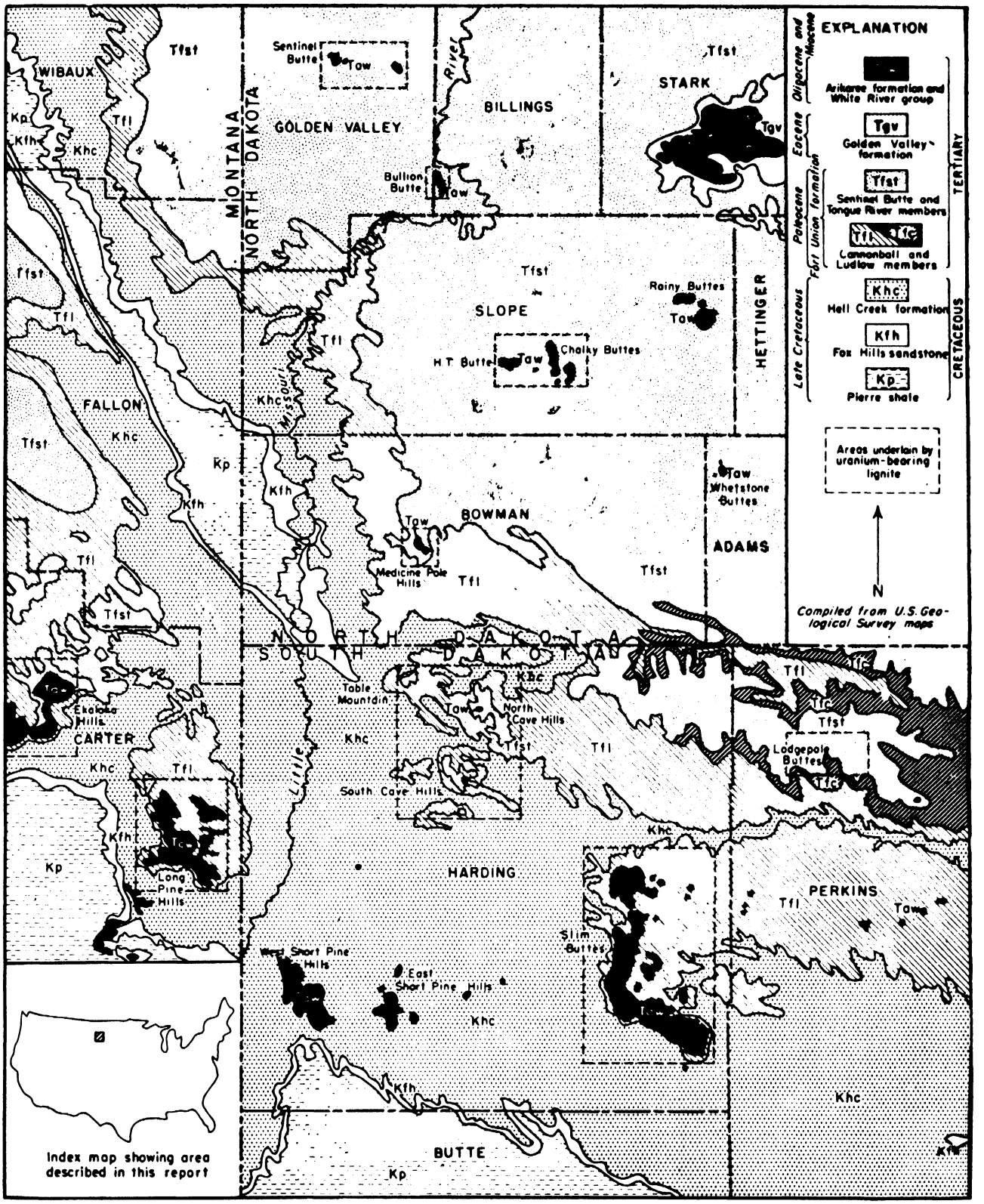


Figure 1. Geologic map showing areas underlain by uranium-bearing lignite in eastern Montana and the Dakotas

uranium minerals impregnate fractures and joints in thin impure lignite beds 18 to 30 inches thick which contain 0.3 to 5 per cent uranium. Several deposits of similar radioactive lignitic material have been found in the Slim Buttes in addition to commercial grade deposits of uranophane-bearing sandstone and metatyuyamunite-bearing carbonaceous shale.

Uranium minerals have not as yet been found in lignite in other areas of the region. Detailed microscopic and analytical studies on some of the lower

grade deposits indicate that the uranium occurs as a disseminated constituent of the carbonaceous material. Petrographic and mineralogic studies by the Battelle Memorial Institute,[2] the US Geological Survey[3,4] and Pennsylvania State University[5] of the lignites of North and South Dakota demonstrated that the uranium, although not present as a distinct mineral, was closely associated with the organic carbonaceous material. Gypsum, analcite, jarosite, limonite, quartz, and other minerals were identified in decreasing order of abundance but had no observed relationship to the amount of uranium in the lignite. Semiquantitative spectrographic analyses of the ash from radioactive lignite cores from South Dakota[6] show that most chemical elements are uniformly distributed through a vertical section of lignite. Uranium and molybdenum were among those which show a marked decrease downward from the top of the bed. The presence of small amounts of nickel, lead, and vanadium is indicated by spectrographic data, but the relationship between their distribution and that of uranium is less obvious.

Lignite from South Dakota has been shown to be a good extractor of uranium from solution.[7] Nonradioactive lignite from the Slim Buttes, South Dakota, was immersed in a solution of uranyl sulfate containing 200 parts per million uranium. After 19 days the lignite contained 0.19 per cent uranium and the solution contained 2.0 parts per million uranium. The experiment confirms in a striking manner the affinities of carbonaceous material for uranium pointed out by Tolmachev[8] and Szalay.[9] Similar adsorptive relationships have been postulated by McKelvey and Nelson[10] for the origin of uranium in marine black shale, and Frederickson[11] has discussed the relation of uranium and other types of carbon.

Three hypotheses of origin have been proposed to explain the uranium-bearing lignite deposits of the Dakota-Montana region. As a result of work in 1948 and 1949 Wyant and Beroni[1] proposed the following two hypotheses of origin: the uranium was deposited with other detrital minerals in sediments overlying or marginal to the lignite and subsequently leached from them, carried downward, or laterally, and fixed by the carbon of the lignite; or the uranium was deposited from surface waters by the action of living organisms or dead organic matter at the same time as the carbonaceous debris from which the lignite formed.

Work of Denson, Bachman and Zeller[12] in 1950 led to the development of a third hypothesis: the uranium is epigenetic in origin, having been extracted by the lignite, subsequent to coalification, from ground water bringing uranium from overlying tuffaceous source rocks by percolating downward or by moving laterally along aquifers near the lignite beds.

The uranium ion is believed to have been held as a disseminated constituent in the volcanic ash or tuffaceous material in the rocks of the White River group and the Arikaree formation. Subsequent release or displacement of the uranium may have been accomplished by weathering and ultimate devitrification of the volcanic materials. Whatever the reason for the displacement, carbonaceous materials are believed to have acted as filters to concentrate and cause fixation of the uranium. Experimental work by Breger, Deul, and Rubinstein[4] with radioactive lignite from the Slim Buttes has led these workers to conclude that the uranium is not held in the coal by ion exchange but seems to be present in the form of organo-uranium complexes or ionic organo-uranium compounds.

Subsequent field work including extensive core drilling in the Dakotas has elaborated and confirmed this hypothesis now termed the "ash leach" or volcanic ash theory.[13,14,15] Recent discoveries of ore-grade deposits of autunite and zeunerite-bearing lignite and uranophane- and carnotite-bearing carbonaceous sandstones closely underlying tuffaceous rocks in the Cave and Long Pine Hills and at Slim and Whetstone Buttes, offer additional confirmatory evidence for the theory.

Some observations supporting an epigenetic theory of origin are as follows:

1. All radioactive lignite deposits are within 40 to 140 feet of the unconformity at the base of Oligo-

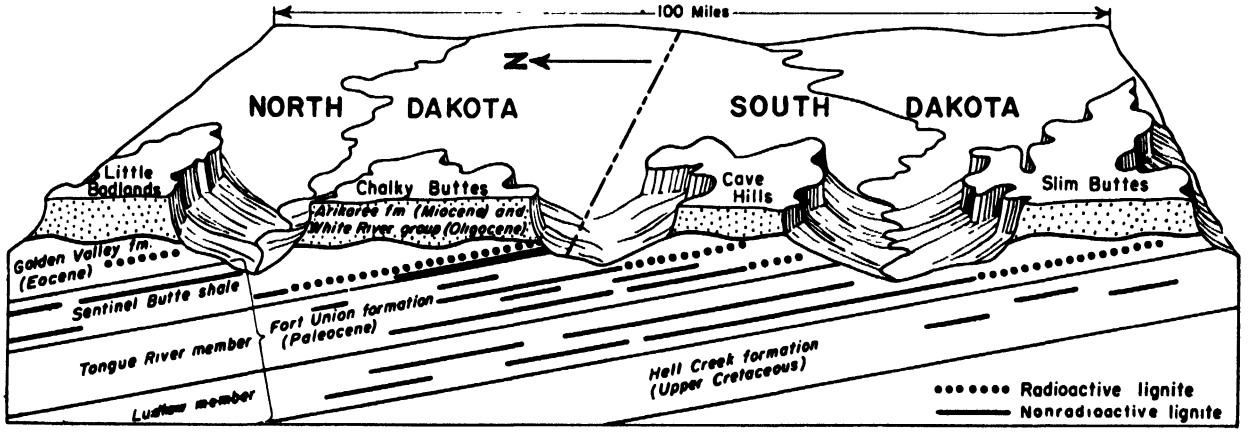


Figure 2. Diagrammatic section across northwestern South Dakota and southwestern North Dakota showing stratographic distribution of uranium-bearing lignite

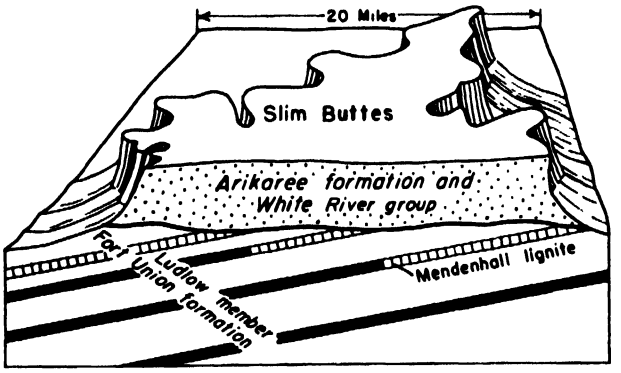


Figure 3. Diagrammatic section across slim buttes showing the stratigraphically highest lignite, beneath the pre-Oligocene unconformity, is the most radioactive

cene or Miocene rocks and bear no apparent relation to the age of the formation in which they occur (Fig. 2). Most of the radioactive lignites occur on the flanks of the highest buttes capped with volcanic materials.

2. In general, within a series of nearly flat-lying beds the stratigraphically and topographically higher lignites are the most radioactive (Fig. 3), the greatest concentrations of uranium occurring at the top of a coal bed and diminishing progressively downward (Fig. 4).

3. At many places throughout the region variations in permeability of the rocks overlying the lignite beds are reflected in the intensity of uranium mineralization. Where a mineralized bed is directly overlain by a permeable sandstone the bed is more highly mineralized than where it is overlain by clay or shale.

4. Rocks of the White River group and Arikaree formation show two to six times normal radioactivity and contain an average of about 0.0015 per cent uranium, about 12 times that of the average sedimentary rock.[16]

5. Chemical analyses show that the water from rocks of the White River group and the Arikaree formation contains greater than normal concentration of uranium in association with arsenic, copper, phosphorus, vanadium, and molybdenum. In the Montana-Dakota lignite areas the uranium minerals zeunerite $[CU(UO_2)_2(ASO_4)_2 \cdot 8H_2O]$, autunite $[CA(UO_2)_2(PO_4)_2 \cdot 10\text{–}12H_2O]$, torbernite $[CU(UO_2)_2(PO_4)_2 \cdot 8\text{–}12H_2O]$ and carnotite $[K_2O \cdot 2UO_3 \cdot V_2O_5 \cdot 2H_2O]$, which are found locally in the lignitic rocks and associated sandstones, contain most of these elements.

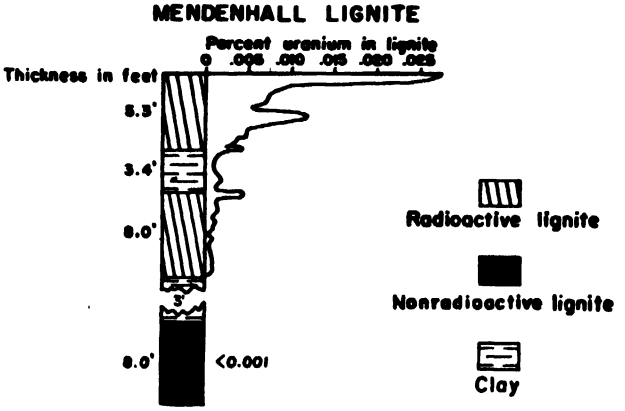


Figure 4. Diagram of radioactive lignite showing typical top preferential distribution of uranium

POTENTIALITIES

Available incomplete data indicate that deposits of radioactive lignite, aggregating about 90 million tons, in eastern Montana and adjacent parts of North Dakota and South Dakota average about 4 feet in thickness, contain 0.005 to 0.02 per cent uranium, and average about 0.008 per cent uranium. The uranium content of ash ranges from 0.05 to 0.1 per cent.

Smaller higher grade uranium-bearing lignite and carbonaceous shale deposits in the region contain conspicuous uranium minerals such as autunite and zeunerite. Such deposits contain from a few hundredths to about 5 per cent uranium. One deposit in the Cave Hills contains a significant tonnage of lignite averaging about 0.3 per cent uranium.

REFERENCES

1. Wyant, D. G. and Beroni, E. P., written communication (1950).
2. Ewing, R. A. *et al.*, written communication (1950).
3. Schopf, J. M. and Gray, R. J., *Microscopic Studies of Uraniferous Coal Deposits,* US Geological Survey Circular 343 (1954).
4. Breger, I. A., Duel, Maurice and Rubinstein, Samuel, *Geochemistry and Mineralogy of a Uraniferous Lignite,* Economic Geology 50: 206–226.
5. Bates, T. F., *et al.*, written communication (1952).
6. Zeller, H. D., written communication (1952).
7. Moore, G. W., *Extraction of Uranium from Aqueous Solution by Coal and Some Other Materials,* Economic Geology 49: 652–658 (1954).
8. Tolmachev, I. M., *Adsorption of Uranyl Salts on Solid Adsorbents;* USSR Academy of Science Bulletin 1: 28–34 (1943).
9. Szalay, S., *The Enrichment of Uranium in Some Brown Coals in Hungary,* Acta Geologica, Magyar Tudomanyos Akademia 11: 299–310 (1954).
10. McKelvey, V. E. and Nelson, J. M., *Characteristics of Marine Uranium-Bearing Sedimentary Rocks,* Economic Geology 45: 35–53 (1950).
11. Frederickson, A. F., *Some Mechanisms for the Fixation of Uranium in Certain Sediments,* Science 108: 184–185 (1948).
12. Denson, N. M., Bachman, G. O., and Zeller, H. D., *Uranium-Bearing Lignite and its Relation to the White River and Arikaree Formations in Northwestern South Dakota and Adjacent States,* US Geological Survey report, in preparation.
13. Thomas, H. D., *Wyoming's Uranium Prospects,* Uranium 1: 8, 46–47 (1954).
14. Hager, Dorsey, *Uranium — the Volcanic Ash Theory,* Uranium 1: 12–13, 38 (1954).
15. Miller, R. L. and Gill, J. R., *Uranium from Coal,* Scientific American 191: 36–39 (1954).
16. Evans, R. D. and Goodman, Clark, *Radioactivity of Rocks,* Geological Society of America Bulletin 52: 459 (1941).

The Los Ochos Uranium Deposit

By R. C. Derzay,* USA

The Los Ochos mine is in the Cochetopa Mining District, Saguache County, Colorado (Fig. 1).

This district is at the northeastern edge of the San Juan volcanic complex and on the western slope of the Sawatch Range where Mesozoic sediments lap onto pre-Cambrian rocks.

GEOLOGY

Structure

Four sets of pronounced high-angle faults traverse the region; the most prominent trends easterly, the others trend northeasterly, north and northwesterly (Fig. 2). Some of the northeasterly faults transect the east-west set while others have been displaced by it. The north-south set apparently postdates east-west faulting. The faults are post-Mancos formation in age, probably late Cretaceous and Tertiary.

Local structure is dominated by a major east-west, high-angle, reverse (Los Ochos) fault, traceable for several miles. The fault zone is 1 to 8 feet in width, and the displacement ranges from 30 to 180 feet. Mullion structure observed underground dips about 6 degrees to the west.

A pitchblende-bearing zone of intense shearing, about 16 feet wide, at the granite-Morrison formation contact extends from 20 feet south of the incline (Fig. 3) to 52 feet north, where it is displaced, probably to the east, by the Los Ochos fault. It is steeply dipping and trends northeasterly. The hanging and footwall limits of this vein zone are locally indefinite. The shear contains no fault gouge, but grades into a complex of fracture, joint, and bedding planes. Mineralization followed these planes for as much as 15 feet into the hanging wall in the Morrison formation and a few feet into the granite footwall.

A third structure, which appears to be upturned into the hanging wall of the northeast trending shear zone and then to flatten to a dip of 3 to 5 degrees to the west, separates a zone of intensely silicified (Saltwash ?) sandstone above from a highly kaolinized (granite) below (AA, Fig. 3). The fault zone is marked by a dense, light green mudstone which varies from 6 inches to 2 feet in thickness and may correlate with a very similar zone noted in the upper part of the incline. If this correlation is correct, the west side of the fault has been dropped about 65 feet. The Saltwash was displaced westward a short distance, movement which helped to provide open spaces for later mineralization in the northeast trending shear zone. Moderate mineralization occurred in this fault zone adjacent to the vein and extended westward, locally as much as 7 feet.

Two parallel east-west faults, 140 feet apart, have been exposed by exploration work about 2000 feet west of the mine. The southernmost of these has been mapped as the Los Ochos fault. The area between the two has been moved down and laterally, probably to the east. Regionally, the Los Ochos fault and the large east-west fault to the north converge eastward. Hence, continuation of the vein zone may be expected about 100 feet north of the Los Ochos fault where the faulted segment is displaced to the east and downward. The north side of the northerly east-west fault has probably moved to the west a distance of several hundred feet (Fig. 2).

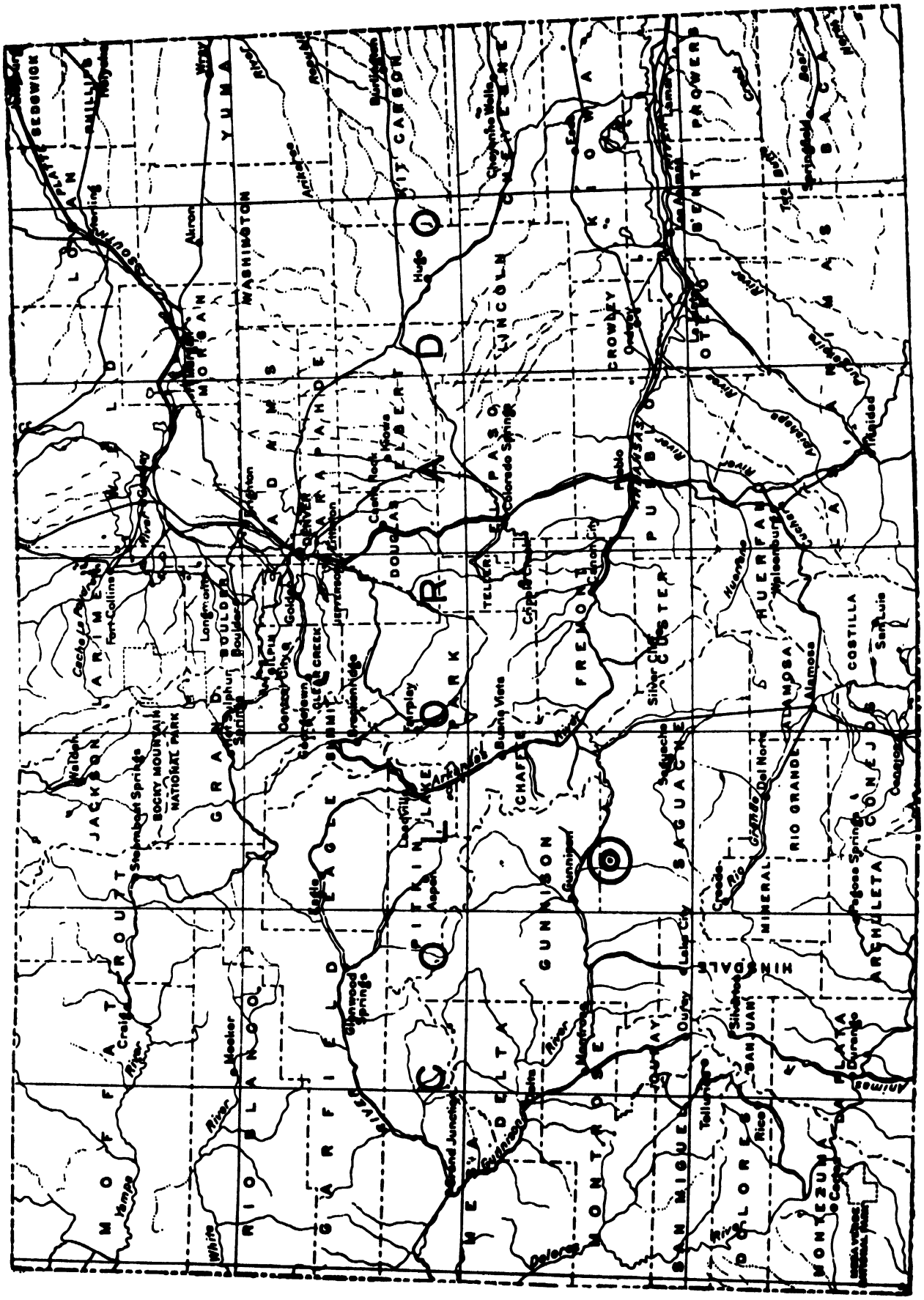
Stratigraphy

Rock units range from pre-Cambrian through the Tertiary, and pre-Cambrian granites, gneisses, schists and quartzites are the most common rock types in the district.

The granite is coarse-grained porphyritic pink to light red and is composed of quartz, biotite, microcline and soda plagioclase. This rapidly grades into a gray granite of similar texture near the mineralized fault zones. The schists are fine-grained, occasionally salt-and-pepper textured quartz-biotite type, with some hornblende, in places exhibiting lit-par-lit injection by the granite and are apparently older than the granite. Commonly there is gradation from schist through gneissic granite into fresh granite.

The Morrison formation of Jurassic age, approximately 200 feet thick, lies directly on a relatively flat erosional surface cut in pre-Cambrian rocks. The lower 60 feet, tentatively called the Saltwash sandstone member, is a white, fine-grained and poorly cemented sandstone. The upper 140 feet, the Brushy Basin shale member, consists of an alternating series of thin variegated mudstones and sandstones. The mudstone is composed of quartz and clay minerals with some microcline and trace amounts of tourmaline. The Dakota sandstone of Cretaceous age, conformably overlies the Morrison. It is about 100 feet thick, and is a gray to light brown, slightly silicified, crossbedded sandstone with a thin conglomerate of cherty pebbles at the base. The youngest sedimentary unit in the district is the Mancos shale of Cretaceous age conformably overlying the Dakota. It is a dark-

* US Atomic Energy Commission.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Golden
Idaho Springs
Central City
Georgetown
Breckenridge
Dillon
Leadville
Aspen
Glenwood Springs
Eagle
Rifle
Meeker
Rangely
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Hot Sulphur Springs
Fraser
Winter Park
Buena Vista
Salida
Canon City
Cripple Creek
Victor
Woodland Park
Castle Rock
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Limon
Burlington
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Kit Carson
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Yuma
Akron
Sterling
Fort Morgan
Brush
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Manitou Springs
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Green Mountain Falls
Chipita Park
Cripple Creek
Victor
Goldfield
Midland
Florence
Penrose
Rockvale
Coal Creek
Williamsburg
Canon City
Texas Creek
Howard
Salida
Poncha Springs
Maysville
Nathrop
Buena Vista
Johnson Village
Granite
Leadville
Twin Lakes
Malta
Wurtsboro
Hayden
Parachute
Rifle
Silt
New Castle
Glenwood Springs
Carbondale
Basalt
Aspen
Snowmass Village
Woody Creek
Old Snowmass
Emma
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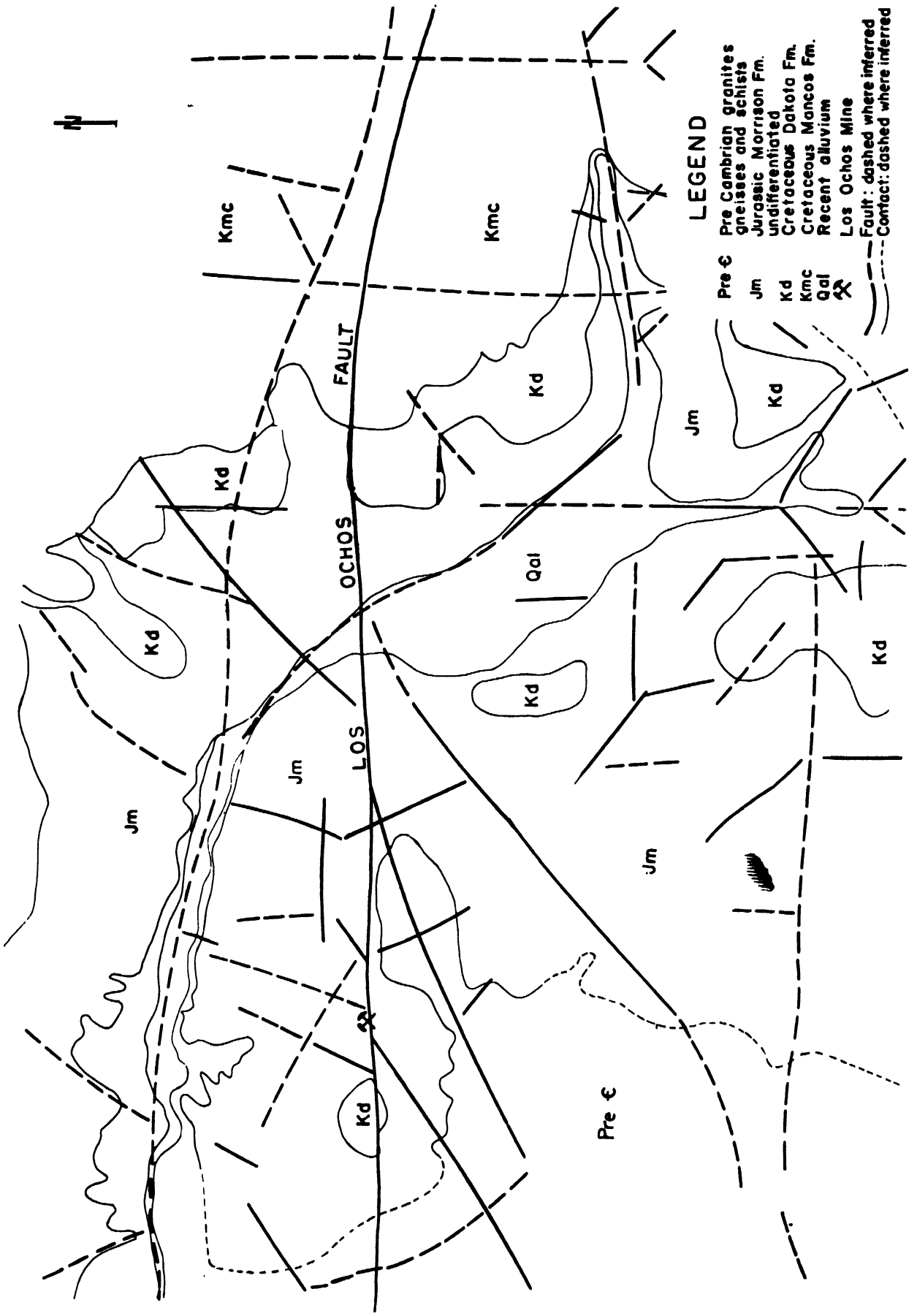
N
LEGEND
Pre Cambrian granites gneisses and schists
Jurassic Morrison Fm. undifferentiated
Cretaceous Dakota Fm.
Cretaceous Mancos Fm.
Recent alluvium
Los Ochos Mine
Fault: dashed where inferred
Contact: dashed where inferred
Pre €
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Figure 2

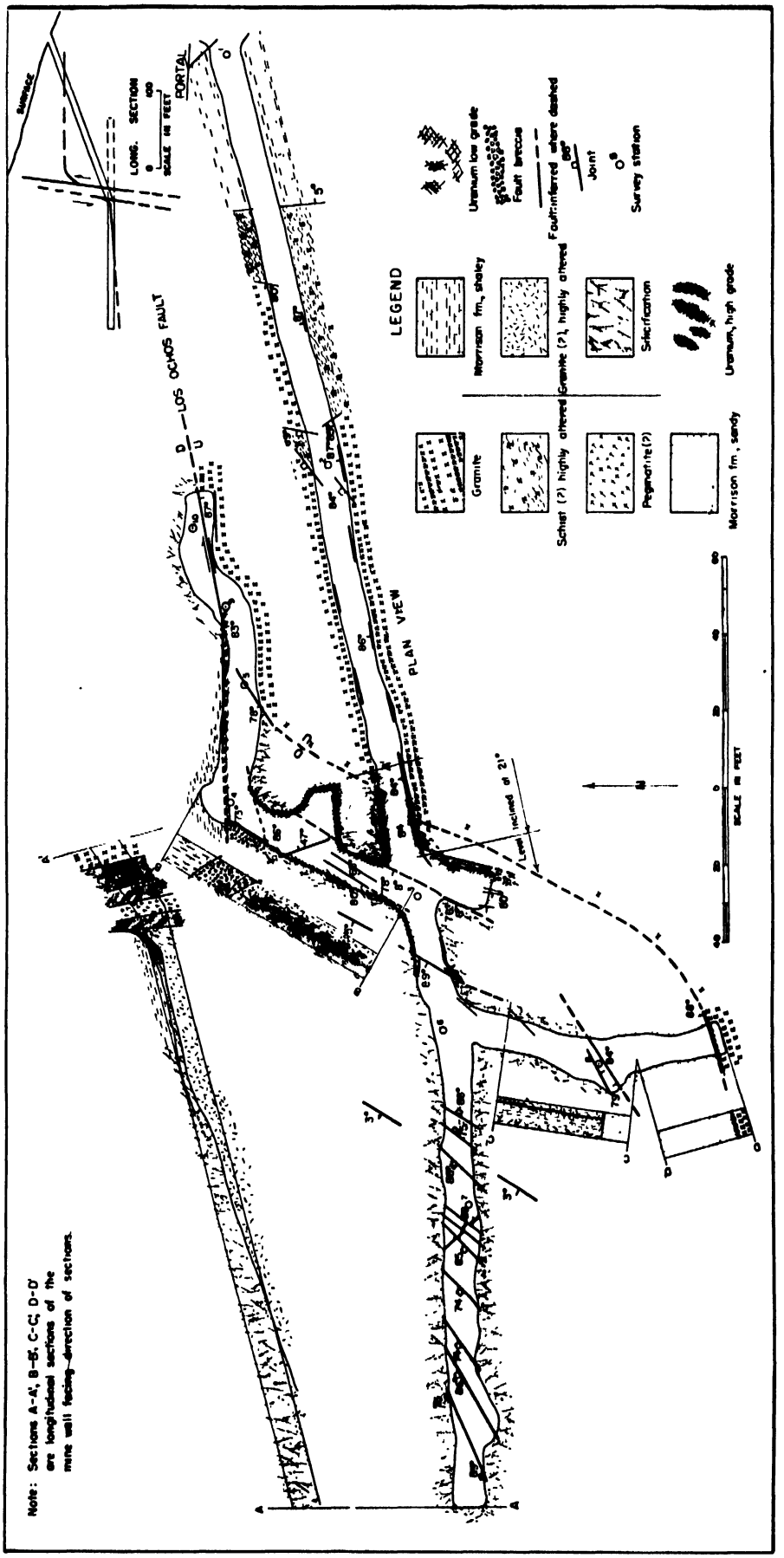


Figure 3. Geologic map, Los Ochos mine, Saguache County, Colorado

gray and drab sandy shale with a white lenticular sandstone about 10 feet thick at the base. Locally, Tertiary dikes and flows, principally of quartz latite, andesite and rhyolite are present.

Pre-Cambrian rocks, and the Morrison and Dakota formations, where faulted, are favorable for uranium deposition in the Cochetopa district. The volcanics locally exhibit low-order anomalous radioactivity, but no economic concentrations of uranium have been discovered in them.

Economic Geology

A northeasterly trending, steeply dipping tabular zone containing pitchblende has been developed at the Los Ochos mine. This intensely sheared zone, at the contact between pre-Cambrian granites and schists and the Morrison formation, is at least 70 feet long, 16 feet thick, and extends downward to an unknown depth. Uranium deposition outward into the permeable Morrison formation, and along adjacent joint and fracture planes, has increased the mineable thickness of the orebody to as much as 30 feet. The northern end of the orebody has been displaced, probably to the east and downward, by the Los Ochos fault, and has been again displaced an undetermined distance to the west by another parallel fault, some 100 feet to the north. On the surface, the northeasterly trending mineralized fault can be traced for a few thousand feet; whether or not it is mineralized for its entire length has not been determined. The spotty occurrence of secondary uranium minerals above the incline, on the upward projection of the sheared zone, suggests upward continuation of the ore. At what depth the vein will become impoverished cannot be surmised.

Other northeast-trending shears, both east and west of the developed vein, and a few northwest-trending shears have been mapped (Fig. 2). Preliminary exploration work has indicated the presence of uranium along several of the northeast-trending shears. Fractures having other trends have not yet been explored.

Mineralogy

The black sooty to semi-hard variety of pitchblende occurs adjacent to clay and as finely disseminated grains in fractures. Small (0.01 mm) grains ar also scattered through the quartz gangue.

Sparse, yellow to orange-yellow, secondary ura nium minerals are associated with the pitchblend notably in the pegmatite zone. A deep yellow, ve vety, secondary uranium mineral appears on the min walls after the vein has been exposed for severa weeks. The above minerals were studied by x-ra diffraction methods but could not be identified sinc no matching diffraction patterns were found. Uranc phane, autunite, and very sparse torbernite have bee noted at the vein outcrop in the Morrison formatio They occur in the interstices of brecciated and rece mented mudstones.

Associated with ore minerals are marcasite an minor islemannite and chalcocite. The marcasite i finely disseminated, concretionary, and occasionall reniform. No copper minerals were identified mega scopically; however chalcocite, probably of second ary origin, was tentatively identified by microscopi examination; it appears as cores of small, rounde grains of a yellow, weakly anisotropic mineral. Spec trographic analysis also indicated traces of titaniun arsenic, barium, cadmium, cobalt, chromium, gallium lanthanum, nickel, lead, strontium, zinc and zirconiun

Quartz blebs, pods, and veinlets which range i color from clear to very dark, and chalcedony an yellowish barite comprise the gangue minerals.

Based largely on laboratory analyses of numerou typical specimens, the following sequence of events i indicated: (1) silicification, (2) fracturing, (3) in troduction of marcasite I, (4) fracturing, (5) intro duction of marcasite II, (6) introduction of pitch blende, and (7) introduction of kaolinite as fractur fillings. Marcasite I occurs as fracture fillings; mar casite II, which is more yellow in color, coats marca site I as radial aggregates, cuts it in narrow veinlets and also is found as discrete spherical aggregate within the clay areas of the veins. This sulfide min eralization was accompanied by the introduction o alunite.

Intense alteration obscures the original nature o the rocks; silicification and kaolinization of the vei zone and wall rocks, where exposed by the develop ment work, are predominant. Chlorite, montmoril lonite, illite, sericite and the iron oxides are als present.

High-Grade Uraniferous Lignites in Harding County, South Dakota

By John W. King,* USA

Lignitic beds of Paleocene age containing uranium in amounts ranging from one tenth of one per cent and several per cent were discovered in northwestern South Dakota during the summer of 1954. Reserves of lignitic material, inferred on the basis of scanty exploration data, approach 100,000 tons containing more than 0.10% U_3O_8; realization of a potential of a million tons of similar grade is possible.

Weekly radioactive lignites in northwestern South Dakota and adjacent areas were studied as early as 1948. A core drilling project[1] between 1951 and 1953 resulted in the calculation of reserves of uraniferous lignite in the amount of 47 million tons at 0.005% uranium.

This paper discusses recently discovered lignitic deposits containing 0.10% uranium or more. Discoveries of such material have been made principally in Harding County, South Dakota with scattered discoveries of unknown potential in adjacent areas of North Dakota and Montana.

This lignite field is near the eastern margin of the Great Plains province north of the Black Hills. The more prominent buttes rising 300 feet to 500 feet above surrounding prairie are the Cave Hills, Slim Buttes and the Short and Long Pine Hills (Fig. 1). The Grand and Little Missouri Rivers and their tributaries drain most of the region.

STRATIGRAPHY

Rocks of Cretaceous, Tertiary, and Quaternary age are exposed in northwestern South Dakota and adjacent areas. Figure 2, a generalized section,[2,3] shows the average thicknesses, characteristics, and relations of the various formations and the stratigraphic positions of the principal coal beds.

Radioactive lignite occurs sporadically throughout the region at many horizons in the Ludlow, Tongue River, and Sentinel Butte members of the Fort Union formation of Paleocene age and in the underlying Hell Creek formation of late Cretaceous age. These formations aggregate 1500 feet or more in thickness and consist predominantly of fluviatile deposits of sombre-colored, soft, sandy clay-shale and massive, thick-bedded, tan and buff-gray sandstone. Overlapping the lignite-bearing sequence with marked regional unconformity are 300 feet or more of ash-gray, mildly radioactive tuffaceous sandstone and bentonitic clay of the White River and Arikaree formations of Oligocene and Miocene age. Remnants of these formations unconformably cap many of the high buttes and escarpments, proof that they once extended over most, if not all, of the lignite-bearing rocks in western South Dakota and adjacent parts of North Dakota and Montana[4] (Fig. 3).

Fort Union Formation

In northwestern South Dakota and adjacent North Dakota, the Fort Union formation (Paleocene) consists of 1200 feet or more of lignite-bearing sandstone, shale, and claystone. The Ludlow member, the lower 300 feet of the formation, intertongues to the east with non-lignite bearing strata of marine origin assigned to the Cannonball member. Overlying the Ludlow and Cannonball units with apparent conformity is the Tongue River member, in turn overlain by the Sentinel Butte shale.[4]

STRUCTURE

Harding County, South Dakota lies between the Black Hills uplift to the south and the Williston Basin to the north. The Cedar Creek anticline trends approximately south 60° east across Montana toward the common corner of North Dakota, South Dakota, and Montana. As the trend passes into Harding Sounty the anticline flattens and loses its identity between Cave Hills and Slim Buttes (Fig. 3). Regional dip is 30 to 40 feet per mile northeastward into the Williston Basin.

Jointing is common in the indurated sandstones of the Cave Hills. Faulting on an important scale has been observed in Slim Buttes but not in the Cave Hills. The Slim Buttes faults trend approximately north 70° west, dip vertically in displacements up to 200 feet. Seismic surveys have indicated as many as ten such faults with displacements between 40 and 200 feet across a one-mile interval.

Many of the lignitic units are involved in sliding and slumping, which characterize the slopes of Slim Buttes and are common on Cave Hills. Correlation is thus rendered difficult in many areas.

MINERALOGY

Coal

Little petrographic work has been done on the strongly weathered, abundantly uraniferous lignitic material from the Cave Hills. Specimens from most

* US Atomic Energy Commission.

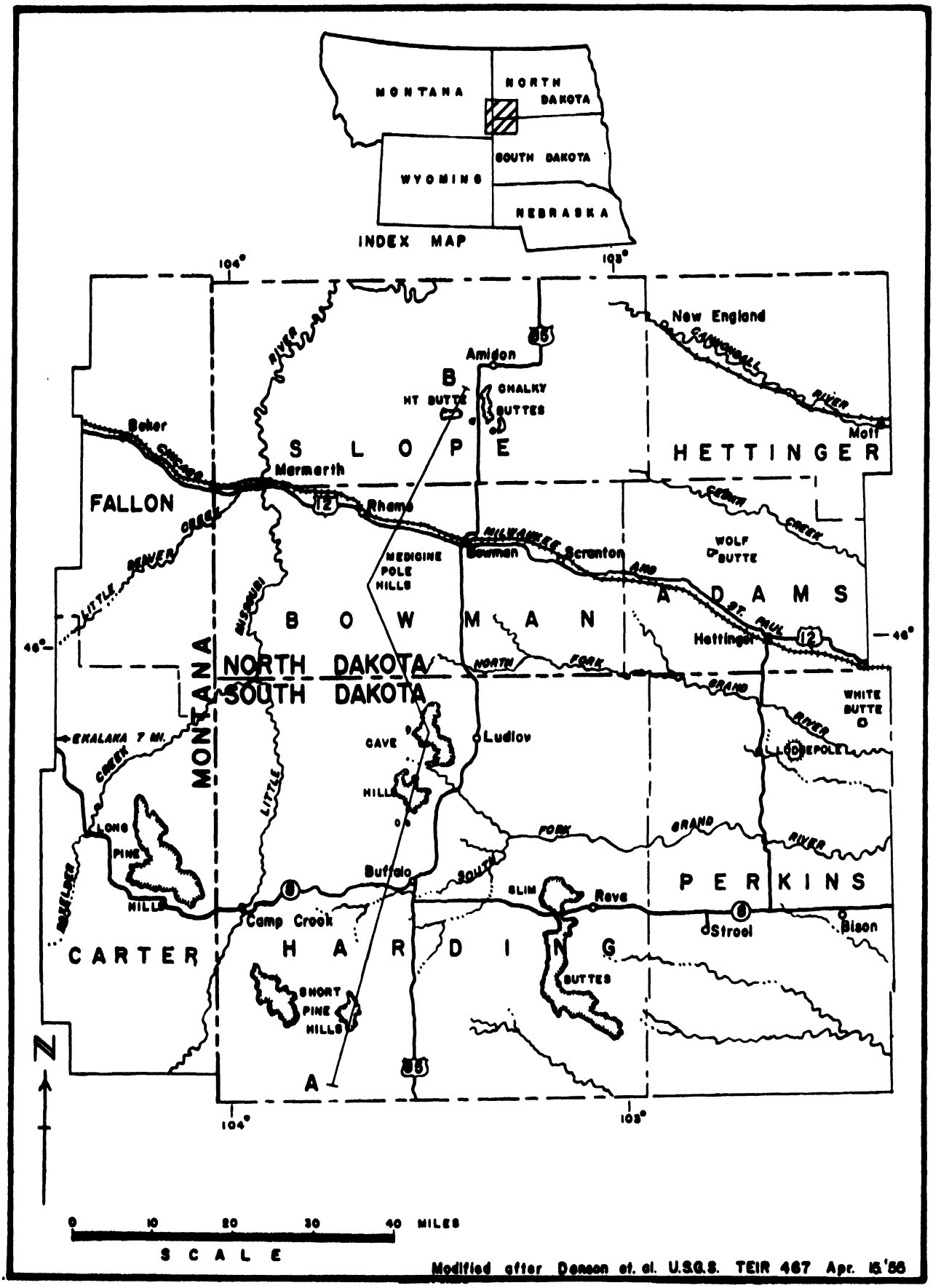


Figure 1. Location map of contiguous portions of North Dakota, South Dakota and Montana

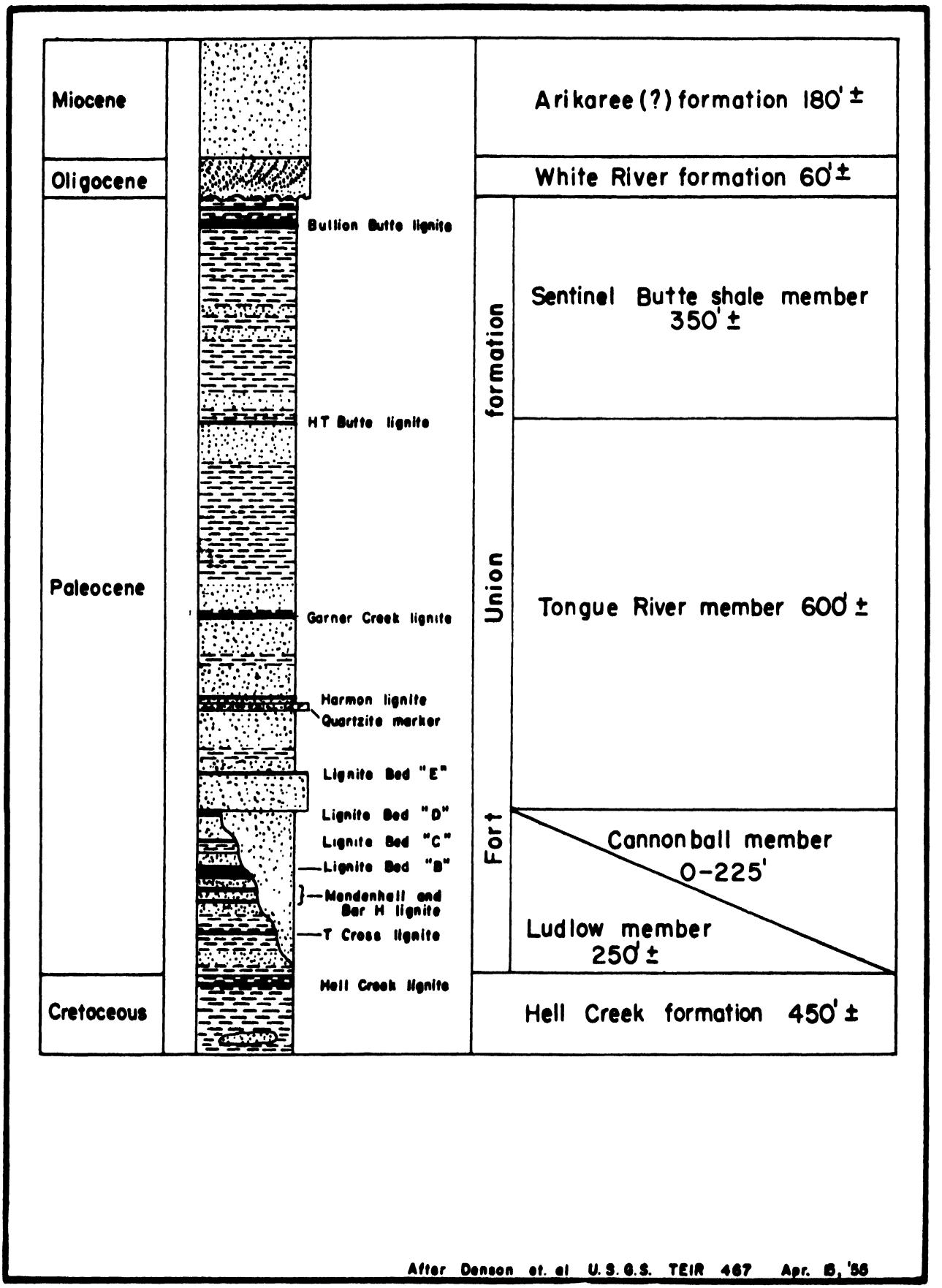


Figure 2. Generalized partial columnar section showing stratigraphic position of principal coal beds in Harding County, South Dakota, and adjacent areas

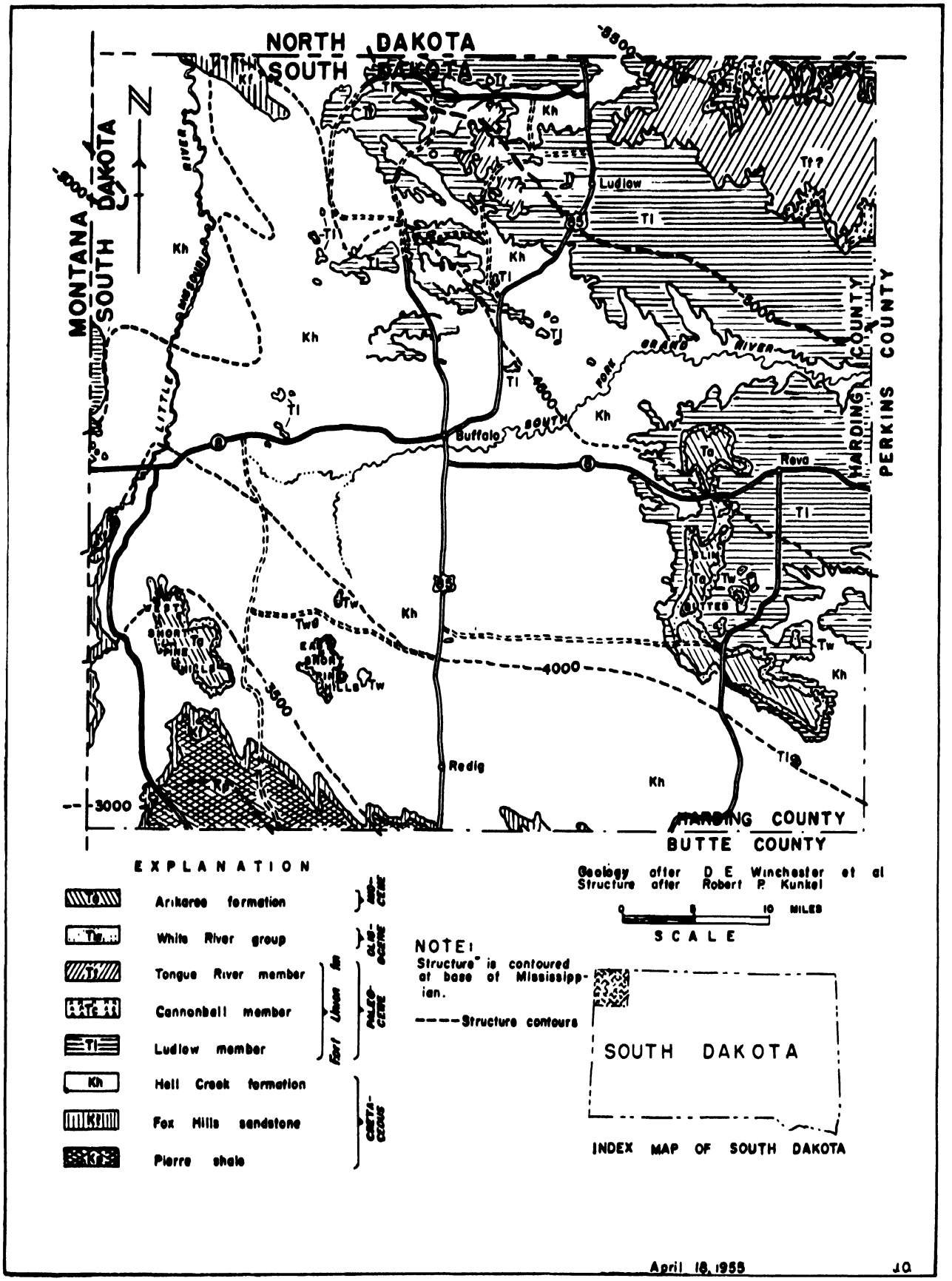


Figure 3. Geologic map of Harding County, South Dakota

of the lignitic exposures will not burn under a blowpipe flame. Moisture content is variable but the average of more than 500 tons shipped as uranium ore is approximately 40%. No unweathered material has been encountered in any of the uranium prospects.

Auger drilling indicated that the abundantly uraniferous lignitic material is reasonably consistent as far as 350 feet back of the outcrop and up to a maximum overburden of 75 feet.

Uranium in the Coal

Uranium (up to 0.85% U_3O_8) has been found in carbonaceous siltstone overlying a weathered black lignitic bed which contains up to 0.26% U_3O_8; in brown, fissile lignitic material in amounts up to 2.4% U_3O_8 in various grades of black, dull, powdery lignite in amounts up to 0.36% U_3O_8 and in lustrous weathered black lignitic material in amounts up to 8.0% U_3O_8; and in red ashed material up to 3.5%. The dull, powdery material is characteristically the poorest and the semi-lustrous material the richest in uranium. At several localities where the semi-lustrous material is fractured into small blocks (½-inch cubes), greenish fluorescent uranium minerals, principally meta-autunite, are visible megascopically. Meta-torbernite and meta-zeunerite have also been identified.[5] Uranium grade amounting to several per cent is common where visible minerals occur. The major portion of the uranium in the lignitic material is contained in a urano-organic complex.[6]

No correlation between uranium content and coal petrographic constituents has been noted in the lignites containing a few thousandths to a few hundredths of one per cent uranium. However, the ash content is higher in some of the more uraniferous layers, perhaps a result of introduction of other materials along with the uranium.

Correlation between different types of recognizable plant materials, their degradation products and uranium was also investigated by Schopf and Gray.[7] No direct correlation was found between any single coal component and the uranium content. They conclude that none of the samples apparently owes its high or low uranium content to its relative position within the bed.

Other Minerals in the Coal

The most common accessory in the lignitic material is analcite in small spheroids and rosettes, less than 1 mm in diameter, in varying amounts with no apparent relationship to the quantity of other minerals. Analcite shows no consistent vertical preference within a lignitic bed and the areal extent of the analcitic portions is unknown. Analcite is not confined to the lignite but is a common accessory constituent of surrounding clastic beds.

It is pointed out by Denson *et al.*[4] that analcite must form in alkaline solutions and it therefore seems improbable that it is of syngenetic origin; it must have been introduced subsequent to coalification.

Limonite and jarosite in blebs, seams, and veinlets cut across the bedding of the lignitic units. Pyrite is common in the concretionary blebs. There is no apparent correlation between the iron minerals and the uranium content. Gypsum in seams and veinlets is common.

Semi-quantitative spectrographic analyses have been made on about 25 samples of ash of lignite from the Cave Hills. The amount of ash varied from 30% to 50%. Arsenic and molybdenum were found in maximum amounts of 3.2% As and 1.4% Mo. A plot of U-As-Mo values indicates that all three elements tend to reach a maximum simultaneously.[8] No minerals of these metals have been identified.

Copper was determined in one sample of uraniferous carbonaceous siltstone overlying a lignitic bed.

Grade averages, maxima and minima, of the first 600 dry short tons of material shipped from Harding County were as follows: (Other assays were not made.)

Per cent	*Average*	*Maximum*	*Minimum*
	0.39	0.86	*
V_2O_5	0.05	0.07	0.00
$CaCO_3$	3.0	10.8	1.2

DISTRIBUTION OF URANIFEROUS LIGNITES

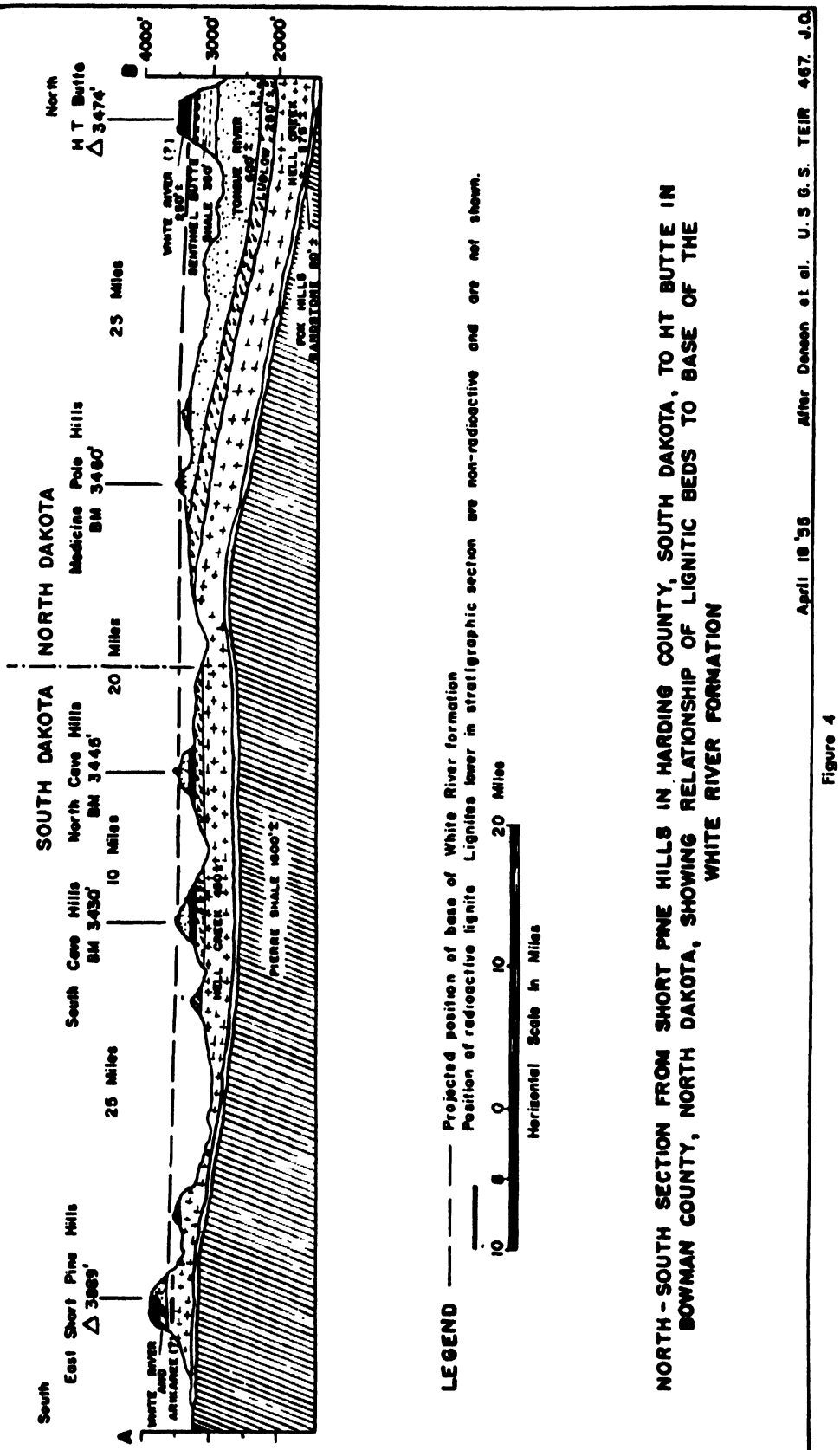
Individual lignitic units extend over several square miles and exceptionally over several tens of square miles. Lignitic beds containing more than 0.10% uranium are characteristically 10 to 13 inches thick but in exceptional cases beds 30 to 36 inches thick are known at that grade. Lignitic beds more than 10 feet thick contain only small amounts of uranium.

Although many of the favorable beds extend over considerable area, uranium mineralization is sporadic in them. Exploration is yet incomplete, but only a few areas are known to contain mineralized patches larger than an acre. Three areas of approximately 10 acres each are estimated to be at least 50% mineralized.

Uraniferous lignitic units are known in Harding County through a stratigraphic interval of approximately 300 feet of Tongue River and Ludlow beds. Local exposures of the favorable horizons are the fortuitous result of erosion; presumably there are others in the subsurface (Fig. 4).

The uppermost unit of importance is the "E" bed (Fig. 2) which lies immediately above the lower massive cliff-forming sandstone of the Tongue River member. The "E" bed is exposed over most of the top of North Cave Hills and on parts of South Cave Hills where its thickness is between one and two feet. Tongue River beds are absent from Slim Buttes and there the White River formation lies directly on the truncated Ludlow rocks. In Cave Hills the "D", "C", and "B" beds of the Ludlow member are notably uraniferous locally. The "D" bed lies at or close to the top of the Ludlow member beneath the lower massive Tongue River sandstone unit. The "C" and "B" beds lie within 100 feet of the top of the Ludlow member.

* Minimum grade purchases is 0.10% U_3O_8.



NORTH-SOUTH SECTION FROM SHORT PINE HILLS IN HARDING COUNTY, SOUTH DAKOTA, TO HT BUTTE IN BOWMAN COUNTY, NORTH DAKOTA, SHOWING RELATIONSHIP OF LIGNITIC BEDS TO BASE OF THE WHITE RIVER FORMATION

April 18 '58 After Denson et al. U.S.G.S. TEIR 467. J.O.

Figure 4

In Slim Buttes all uraniferous lignite beds are confined to the Ludlow member. Pre-Oligocene erosion truncated the Ludlow which dips gently to the north, so that the White River formation overlies lower sections of the Ludlow progressively to the south (Fig. 4). Several lignitic beds are known to be uraniferous in the Slim Buttes from the northern extremity nearly to the southern tip. Stratigraphy of the deposits is not known to the extent that host beds can be correlated with horizons at Cave Hills. The Slim Buttes deposits are, however, at lower horizons than those exposed around the periphery of the Cave Hills.

MODE OF OCCURRENCE

Proximity to aquifers is believed to be an important factor in mineralization of the lignite. The "E" bed of Cave Hills is in direct contact with a permeable underlying massive sandstone. It is overlain in some localities by a highly impermeable mudstone and elsewhere such mudstone units occur only a few feet stratigraphically above the "E" bed. Less prominent aquifers are in contact with other lignitic beds but no deposit of economic potential is known where highly impermeable beds directly overlie and underlie the lignite.

The abundantly uraniferous lignitic bed is not necessarily the uppermost of any group of lignites as early observations indicated. The deposits at Lonesome Pete claim (described below), Carbonate claims, and those near the Travers Ranch are examples where two, three, or four barren lignitic beds overly the most uraniferous bed.

Although preference of uranium for the top portion of a lignite bed has been noted in some of the low grade (+0.005% U) beds, field evidence concerning the high grade (+0.10% U) deposits shows no similar consistent preference. A preference does exist, however, in relation to grade of coal (see above: Uranium in the Coal). At one location in Craig Pass where brown lignitic material predominates but black lignitic lenses and seams are present, the transition zone of a fraction of an inch around the black material is the most radioactive portion.

No clear example of structural control of uranium deposition is known. A broad basin in the vicinity of Riley Pass contains several large deposits but exposures are particularly good in this area and the relationship may be coincidental.

At the Carbonate group in North Cave Hills, strong joint control has been observed but the relationship has not been observed elsewhere. At this deposit, two joints in the lignite, separated by an interval of two to three feet, are filled with an inch or two of limonite-stained, non-carbonate-bearing clastics. Between the joints and slightly less than a foot on either side, high radioactivity is obvious. It decreases rapidly to an insignificant level three to four feet from the joints. Two exposures on this claim exhibit the above relations.

All deposits recognized to date are at shallow depth and all are confined to weathered lignitic material. Weathering is not believed to have an important bearing on the uranium content but it is unfortunate that no deep exploration has yet sought the fresh lignite.

Radiometric inequilibrium in the lignite is characteristically in favor of the chemical assay by approximately two to one. In the two abundantly carbonaceous siltstone deposits known at present, one is nearly in equilibrium and the other is out of equilibrium in favor of the radiometric assay by 1.5 to 1.

In view of the above relationships, it is believed that the uranium was brought to the lignitic beds by solutions whose predominant direction of movement was lateral. A syngenetic theory of origin does not fit recorded facts nor does it appear logical that such locally abundant uranium can thus be easily explained. Predominant vertical movement of mineralizing solutions appears difficult of demonstration in view of many extensive overlying impermeable units and the presence, at several localities, of one to four lignite units of comparable quality, overlying the abundantly uraniferous unit. The presence of relatively large amounts of arsenic and molybdenum is strongly suggestive of an ultimate hydrothermal source. If the uranium was deposited before weathering took place, and if mineralizing solutions traveled laterally through adjacent aquifers, then many lignitic units now buried should be potential uranium hosts.

An alternative hypothesis has been presented by Denson *et al.*,[4] who believe that the uranium was derived by leaching of weakly uraniferous (0.0015% U) tuffaceous beds of the Arikaree and White River formations and transported by downward percolating waters to the present host beds.

THE DEPOSITS

A deposit in the Tongue River and two in the Ludlow are the best exposures developed to date.

Billy Dale Group

The Billy Dale group comprises 3½ claims on an isolated mesa immediately east of North Cave Hills (Fig. 5).

Only rocks of the Tongue River member are exposed in the area. The "E" bed lies directly on the lower massive Tongue River sandstone, a contact which is uneven with small swells and swales one to four feet in extent with a maximum of 6 inches of relief. Regional dip is less than one-half degree to the northeast. Jointing is sparse, faulting has not been observed. The uranium-bearing "E" bed is overlain by a maximum of 75 feet of sandstones and shales.

The uraniferous horizon has been exposed for about 90 feet along the outcrop and 30 feet in from the rim. The "E" bed can be followed completely around a butte which covers about 11 acres above that horizon. Abnormal radioactivity is noted on all

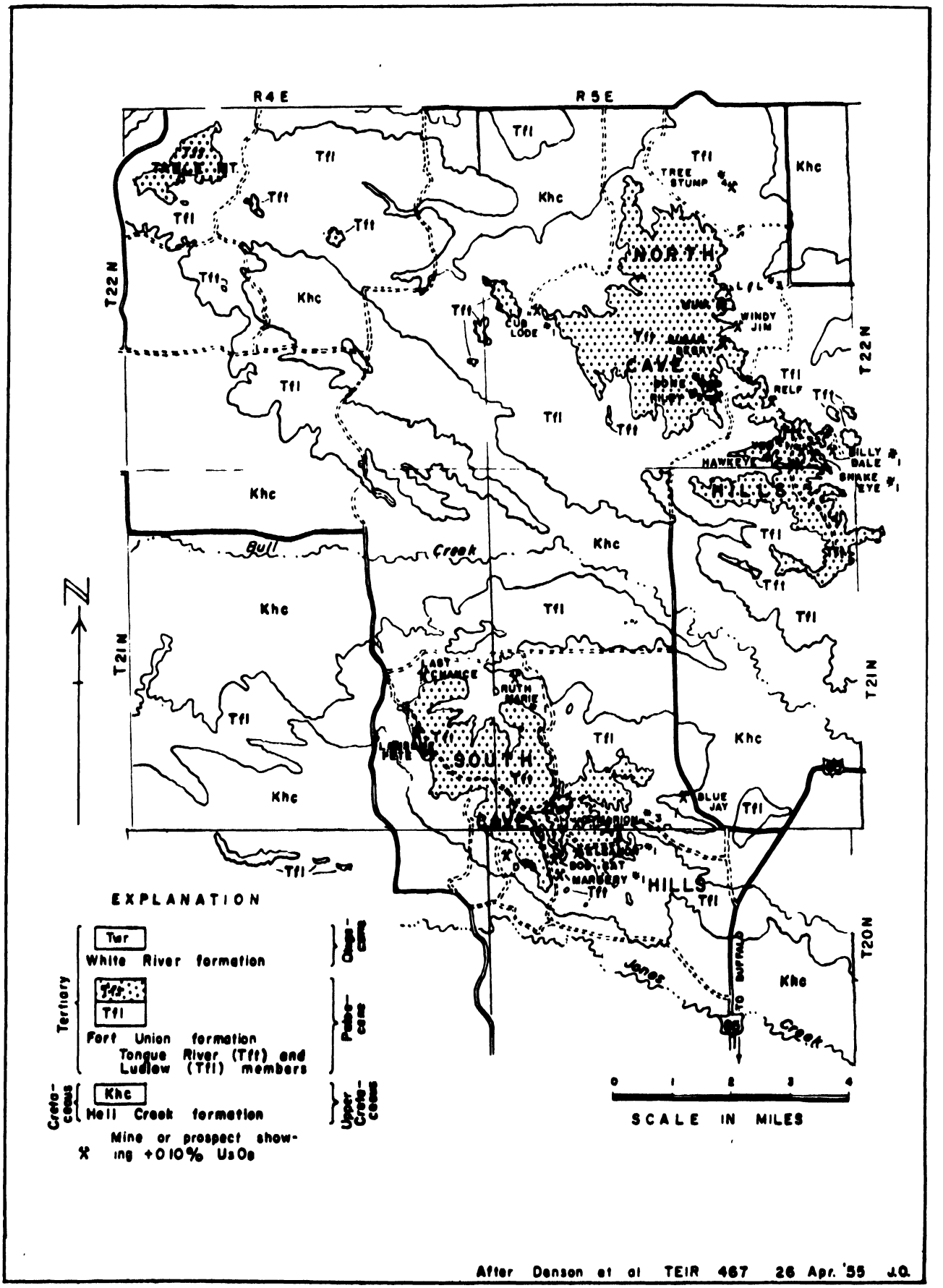


Figure 5. Location of mines and prospects, Cave Hills, Harding County, South Dakota

"E" bed outcrops around a large butte on the property and at numerous places on the nearby hills.

The "E" bed in the stripped area is composed entirely of black weathered lignite nine to ten inches thick. Some of the lignite is powdery, granular, and dull; the remainder is composed of small cubes less than ½ inch in size with semi-lustrous surface. The latter material is higher in uranium content and locally exhibits on the fracture surfaces a yellow-green fluorescent uranium mineral, tentatively identified as meta-autunite. This type of lignite is the richest of any in uranium content with picked samples assaying as high as 10% U_3O_8.

Unlike lignitic beds at many other properties, the coal at Billy Dale will burn in forced draft and with abundant smoke. Analcite is conspicuously rare at this deposit. Limonite and jarosite veinlets and stringers and clay stringers are moderately abundant.

Background count in the area is 0.012 mr/hr, the average along the outcrop is 0.60 mr/hr, maximum in the stripped area is 4.1 mr/hr. Radiometric assays range from 1.17% eU_3O_8† in black strongly weathered lignite to 0.07% eU_3O_8 in black powdery lignite. In general, equilibrium favors the chemical assay by two to one. A ten-inch channel sample from this property assayed 7.18% eU_3O_8.

Altogether 15 auger holes have penetrated the "E" bed. Probing indicated that 13 were in material containing more than 0.2% eU_3O_8, one slightly diluted sample assayed 4.57% cU_3O_8.‡ The two holes containing low count indicate that the uranium content is not consistent. Three holes from the top of the butte penetrated the "E" bed at a depth of 75 feet, approximately 350 feet from the outcrop. All were probed with readings of one, four, and five mr/hr respectively.

Somewhat more than 5000 tons of material, containing an average grade of 0.40% U_3O_8 is estimated for this deposit.

Lonesome Pete

The Lonesome Pete claim is located along the western side of South Cave Hills (Fig. 5) where local relief is approximately 250 feet.

The lower massive sandstone of the Tongue River member caps the hills in this area but the "E" bed is not present in the immediate vicinity. The Ludlow member makes up the lower slope of the South Cave Hills in this area. The "B" bed, approximately 110 feet below the top of the Ludlow member is the horizon of principal uranium mineralization. The regional dip is approximately 40 feet per mile to the northeast and heavy slumping in the Ludlow tends to mask local structure. Jointing is moderately spaced; faulting has not been observed.

The ore horizon was exposed by stripping for 550 feet along the bed and into the hill about 30 feet. Two horizons at this property are abundantly mineralized. The upper zone consists of one and one-half to two feet of very carbonaceous, locally sandy, mudstone and claystone. Much of the organic material occurs in rounded particles 1 to 3 mm in diameter. Channel samples of four inches of the most radioactive portion indicate up to 0.85% cU_3O_8. A bed of medium gray claystone, three inches thick, containing abundant limonite stringers and limonite stain, separates the uraniferous mudstone from the underlying lignite bed. Although less than two feet of the lignite has been exposed, a hand auger hole indicates that the bed is 12 feet thick. The upper two feet consists of earthy black weathered lignite containing some analcite. Limonite and jarosite occur in thin veins.

No uranium minerals are visible in the mudstone but minor amounts of yellow-green fluorescent uranium minerals (meta-autunite ?) have been observed on fracture surfaces in the lignite. Chemical assays of samples of the accessible portion of the lignite average 0.26% cU_3O_8. A bulk sample (100 lb) of the uraniferous mudstone gave assay results, as follows: eU_3O_8—0.85%; cU_3O_8—0.85%; V_2O_5—0.03%; $CaCO_3$—7.6%; Cu—0.02%. No other assays were made.

Insufficient work has been done on this property to allow a calculation of reserves but geologic evidence suggests that the deposit may be significant. This property has produced 95 short tons to April, 1955. Average grades were 0.34% U_3O_8, 0.02% V_2O_5, and 6.1% $CaCO_3$. An extensive stripping operation to expose the uraniferous horizon was near completion on April 15, 1955. It is perhaps significant that two, and probably three, barren lignite beds overlie the uraniferous horizon.

Hilltop Mine

The Hilltop Mine is in the southern portion of Slim Buttes (Fig. 6) on a slope approximately 75 feet below the base of the Arikaree cap. Local relief is 250 to 300 feet.

The deposit lies in the Ludlow member probably near the base, although the exact stratigraphic position is not known. Only the lower Ludlow beds remained in this area after pre-Miocene erosion. There is extensive slumping in the vicinity of the Hilltop but the mine itself is believed to be in place. That normal section of White River beds is not present in the area is indicated by the close proximity of the Ludlow beds to those of the Arikaree. Dip of sediments in this vicinity is less than 50 feet per mile to the north.

The uraniferous lignitic horizon has been traced for several hundred feet along the hillside where radioactivity has been measured at 5 mr/hr locally.

The uraniferous lignitic bed comprises 10 to 16 inches of brownish-black to black, weathered, powdery lignite containing lenses of hard, semi-lustrous material exhibiting conchoidal fracture. Iridescence grading into a dark brown coating is present on fracture surfaces. Abundant limonite and some jaro-

† U_3O_8 equivalent as determined by radiometric assay.

‡ U_3O_8 as determined by chemical assay.

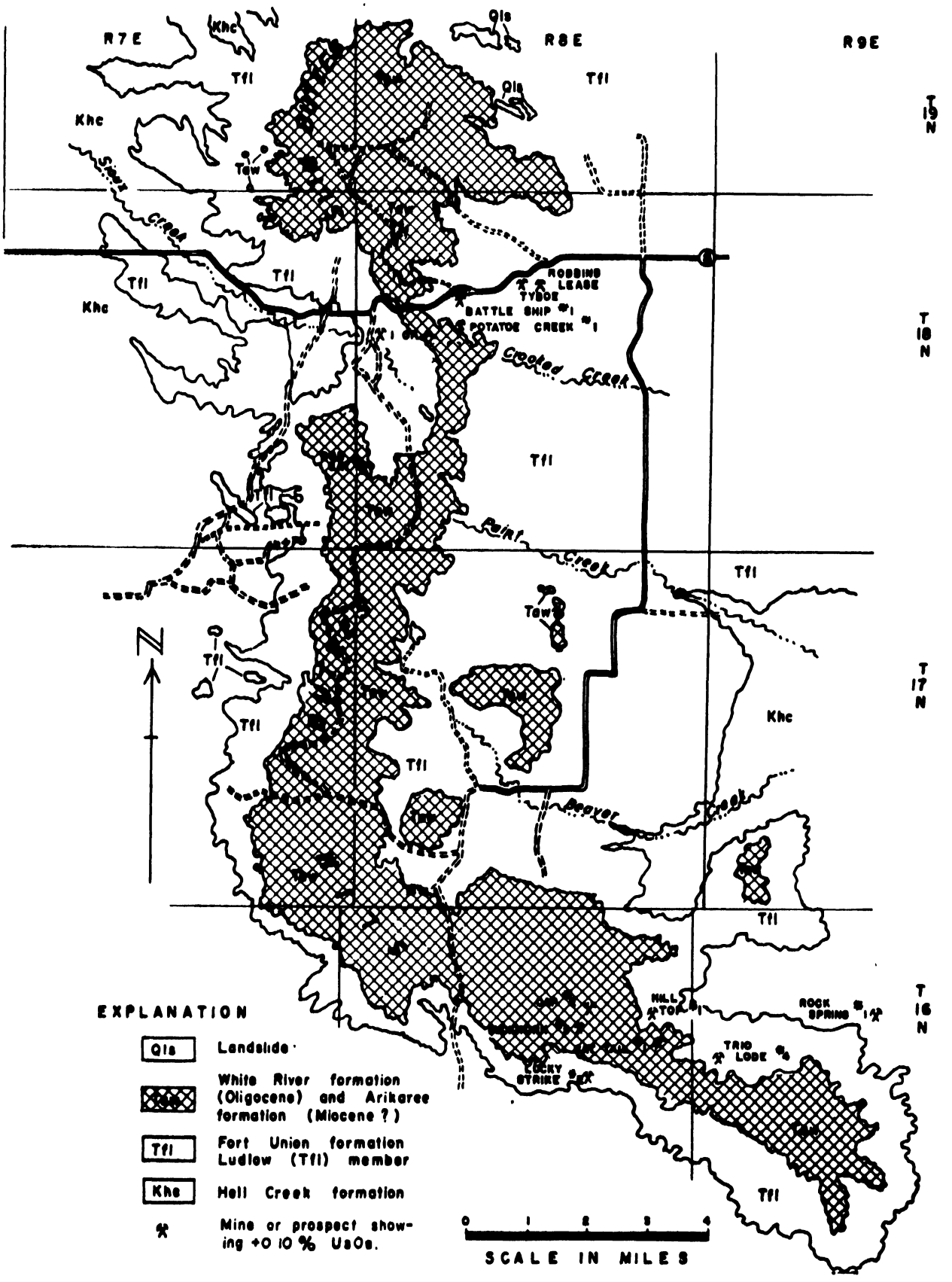


Figure 6. Location of mines and prospects, Slim Buttes, Harding County, South Dakota

site are present locally. Gypsum seams, commonly ⅛ inch thick, are present throughout the bed and gypsum crystals up to 2 inches across have been noted in the upper portion. No analcite is present. A green, micaceous mineral, commonly exhibiting green fluorescence, has been noted but is rare on cleat faces.

Chemical assays as high as 5.0% U_3O_8 have been obtained from picked samples.

The mineralized horizon is overlain by several feet of interbedded mudstones and unconsolidated sandstones. In addition, it is directly underlain by considerably more than two feet of brown peaty impermeable mudstone.

More than 300 tons with an average content of 0.33% U_3O_8 have been shipped from the Hilltop. V_2O_5 content was 0.04% and $CaCO_3$ content was 3.4%.

REFERENCES

1. Gill, James R., *Results of core drilling for uranium-bearing lignite, Mendenhall Area, Harding County, South Dakota,* US Geol. Survey TEIR–456: 32–35 (1954).
2. Winchester, D. E. *et al., The lignite field of northwestern South Dakota,* US Geol. Survey Bull. 627 (1916).
3. Hares, C. J., *Geology and lignite resources of the Marmorth Field, Southwestern North Dakota,* US Geol. Survey Bull. 775 (1928).
4. Denson, N. M., Bachman, G. O. and Zeller, H. D., *Uranium-bearing lignite and its relation to the White River and Arikaree formations in Northwestern South Dakota and adjacent states,* US Geol. Survey TEIR–467 (1954).
5. Gill, J. R., personal communication.
6. Various authors, *Geologic investigations of radioactive deposits,* Semi-annual progress report June 1–November 30, 1953, US Geol. Survey TEI–390.
7. Schof, J. M. and Gray, R. J., *Microscopic Studies of Uraniferous Coal Deposits,* US Geol. Survey TEIR–408 (1954).

Uranium-Bearing Coal in the Central Part of the Great Divide Basin, Sweetwater County, Wyoming

By George N. Pipiringos,* USA

The Eocene coal beds in the central and eastern parts of the Great Divide Basin, mapped in reconnaissance by Smith,[1] were discovered to be radioactive by Slaughter and Nelson.[2] Wyant, Sharp, and Sheridan[3] concluded, from reconnaissance investigations, that these areas contain large low-grade potential reserves of uranium-bearing coal and carbonaceous shale.

The author was associated with Harold Masursky in 1951 and 1952 in detailed investigations of the uranium-bearing coal in the eastern and central parts of the Great Divide Basin.[4] This paper is based on the geology of the central part of the Great Divide Basin (Fig. 1) which was mapped by the author in 1951—1952, and by the author and J. C. MacLachlan in 1953. The author was assisted in the field season of 1952 by A. E. Burford, H. D. Gower, and G. W. Moore.

The Great Divide Basin is an oval-shaped undrained topographic depression on the Continental Divide and embraces about 4000 square miles in Sweetwater, Carbon, and Fremont Counties, south-central Wyoming (Fig. 1). The central part of the basin contains several dry lake flats; Battle Spring Flat, the lowest part of the area, is about 6500 feet above sea level. The highest parts of this area are on the north and south branches of the Continental Divide and range from about 7300 to 7450 feet in altitude.

GENERAL GEOLOGY

Most of the Great Divide Basin is underlain by approximately 5000 feet of Tertiary rocks. The lower part of this sequence is the Fort Union formation of late Paleocene age (Tiffanian) according to Gazin,[5] and consists of coal-bearing clay shale, siltstone, and fine-grained sandstone. It rests unconformably on Cretaceous rocks and is overlain unconformably by Eocene rocks. The Fort Union formation is about 1100 feet thick in the western part of the Great Divide Basin, about 1000 feet thick in the northern part,[6] and is probably much thicker in the eastern part.

Near the Steamboat Mountain, in the western part of the Great Divide Basin, Bradley,[7] has recognized, in ascending order, the main body of the Wasatch formation, the Tipton tongue of the Green River formation, the Cathedral Bluffs tongue of the Wasatch formation, the Laney shale and Morrow Creek members of the Green River formation and the Bridger formation—all of Eocene age. These units also occur in the central part of the Great Divide Basin and their predominant lithologies and stratigraphic relationships are shown in the restored section, Fig. 1. The stratigraphy of this area differs from that of the area described by Bradley in that the main body of the Wasatch is split into two coal-bearing sequences, the Red Desert and Niland tongues, by the Luman tongue of the Green River formation,[8] in that nearly all of the Green River-Wasatch sequence intertongues with and is replaced northeastward by the Battle Spring formation of early and middle Eocene age,[8] and in the presence of the Browns Park formation of Miocene age. The transition from fine-grained rocks of the Wasatch-Green River sequence to the very coarse-grained rocks of the Battle Spring formation takes place in a relatively narrow zone which coincides approximately with the Red Desert syncline which trends southeast across the Great Divide Basin (Fig. 1, index map). The minimum thickness of the Wasatch-Green River-Battle Spring sequence is about 3400 feet.

The overlying Bridger formation ranges from 60 to 100 feet in thickness, as well as the Morrow Creek member, contains fossils of probable middle Eocene age. The age of the Cathedral Bluffs tongue is less certain and is probably of middle Eocene age as suggested by Morris.[9] The stratigraphically highest fossil collection of probable early Eocene age was collected from the lower part of the Tipton tongue[10] in the vicinity of Lost Creek in the northeastern part of the map area. Thus the early Eocene-middle Eocene boundary probably lies within the upper part of the Tipton or in the lower part of the Cathedral Bluffs.

Unconformably overlying the Bridger formation is a sequence of interbedded conglomerate, very coarse-grained sandstone, and fine-grained tuffaceous sandstone about 500 feet thick. Bell[11] has collected Miocene fossils from these rocks a few miles west of Lost Creek. On the basis of lithologic similarity and stratigraphic position, this sequence is correlated with the Browns Park formation, a middle Miocene sequence described by McGrew,[12] in the Split Rock

* US Geological Survey.

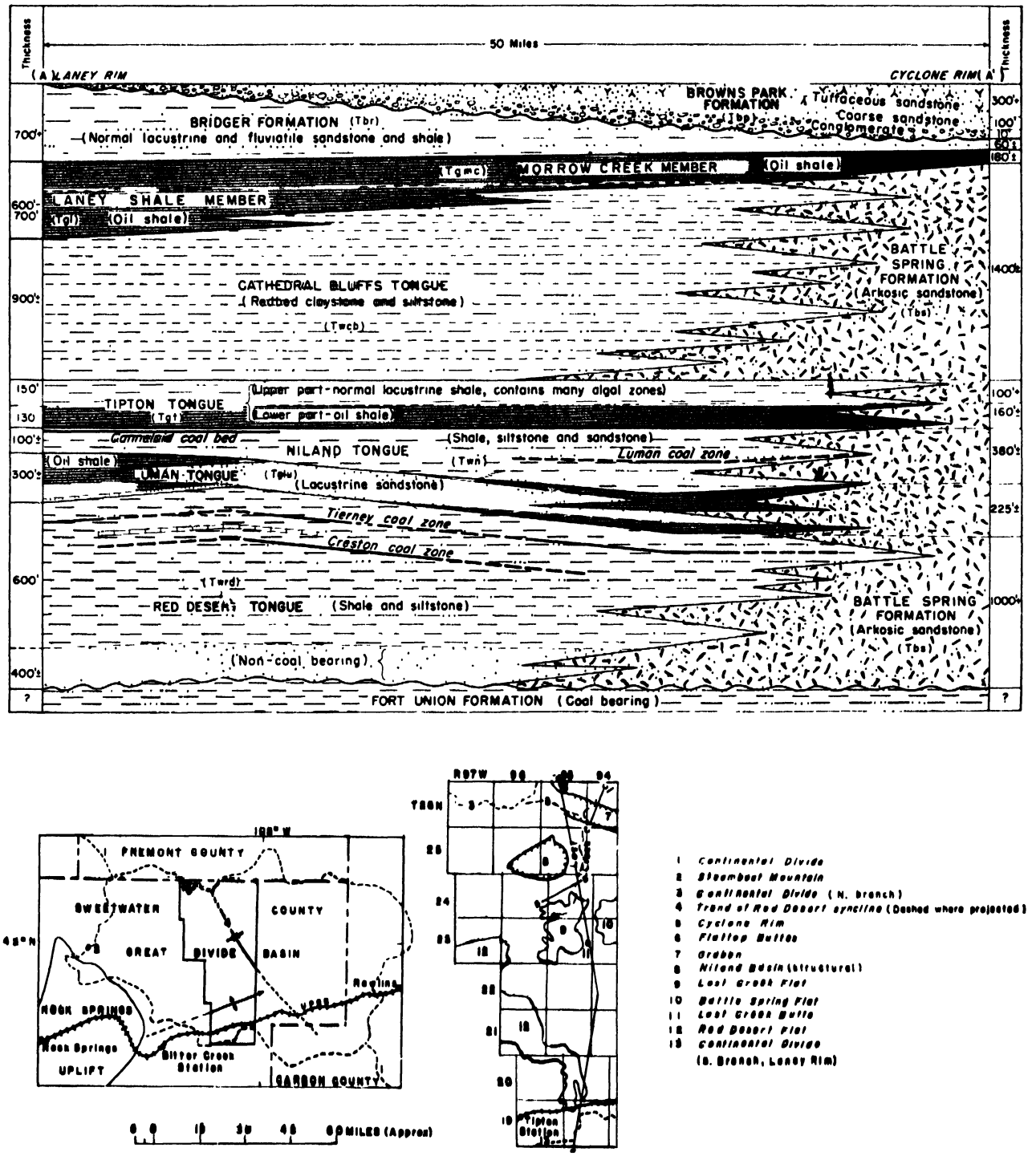


Figure 1. Restored section of Tertiary rocks and index map showing area investigated in Great Divide Basin, Sweetwater County, Wyoming

area several miles to the northeast. The Browns Park and remnants of similar tuffaceous rocks occur along the northern and eastern margins of the Great Divide Basin, and probably once blanketed the entire Great Divide Basin.

Several isolated sand and gravel terrace deposits, at altitudes ranging from 6750 to 6900 feet, are scattered throughout an area extending from the north line of T. 19 N to the north edge of Niland Basin and seem to be remnants of a single continuous layer. South of the middle of T. 21 N they are separated from the underlying bedrock by several feet of red or brown silty clay very similar to that in the floors of the dry lake flats. It seems probable that these deposits are of Pleistocene rather than recent or Miocene age.

A broad gentle arch whose axis trends about N 70° E plunges eastward across the south-central part of the Great Divide Basin (Fig. 1). To the north the shallow Red Desert syncline plunges about

N 30° W into the nearly circular structural Niland Basin. The axis of the Red Desert syncline is associated with the thickest coal beds, with the transition from coal beds of relatively high uranium content in the northeast to coal beds of relatively low uranium content in the southwest, and with the transition from coarse-grained rocks of good permeability in the northeast to fine-grained rocks of moderate to slight permeability on the southwest (Fig. 2).

A graben, about 3 miles wide, trends about N 70° W across the northeast corner of the map area and is outlined for the most part by remnants of the Browns Park formation. The normal fault on the north side of the graben has a vertical displacement of about 3000 feet and extends for several miles to the northwest and for an undetermined distance to the southeast. The normal fault on the south side has a vertical displacement of from about 200 to 300 feet in the vicinity of Lost Creek, but a few miles to the northwestward it passes into an anticline or monocline. It appears to extend for a few miles to the southeast.

URANIUM IN COAL

Uraniferous coal beds crop out in the central part of the Great Divide Basin in an area that extends from T. 19 N to T. 24 N. The least uraniferous are those in the western and southern parts of the coal-bearing area; the most uraniferous are in the central and northeastern parts. Two coal groups, those in the Niland tongue,[8] which includes the Luman coal zone, and those in the Red Desert tongue are separated by the noncoal-bearing Luman tongue of the Green River formation (180 to 390 feet thick). The stratigraphic interval between the highest and the lowest exposed coal beds is about 1000 feet. The coal beds of the Red Desert tongue are subbituminous B rank, those of the Niland tongue are subbituminous B and C. The restored section (Fig. 1) shows only a few of the numerous coal zones that occur in this area.

Figure 2 (section B–B′) shows the apparent relationship of uranium content in the Luman coal zone to facies changes across the Red Desert syncline. The coal zone contains two beds, the Luman No. 1 and No. 2 (Fig. 2), and is second from the bottom of the four coal zones in the Niland tongue. The geologic setting of the Luman coal zone is similar to that of all the coal zones in this area. The average uranium and ash content shown in the graphs for each locality is the weighted average of the coal bed exclusive of clay shale and carbonaceous shale partings. As shown in Fig. 2, the uranium content of the Luman No. 2 coal bed ranges from about 0.002 at the left or west side of the diagram to about 0.012 per cent in the middle, near the axis of the syncline. From locality 1 to locality 4, about 1.8 miles apart, the uranium content ranges from 0.0023 to 0.0055, an increase of 0.0032 per cent. From locality 4 to locality 5, about 0.7 mile apart the uranium content rises to 0.009, an increase of 0.0035 per cent in less than half the distance between localities 1 and 4. Eastward from locality 5 the uranium content increases to a maximum of 0.012 per cent at locality 7 and then decreases again at locality 8, beyond which the Luman No. 2 coal bed grades into a carbonaceous shale and then pinches out. At locality 15, the Luman No. 2 consists of a few inches of carbonaceous shale and contains 0.002 per cent uranium.

The relatively sharp rise in uranium content of the Luman No. 2 coal bed between localities 4 and 5 coincides with the first appearance in the section of coarse-grained permeable rocks, and all the localities (5–8) with the relatively higher concentrations of uranium are in or near the lowest part of the syncline.

The Luman No. 1 coal bed also shows a rise in uranium content from southwest to northeast (Fig. 2). The uranium content rises from 0.002 at locality 9 to a maximum of 0.0081 at locality 13 and gradually diminishes to 0.006 per cent uranium at locality 15. About 3 miles east of locality 15, the Luman No. 1 consists of about 5 feet of carbonaceous shale and has a uranium content of 0.002 per cent. The greatest concentration of uranium in the coal coincides with that part of the section containing the largest amounts of coarse-grained permeable rocks. The maximum concentration is at the first locality east of the axis of the syncline. At locality 15 where there is a local decrease in the permeability of the rocks, the uranium content likewise decreases.

This general relationship was observed in all the coal beds of this area and it seems highly probable that the uranium entered the coal beds from groundwater moving down-structure along permeable beds.

Locally, relatively high uranium concentrations in coal beds appear to be related to sand and gravel deposits of probable Pleistocene age. At a locality about a mile south of Lost Creek Butte a layer of sand and gravel about 20 feet thick rests on a 10-foot sequence of coarse-grained sandstone that directly overlies a 10-inch coal bed. The average uranium content of the coal bed is 0.009. Two other samples of the coal bed collected from outcrops 500 and 1,000 feet east of the first locality contained 0.005 and less than 0.001 per cent uranium respectively. The eastward decrease in uranium content is associated with an increase in interval between the coal bed and the sand and gravel layer and also is associated with a gradation from coarse-grained sandstone to a clay shale in the rocks directly above the coal.

At a locality about 8 miles south of Lost Creek Butte, the uranium contents of 5 coal beds distributed through 80 feet of section decrease with lower stratigraphic position. The highest bed contains 0.014 per cent uranium but the lowest contains none. The highest coal bed is directly overlain by a 20-foot sequence of medium-grained sandstone beds which is capped by a layer of sand and gravel about 10 feet thick. The four lower coal beds are interbedded with clay shale, siltstone, and fine-grained sandstone.

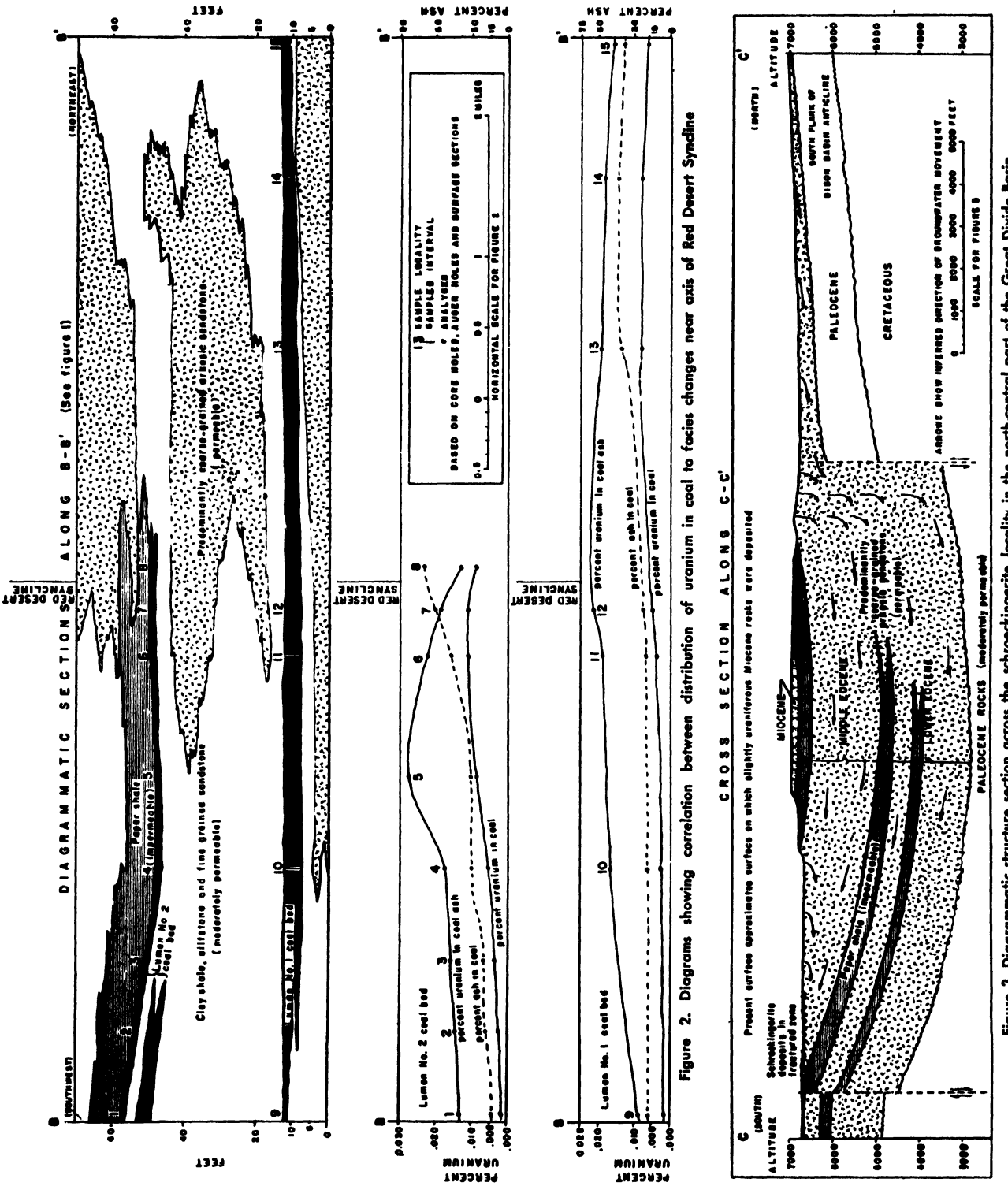


Figure 2. Diagrams showing correlation between distribution of uranium in coal to facies changes near axis of Red Desert Syncline

Figure 3. Diagrammatic structure section across the schroeckingerite locality in the north-central part of the Great Divide Basin

SCHROECKINGERITE DEPOSITS

In the southern part of T. 26 N, R. 94 W, caliche-like schroeckingerite deposits occur in alluvium and the upper several feet of the underlying bedrock.[13] The schroeckingerite deposits are on the southern border of the graben (Fig. 3). Only major stratigraphic units and structural features are shown in the figure and a structure section drawn nearly normal to section C–C′ (Fig. 3) would show that the eastward plunge of the syncline flattens northwest of the schroeckingerite deposits and then rises again to the east. Thus the ground water north of the schroeckingerite deposits presumably is under hydrostatic pressure from the west, north, and east. The stratigraphic and structural circumstances and the caliche-like nature of the schroeckingerite make it highly probable that the deposits were formed by the evaporation of uranium-charged ground water brought to the surface by a combination of artesian conditions and capillary action.

SOURCE OF THE URANIUM

The uranium in the coals and in the schroeckingerite could have come from a deep seated source, from granite-derived uranium minerals in the arkose, or from overlying uraniferous rocks. The writer believes that the evidence favors the last of these possibilities. Remnants of the weakly radioactive tuffaceous sandstone beds of the Browns Park formation crop out less than a mile from the schroeckingerite deposits, and at one time these tuffaceous rocks probably covered the entire Great Divide Basin. Chemical analyses of the tuffaceous beds in the Browns Park formation of the map area indicate that they contain 0.001 per cent uranium and 0.003 per cent equivalent uranium. The most probable source of uranium in the coal beds and schroeckingerite deposits in the central part of the Great Divide Basin was and is the weakly uraniferous tuffaceous sandstone beds of the Browns Park formation. The uranium contained in these tuffaceous rocks is subject to leaching and transport by ground water as indicated by the field relationships of the uranium-bearing coal to the closely overlying tuffaceous beds described by Denson, Bachman, and Zeller[14] and by Denson and Gill[15] for areas in the Dakotas and eastern Montana.

Transfer of the uranium from these source rocks directly downward was prevented throughout most of the coal-bearing area by intervening thick sequences of nearly impermeable beds of the Green River formation. Where the source rocks rested on the permeable Battle Spring formation, uranium-bearing water percolated downward and laterally for several miles in response to structural and permeability controls such as the Red Desert syncline and the described zone of facies changes. The coal beds nearest the permeable tongues of the Battle Spring formation accumulated higher concentrations of uranium than did the coal beds farther away. The process of leaching and transport of uranium from the Browns Park formation to its present sites of deposition presumably commenced as soon as that formation came into existence and probably reached a climax in the wet periods of the Pleistocene but continues at a greatly diminished rate today. The vast areas once underlain by the Browns Park formation are now represented by relatively small remnants and only in their near vicinity, as at the schroeckingerite locality, is the process of leaching, transport, and deposition of uranium noticeably operative.

REFERENCES

1. Smith, E. E., *The Eastern Part of the Great Divide Basin Coal Field, Wyoming,* US Geological Survey Bulletin 341 (See p. 220–242) (1909).
2. Slaughter, A. L. and Nelson, J. M., written communication.
3. Wyant, D. G., Sharp, W. N. and Sheridan, D. M., *Uranium deposits in the Red Desert of the Great Divide Basin, Sweetwater County, Wyoming,* US Geological Survey Bulletin, in preparation.
4. Masursky, Harold and Pipiringos, G. N., *Preliminary Report on Uranium-Bearing Coal in the Red Desert, Great Divide Basin, Sweetwater County, Wyoming,* US Geological Survey Bulletin, in preparation.
5. Gazin, C. L., written communication.
6. Bell, W. G., *Stratigraphy and Geologic History of Paleocene Rocks in the Vicinity of Bison Basin, Wyoming* (abstract), Bulletin of the Geological Society of America 65: 1371 (1954).
7. Bradley, W. H., *Shore Phases of the Green River Formation in Northern Sweetwater County, Wyoming,* US Geological Survey Professional Paper 140 (See p. 121–131) (1926).
8. Pipiringos, G. N., *Tertiary Rocks of the Central Part of the Great Divide Basin, Sweetwater County, Wyoming,* Guidebook 10th Annual Field Conference, Wyoming Geological Association, Casper, Wyoming (1955).
9. Morris, W. J., *An Eocene Fauna from the Cathedral Bluffs Tongue of the Washakie Basin, Wyoming,* Journal of Paleontology 28: 195–203 (1954).
10. Sheridan, D. M., written communication.
11. Bell, W. G., written communication.
12. McGrew, P. O., *Tertiary Stratigraphy and Paleontology of South Central Wyoming,* Guidebook 6th Annual Field Conference, Wyoming Geological Association, Casper, Wyoming (See p. 54–57) (1951).
13. Sheridan, D. M., Maxwell, C. H. and Collier, J. T., *Geology of the Lost Creek Schroeckingerite Deposits, Sweetwater County, Wyoming,* US Geological Survey Bulletin, in preparation.
14. Denson, N. M., *et al,* written communication.
15. Denson, N. M. and Gill, J. R., P/57, *Uranium-Bearing Lignite and its Relation to Volcanic Tuffs in Eastern Montana and the Dakotas,* Vol. 6, Session 6B, these Proceedings.

Uranium in Asphalt-Bearing Rocks

By W. J. Hail, Jr., A. T. Myers and C. A. Horr,* USA

Field investigations and laboratory research on uranium in asphalt-bearing rocks were carried on during 1953 and 1954 by the U. S. Geological Survey. Previous work by the Geological Survey[1] showed that the uranium content of the ash of natural asphalt and oil extracted from petroliferous rock is significantly high compared with crude oil, sea water, and granitic rock. This suggested that some of the numerous deposits of asphalt-bearing rocks of the western United States might contain appreciable amounts of uranium. The term "asphalt-bearing rocks" is here used to designate rocks that contain any type of naturally occurring petroleum residue. Selected deposits of asphalt-bearing rocks were examined, tested for radioactivity in the field, and sampled in 45 areas in 8 western states to evaluate this type of rock as a possible source for uranium (Fig. 1). Deposits in 24 geologic formations including rocks of Ordovician, Pennsylvanian, Permian, Triassic, Jurassic, Cretaceous, Paleocene, Eocene, Miocene, and Pliocene ages were sampled. Host rocks containing the asphalt include sandstone, conglomerate, arkose, tuff, limestone, and diatomite. Many of the asphalt-bearing rock deposits are large and have been quarried commercially for asphalt.

Laboratory research was directed toward perfecting analytical techniques and determining the nature of the occurrence of uranium in asphalt-bearing rocks. Chemical analyses for uranium of several selected samples of the asphalt and the extracted-rock residue showed that the uranium is concentrated as an organo-uranium complex in the asphaltic portion of the sample and not in the rock residue. Similar analyses by Erickson, Myers, and Horr[1] also showed that the uranium is concentrated in the oil and not in the rock residue. About 200 representative samples from the 45 areas were analyzed for uranium and oil content by the following analytical procedures. The samples of asphalt-bearing rocks were crushed, and the oil was exhaustively extracted with a hot mixture of 75 parts benzene, 15 parts acetone, and 10 parts methanol. This mixture is a modification of that used by Smith.[2] The extract was evaporated to reduce possible loss of ash by rapid burning of the benzene-acetone-methanol mixture, and then dry ashed with final ignition at 500° C under oxidizing conditions. The ash was ground in an agate mortar, weighed, and analyzed chemically for uranium. The chemical analysis for uranium is essentially the same as that described by Grimaldi and others[3] with a few modifications. The writers are indebted to Mary C. Curtis, who made the asphalt extractions.

* US Geological Survey.

SUMMARY OF RESULTS

The average concentrations of uranium in asphalt-bearing rocks in all of the 45 areas ranged from 0.001 to 0.376 per cent in the ash of the extracted oil (Table 1). Whether any of the asphalt deposits might provide a low-grade source for uranium probably depends upon recovery methods in the utilization of the asphalt for other purposes.

The ash of extracted oil from deposits in seven areas contained significant amounts of uranium. These areas, listed with the uranium content of their richest samples of ash, are: Chalone Creek (0.50 per cent U), McKittrick (0.15 per cent U), Edna (1.9 per cent U), and Los Alamos (0.33 per cent U) areas in California; Vernal area, Utah (0.15 per cent U); Sulphur area, Oklahoma (0.22 per cent U); and the Ellis area, Missouri (0.40 per cent U). The average uranium content of samples from these 7 areas ranges from 0.028 per cent in the Vernal area, to 0.376 per cent in the Edna area. All the deposits except those in the Chalone Creek area contain large estimated reserves of asphalt-bearing rock, ranging from about 15 million short tons to almost 2000 million short tons.

The average uranium content of samples from 13 other areas ranges from 0.020 to 0.068 per cent in the ash of the extracted oil. These areas are: Point Arena, Santa Cruz, San Lorenzo Creek, San Ardo, Bradley, Casmalia, and Goleta areas in California; Sunnyside area, Utah; Muddy Creek and Jameson Ranch areas in Wyoming; Santa Rosa area in New Mexico; and the Cameron and Lawton Township areas in Oklahoma. Reserves of asphalt-bearing rocks in these 13 areas range from a few thousand short tons to about 2800 million short tons.

Some of the uranium in the asphalt was probably an original constituent of the oil but some may have been introduced during the migration of the oil. The concentration of uranium in the asphalts appears to bear no consistent relationship to the age of the host rock nor to the age of the original oil. High concentrations of uranium were found in one or more samples of rocks representing all the geologic ages examined, ranging from Ordovician to Pliocene. Most of the California deposits, which are generally

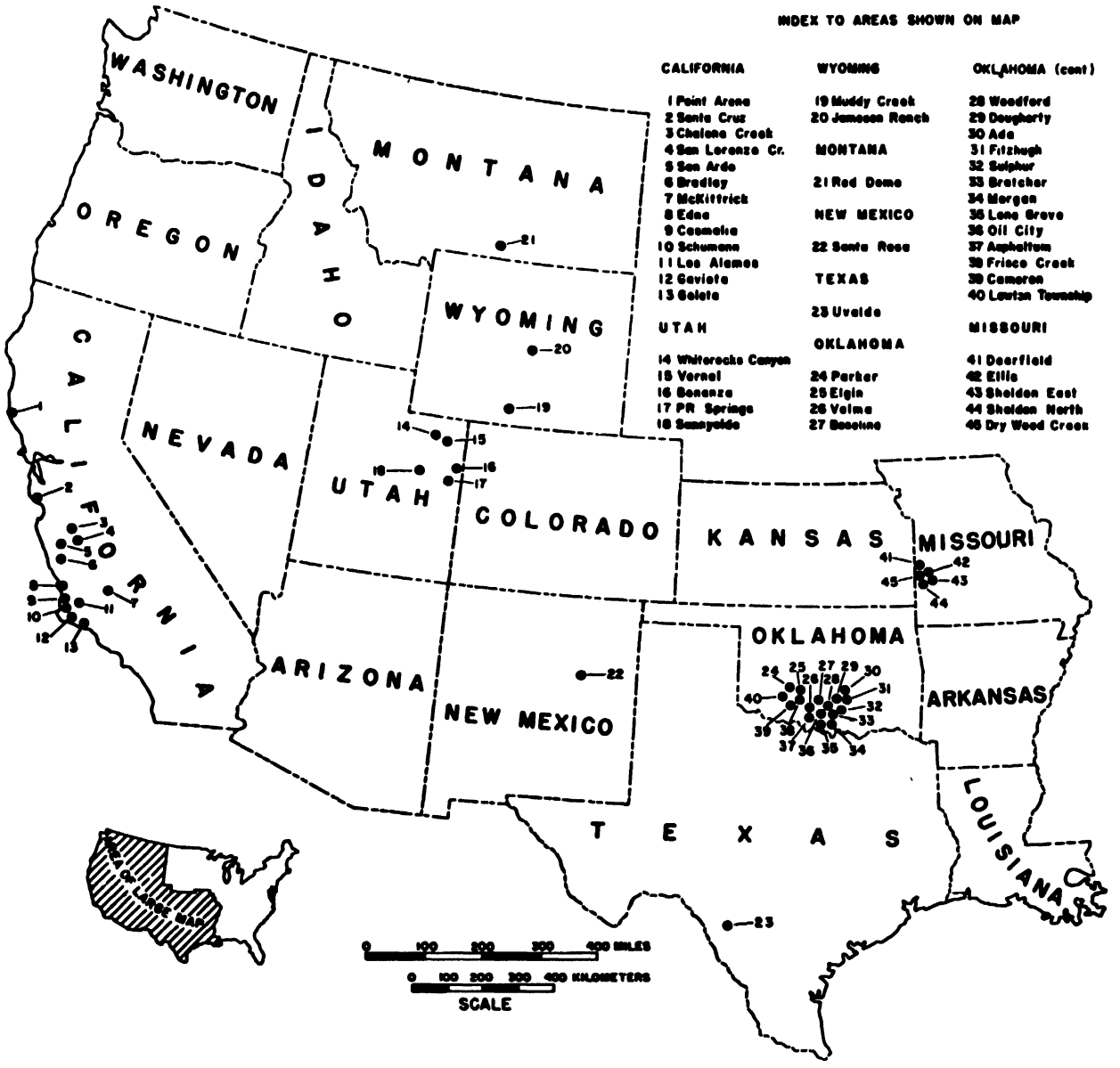


Figure 1. Map of Western United States showing areas examined for uranium in asphalt-bearing rocks

high in uranium, are Tertiary in age, whereas most of the Oklahoma deposits, which are generally low in uranium, are Paleozoic in age, but this difference is believed due not so much to the relative age of the deposits as to the geologic environment during the origin or migration of the oil. The high-uranium California asphalts, for example, occur in tuffaceous, arkosic, and diatomaceous rocks that are relatively high in uranium, wheras the low-uranium Oklahoma asphalts occur in quartzose sandstones, and limestones that are relatively low in uranium.

DESCRIPTIONS OF SELECTED DEPOSITS

The asphalt-bearing rocks in California appear to be more favorable for the occurrence of uranium than those examined in other western states. In 11 of the 13 California areas sampled, the average uranium in the ash of the extracted oil ranged from 0.023 per cent to 0.376 per cent. The California asphalts occur in formations of Miocene or Pliocene age, and it is possible that the asphalt in most of these formations originated in the Monterey shale, of Miocene age. The Monterey shale and most of the other formations in which the asphalt occurs contain abundant volcanic and granitic material. Typical rock types in these formations are arkosic sandstone and conglomerate, tuffaceous sandstone, diatomaceous sandstone and shale, organic siliceous shale, and chert. These rocks are relatively rich in uranium, and they may have supplied uranium to the asphalts at the time of their origin or during their migration into the present host rocks. Another factor favoring a higher concentration of uranium in the California asphalts is that California crude oils are generally heavy oils and uranium tends to be concentrated in the heavier, more asphaltic portions of petroleum.[1]

Table 1. Summary of Data from Areas Examined for Uranium in Asphalt-Bearing Rocks

Map no. (Fig. 1)	Area	Formation sampled	Age	No. of samples	Average oil in samples (per cent)	Average ash in oil (per cent)	Average U in ash (per cent)
	California						
1	Point Arena	Monterey shale	Miocene	6	4.13	0.80	0.030
2	Santa Cruz	Vaqueros sandstone	Miocene	8	10.34	.39	.027
3	Chalone Creek	Unnamed formation	Pliocene	3	11.18	.48	.182
4	San Lorenzo Creek	Unnamed formation	Pliocene	3	10.54	.23	.032
5	San Ardo	Santa Margarita formation	Miocene	2	6.24	.49	0.68
6	Bradley	Unnamed formation	Pliocene	1	10.49	.44	.045
7	McKittrick	Etchegoin and Tulare formations	Pliocene	5	26.91	1.66	.047
8	Edna	Pismo formation	Miocene and Pliocene	7	6.29	.56	.376
9	Casmalia	Sisquoc formation	Miocene and Pliocene	3	29.57	.19	.040
10	Schumann	Sisquoc formation	Miocene and Pliocene	1	17.88	.23	.009
11	Los Alamos	Careaga sandstone	Pliocene	7	12.40	.78	.081
12	Gaviota	Monterey shale	Miocene	1	23.32	1.04	.002
13	Goleta	Monterey shale	Miocene	2	18.94	2.05	.023
	Utah						
14	Whiterocks Canyon	Navajo sandstone	Jurassic and Jurassic (?)	4	5.59	.66	.009
15	Vernal	Uinta formation	Eocene	21	8.10	2.68	.028
16	Bonanza	Green River and Uinta formations	Eocene	7	100.00	.48	.003
17	PR Springs	Green River formation	Eocene	10	6.55	1.11	.014
18	Sunnyside	Green River formation	Eocene	11	5.38	1.10	.021
	Wyoming						
19	Muddy Creek	Fort Union formation	Paleocene	4	6.04	.36	.040
20	Jameson Ranch	Teapot sandstone member of the Mesaverde formation	Cretaceous	2	3.81	.59	.023
	Montana						
21	Red Dome	Chugwater formation	Triassic	5	4.91	.60	.010
	New Mexico						
22	Santa Rosa	Santa Rosa sandstone	Triassic	6	3.99	1.24	.025
	Texas						
23	Uvalde	Anacacho limestone	Cretaceous	11	8.52	.43	.002
	Oklahoma						
24	Parker	Wichita formation	Permian	1	2.16	1.62	.004
25	Elgin	Wichita formation	Permian	1	1.76	1.98	.006
26	Velma	Wichita formation	Permian	1	.94	1.68	.001
27	Baseline	Wichita formation	Permian	2	.98	2.85	.005
28	Woodford	Springer formation	Pennsylvanian	3	2.79	4.95	.010
29	Dougherty	Viola limestone	Ordovician	3	3.18	.07	.001
30	Ada	Ada formation	Pennsylvanian	4	3.29	1.95	.014
31	Fitzhugh	Ada formation	Pennsylvanian	2	1.35	2.00	.002
32	Sulphur	Oil Creek formation	Ordovician	7	4.56	.70	.043
33	Bratcher	Deese formation	Pennsylvanian	3	8.72	.59	.008
34	Morgan	Deese formation	Pennsylvanian	1	5.71	.76	.005
35	Lone Grove	Wichita formation	Permian	1	.87	3.31	.010
36	Oil City	Wichita formation	Permian	1	12.28	4.49	.002
37	Asphaltum	Wichita formation	Permian	5	6.15	1.60	.007
38	Frisco Creek	Wichita formation	Permian	2	2.08	10.39	.004
39	Cameron	Wichita formation	Permian	1	5.70	2.06	.054
40	Lawton Township	Wichita formation	Permian	1	1.19	3.14	.020
	Missouri						
41	Deerfield	Bartlesville sand	Pennsylvanian	7	4.63	.79	.006
42	Ellis	Bartlesville sand	Pennsylvanian	3	4.64	.62	.145
43	Sheldon East	Bartlesville sand	Pennsylvanian	4	3.99	1.46	.016
44	Sheldon North	Bartlesville sand	Pennsylvanian	3	1.43	1.27	.004
45	Dry Wood Creek	Bartlesville sand	Pennsylvanian	16	2.30	1.58	.004

The deposits of asphalt-bearing rock in the Edna area, San Luis Obispo County, contain the highest concentration of uranium of all the deposits examined in the western states. The uranium content of the seven samples collected in the Edna area ranges from 0.035 to 1.9 per cent in the ash of the extracted oil. The asphalt occurs in the Pismo formation of Miocene and Pliocene age, which unconformably overlies the Monterey shale of Miocene age. The Pismo formation consists of arkosic conglomerate and sandstone, siliceous shale, and chert. The Monterey shale in the Edna area consists of tuff, diatomaceous and siliceous shale, and chert. The asphalt occurs mostly in lenticular and discontinuous beds of arkosic sandstone, which range in thickness from a few feet to almost 300 feet.[4]

The uranium content of 7 samples collected in the Los Alamos area, Santa Barbara County, ranges from 0.010 to 0.330 per cent in the ash of the extracted oil. The asphalt occurs in the Careaga sandstone of Pliocene age, which, unlike most of the California asphalt-bearing rocks, is composed mainly of quartzose sandstone.[5] The Careaga sandstone is unconformably underlain by the Monterey shale, which consists of tuff, siliceous shale, and chert. In the Los Alamos area, the exposed asphalt-bearing beds have an aggregate thickness of about 225 feet and the intervening barren zones an aggregate thickness of about 35 feet. The asphalt-bearing beds extend for a distance of about 5 miles along their outcrop, and probably underlie an area of at least 5 square miles.

In Utah, all five of the asphalt-bearing areas sampled are in the Uinta Basin in the east-central part of the state. The deposits in the Vernal, Bonanza, PR Springs, and Sunnyside areas are in the Uinta or Green River formations of Eocene age and the deposits in the Whiterocks Canyon area are in the Navajo sandstone of Jurassic and Jurassic(?) age. The asphalt deposits in the Bonanza area are gilsonite, and the deposits in the other areas are asphalt-bearing sandstones.

The asphalt in the Vernal area, Uintah County, was the most uraniferous found in Utah. It occurs mainly in the Uinta formation of Eocene age,[6] in lenticular sandstone beds ranging in thickness from a few feet to 190 feet, within a section which may be as much as 300 feet thick. The uranium content of 21 samples collected in the Vernal area ranges from 0.001 to 0.150 per cent in the ash of the extracted oil. Ash of three of the samples contain more than 0.1 per cent uranium.

The Sunnyside area contains one of the largest asphalt-bearing sandstone deposits in the United States.[7] The uranium content of 11 samples collected in the Sunnyside area ranges from 0.003 to 0.048 per cent in the ash of the extracted oil. Samples collected from the other Utah deposits are generally low in uranium.

In Wyoming, lenticular beds of weathered asphalt-bearing sandstone in the Fort Union formation of Paleocene age crop out in the Muddy Creek area, Carbon County. The asphalt occurs throughout a section of sandstone about 100 feet thick, but the richest impregnation is in the lowest 15 feet and in a 5-foot-thick zone in the upper part of the section. The outcrop of the asphalt-bearing sandstone extends about 2 miles. The uranium content of 4 samples collected in the area ranges from 0.015 to 0.091 per cent in the ash of the extracted oil.

The only area examined in Montana was at Red Dome, Carbon County. In this area, asphalt-bearing sandstone in the Chugwater formation of Triassic age is exposed on the crest of a breached anticline.[8] The uranium content of the richest of 5 samples was 0.013 per cent in the ash of the extracted oil.

The asphalt of the Santa Rosa area in New Mexico occurs in the Santa Rosa sandstone of Triassic age. Exposures of the asphalt-bearing sandstone range from 4 to 18 feet in thickness, but core holes have penetrated a thickness of as much as 100 feet.[9] The uranium content of 6 samples collected in the area ranges from 0.002 to 0.052 per cent in the ash of the extracted oil.

In Texas, asphalt-bearing limestone in the Anacacho limestone of Cretaceous age crops out in Uvalde County.[9] The uranium content of the asphalt is exceptionally low, ranging in 11 samples from 0.001 to 0.004 per cent in the ash of the extracted oil.

The asphalt deposits examined in Oklahoma occur in formations of Ordovician, Pennsylvanian, and Permian age. One of the asphalt deposits occurs in limestone, the rest in quartzose sandstones. Most of the areas examined do not contain large amounts of uranium in the ash of the extracted oil. Asphalt-bearing limestone from the Dougherty area is exceptionally low in uranium.

The asphalt-bearing sandstone in the Sulphur area, Murray County, is the only large asphalt deposit in Oklahoma that yielded samples containing significantly large amounts of uranium. The uranium content of 7 samples collected in the Sulphur area ranges from 0.001 to 0.22 per cent in the ash of the extracted oil. The asphalt occurs in the Oil Creek formation of Ordovician age. Beds of the asphalt-bearing sandstone crop out in an area of about a square mile and range in thickness from about 6 to 90 feet, although a well is reported to have penetrated a thickness of more than 240 feet.[10]

The asphalt deposits in all five areas examined in Missouri occur in one or more lenticular sandstone beds in the Cherokee shale of Pennsylvanian age. This sandstone probably correlates with the Bartlesville sand of the midcontinent oil fields. It is mainly a fine-grained quartzose sand, containing mica.[11]

Three samples of asphalt-bearing sandstone collected in the Ellis area, Vernon County, contain uranium in amounts ranging from 0.011 to 0.40 per cent in the ash of the extracted oil. The asphalt-bearing sandstone is exposed in an abandoned quarry 160 feet wide and 265 feet long, and the thickness of the beds ranges from 15 to 30 feet. The asphalt-bearing beds probably extend over a much wider area under shallow cover.

REFERENCES

1. Erickson, R. L., Myers, A. T. and Horr, C. A., *Association of Uranium and Other Metals with Crude Oil, Asphalt, and Petroliferous Rock,* American Association of Petroleum Geologists Bulletin, 38: 2200–2218 (1954).
2. Smith, Paul V., Jr., *The Occurrence of Hydrocarbons in Recent Sediments from the Gulf of Mexico,* Science, 116: 437–439 (1952).
3. Grimaldi, F. S., May, Irving and Fletcher, M. H., *US Geological Survey Fluorimetric Methods of Uranium Analysis,* US Geological Survey Circular 199: 20 (1952).
4. Page, B. M., Williams, M. D., Henrickson, E. L., Holmes, C. N. and Mapel, W. J., *Geology of the Bituminous Sandstone deposits Near Edna, San Luis Obispo County, California,* US Geological Survey Oil and Gas Preliminary Map 27 (1944).
5. Eldridge, G. H., *The Asphalt and Bituminous Rock Deposits of the United States,* US Geological Survey, 22d Annual Report, 1900–1901: 209–452 (See p. 433) (1901).
6. Spieker, E. M., *Bituminous Sandstone Near Vernal, Utah,* US Geological Survey Bulletin 822–D: 77–100 (1930).
7. Holmes, C. N., Page, B. M. and Averitt, Paul, *Geology of the Bituminous Sandstone Deposits Near Sunnyside, Carbon County, Utah,* US Geological Survey Oil and Gas Preliminary Map 86 (1948).
8. Knappen, R. S. and Moulton, G. F., *Geology and Mineral Resources of Parts of Carbon, Big Horn, Yellowstone, and Stillwater Counties, Montana,* US Geological Survey Bulletin 822–A: 1–70 (1930).
9. Gorman, J. M. and Robeck, R. C., *Asphalt Deposits Near Uvalde, Texas,* US Geological Survey Open File Report (1945).
10. Gorman, J. M., *et al., Geologic Map of the Sulphur Asphalt Area, Murray County, Oklahoma,* US Geological Survey, Oil and Gas Preliminary Map 22 (1944).
11. Greene, F. C. and Pond, W. F., *The Geology of Vernon County,* Missouri Bureau of Geology and Mines, XIX, Second Series (See p. 45) (1926).

Radioactive Elements and their Daughter Products in the Texas Panhandle and Other Oil and Gas Fields in the United States

By A. P. Pierce, J. W. Mytton and G. B. Gott,* USA

Abnormal concentrations of radioelements and their daughter products, including radon, helium, argon, radium, uranium, and thorium have been found in some oil and gas fields in the United States. Helium in natural gas was discovered by Cady and McFarland in 1905[1] at Dexter, Kansas. Investigations by the U. S. Bureau of Mines[2] since that time have provided quantitative information regarding the distribution of helium in all natural gas fields and significant exploratory test wells in the United States.

Significant quantities of helium were first noted in the natural gas of the Panhandle Field of Texas in the early 1920's. In 1949, the Geological Survey found abnormal concentrations of radon in natural gas from flowing wells in the Panhandle Field. Intensive studies, particularly in the Texas Panhandle Field, have been made in recent years because of the possibility that appreciable amounts of the helium in these natural gases may have been derived from sources abnormally high in uranium or thorium. These have included studies of radium in oil well precipitates and brines, a survey of radon in the Panhandle and other gas fields, and a study of "asphaltite" (a carbonaceous mineraloid similar to thucolite) found in various places in the western United States, in an effort to determine the distribution and source of the radon, helium, and their parent elements in the gas reservoir.

URANIUM IN CRUDE OIL AND PETROLEUM ASHES

Analyses for uranium and other elements have been made of the ashes of a variety of crude oils, oil seeps, and extracts from petroliferous rocks from several western states.[3] These and additional analytical data show that petroleum ashes are generally enriched in uranium and an assemblage of other metals including arsenic, vanadium, nickel, cobalt, copper, lead, zinc and tin. The concentration of these elements in petroleum averages only a few parts per million, but their concentration in the ash relative to that of the common elements is unusual. The percentage ratio of uranium to the common rock-forming elements (calcium, sodium, silicon, magnesium, aluminum, potassium, strontium, barium, and titanium) in sedimentary rocks in which there is about 1 ppm uranium is 0.0002. The average in crude oil ashes from 26 different oil fields is 0.01; in ash of petroleum extracts from 24 different petroliferous rocks, 0.1; in crude oil ashes from 12 different oil wells in the West Panhandle Field, Texas, 0.1; and in 31 samples of oil field water from the West Panhandle Field, Texas, 0.00003.

The uranium and associated metals may be present in the petroleum as colloidal-sized impurities derived from the interstitial parts of the reservoir rocks, or they may be present as metallo-organic complexes soluble in the petroleum. If they occur as impurities, the concentration of uranium in the source material must be on the order of 0.01 to 0.1 per cent. If the metals occur as metallo-organic complexes, they probably are concentrated in a surface active fraction of petroleum which tends to adhere to the pore-walls of the reservoir rock. The increased uranium content in the ash of petroleum extracts compared to the uranium in the ash of crude oils suggests that the latter is the case.

ASPHALTITE

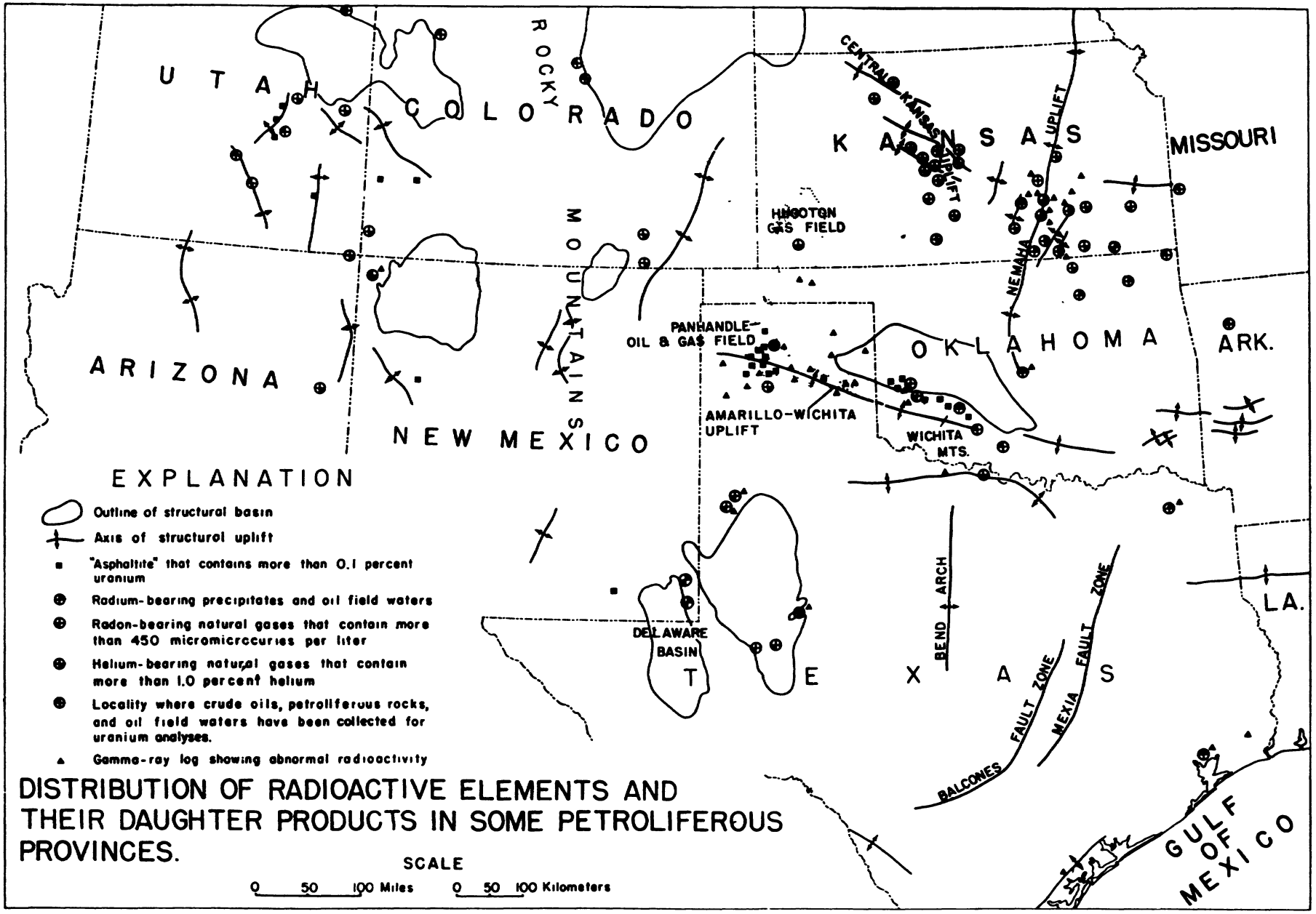
Uraniferous asphaltic materials, possibly derived from the surface-active fractions of petroleum, are widely distributed in oil and gas fields along the Amarillo-Wichita Uplift.

Concentrations of uranium in the form of epigenetic carbonaceous material termed asphaltite, have been found in drill cuttings of the oil and gas reservoirs and associated rocks in the Texas Panhandle Field, and also in numerous places in the western part of the United States including the north flank of the Wichita Mountains, Oklahoma; the northwest rim of the Delaware basin in southeastern New Mexico; and in southeastern Utah and southwestern Colorado.

The asphaltite occurs as botrayoidal nodules and as impregnations filling secondary pore spaces and fractures. The nodular asphaltite is a metalliferous carbonaceous mineraloid similar to thucolite, carburan, and huminite.[4] The asphaltite is a solid, brittle, highly lustrous, black substance that is essentially insoluble in organic reagents and is combustible at high temperatures. The hardness is between 4 and 5, the average specific gravity is 1.3, and the index of refraction is about 1.7.

The metal content of the asphaltite is consistently high, on the average about 3 per cent arsenic, 1 per cent uranium, and 0.1 per cent each of nickel, cobalt, and copper. Rare-earth elements of the yttrium group are always present in amounts as much as 0.1 per

* US Geological Survey.



DISTRIBUTION OF RADIOACTIVE ELEMENTS AND THEIR DAUGHTER PRODUCTS IN SOME PETROLIFEROUS PROVINCES.

Figure 1

cent. The iron content is erratic but generally appreciable. Silver is consistently present in amounts that range from a trace to as much as 0.03 per cent. The vanadium content is generally in the order of 0.01 per cent. Alpha tracks recorded on nuclear emulsion indicate that the uranium is rather evenly distributed throughout the asphaltite.

Polished sections of the asphaltite reveal numerous micron-sized metallic inclusions. These minerals are finely dispersed within the carbonaceous matrix generally in diffuse patterns concentric to the center of the asphaltite nodules. In some samples the fine crystals grade into larger crystals which possess euhedral boundaries and show definite evidence of having been fractured and floated apart in the asphaltite matrix prior to its solidification. Another feature relating to the micron-sized mineral dispersions is the occurrence of patches of fine mineral-filled pores that resemble the "fingerprint structure" of the thucolite of Boliden, Sweden, described by Grip and Odman.[5]

X-ray analyses of the asphaltite show the presence of uraninite, coffinite, thorite, chloanthite-smaltite, pyrite, dolomite, celestite, quartz, and submicrocrystalline carbon. Although uraninite and coffinite have been identified in some of the nodules, in most of them the uranium-bearing compound, which may be a metallo-organic complex, has not been identified. Other metallic minerals that are associated with asphaltite in the host rock are galena, sphalerite, chalcopyrite, and native copper. The principal organic elements in the asphaltite are carbon, hydrogen, oxygen, sulfur, and in some samples, a trace of nitrogen.

The botryoidal character of the nodules is evidently caused by an aggregation of numerous tiny pellets of asphaltite that appear to have been welded together into one rounded and knobby nodule. These nodules ordinarily are not more than 5 mm in diameter, but larger nodules probably are shattered and lost during drilling. Much of the veinlet type of asphaltite is composed of closely packed pellets. Similar features have been noticed in the "warty hydrocarbon granules" of the Witwatersrand, South Africa,[6] and in the "nodular thucolite" of Boliden, Sweden.[5]

The asphaltite in the Panhandle Field occurs in rocks of Pennsylvanian through lower Permian age which comprise the reservoir and cap rocks of the gas field. Most of the asphaltite is associated with secondary crystalline anhydrite and celestite that occur as cements in siltstones and as fillings in fractures and solution cavities in dolomites. Some of the nodules are completely occluded by secondary anhydrite crystals.

The evidence now available on the origin of the asphaltite indicates that the process responsible for its localization must have operated in the presence of petroleum or in a combination of petroleum and water, within the rock pores; been capable of concentrating uranium and the other metals in the form of disseminated point-segregates; operated independently of the type of rock in which concentration took place; and been effective over broad structural provinces.

RADIUM

Radium is concentrated in precipitates derived from brines in many oil fields in the central and southwestern United States. The precipitates are composed predominantly of strontium, barium, and calcium sulfates and small amounts of ferrous oxide in the form of celestite, barite, gypsum, and limonite. The radium in these precipitates is as much as 6×10^{-8} gm Ra/gm, depending on the amount of radium in the brines from which the precipitates were derived. The uranium content ranges from less than 1 part to 30 parts per million.

Radium in the brines that are associated with the precipitates is as much as 7.3×10^{-9} gm Ra/liter, and the uranium varies from zero to 200×10^{-6} gm U/liter. No correlation has been observed between the radium and uranium content of the brines that have been investigated. The brine having the highest radium concentration (7.3×10^{-9} gm Ra/liter) had only 1.3×10^{-6} gm U/liter, less than one-thousandth the amount of uranium required to "support" the radium. The radium-bearing precipitates have resulted from the co-precipitation of radium with barium and strontium because of changes in solubility during the process of pumping oil field brines. These precipitates also have resulted from the mixing of two waters, one rich in strontium and barium and the other in sulfate.[7,8]

Radiochemical analyses have shown that Ra^{226}, Ra^{223}, and Ra^{228} are present in the brines and precipitates. This has a bearing on the interesting problem of whether the radium was leached from rocks having normal or enriched amounts of its parent radioelements. The presence of Ra^{223} (half-life 11.2 days) indicates that the time required for leaching of radium by the brines is short, especially compared to the half-lives of Ra^{226} (1620 years) and Ra^{228} (6.7 years). The Ra^{226}/Ra^{228} ratio should therefore reflect the equivalent uranium/thorium ratio in the source rock. The equivalent uranium/thorium ratios based on measurements of radium isotopes in precipitates from three oil fields that have been investigated are 0.5, 1.0, and 5.0. The uranium/thorium ratio in common rocks is about 0.3. These ratios indicate that there is some enrichment of uranium or its long-lived daughter ionium relative to thorium in the source rock. Concentrations of ionium that were in excess of the equilibrium amount of ionium due to the uranium present have been found on the pore-walls of reservoir rocks in the Augusta and Panhandle fields.

The presence of high concentrations of radium and other radioelements in many oil fields indicates that extensive migrations of aqueous and organic solutions throughout effectively permeable sedimentary rocks have resulted in the redistribution and concentration or uranium within the interstices of the rocks where its daughter products are readily accessible to the same solutions and associated gases.

RADON

In addition to the radium, radioactivity anomalies had been observed on gamma-ray logs of wells in the vicinity of helium-bearing gas wells. These suggested possible correlation between radon and helium in the natural gases. In order to test this possibility a detailed survey was made of Rn^{222} in gas wells of the West Panhandle Field, Texas,[9] and in the gases of 66 other natural gas fields in central and southwestern United States.

The average radon content of the gases from all fields tested was 460 $\mu\mu$c Rn/liter (Reservoir Temperature and Pressure), while the most frequent radon concentration measured was about 200 $\mu\mu$c Rn/liter STP. In forty-two of sixty-six gas fields tested gases contained as much as 200–400 $\mu\mu$c Rn/liter (STP). In eleven other fields the radon concentrations were greater than 1000 $\mu\mu$c Rn/liter (STP), and in the Panhandle, Pegasus, and Elk City fields gases contained as much as 8000–10,000 $\mu\mu$c Rn/liter (STP). In comparison, the average radon content of most soil gases is 200–400 $\mu\mu$c Rn/liter (STP),[10] and the average radon content in the open pore spaces of a rock with 1 ppm uranium, 5 per cent emanating power, and 10 per cent porosity is about 400 $\mu\mu$c/liter (STP).

No direct correlation was found between the radon and helium contents among the gases tested. However, the highest radon concentrations in the helium-bearing gases of the Panhandle Field coincide with occurrences of uraniferous asphaltite in the reservoir rock.

Many of the gases tested had radon contents of less than 100 $\mu\mu$c/liter. These subnormal values are believed to have resulted from the absorption of radon by petroleum in the pore-spaces of the gas-producing rocks. This, and other effects, make it difficult to interpret radon data without detailed information upon the nature of the gas reservoir and the behavior of radon in it. Though some of the gas fields contain high amounts of radon in their natural gases, the absence of high radon concentrations in natural gases of a field cannot be interpreted to mean that the reservoir is not abnormally radio-active.

HELIUM AND OTHER GASES

The major helium-bearing gas fields of the United States occur in the Central Kansas, Bend Arch, Amarillo-Wichita, and Nemaha uplifts, and on parts of the Colorado Plateau. Structurally these fields are located on uplifts marginal to large sedimentary basins, and the gases are produced from formations that extend with little change into the adjacent basins. The association of helium with accumulations of petroleum and natural gas suggests that an important part of the helium may have been derived from the petroleum source-rocks and the rocks through which the petroleum migrated. Furthermore, the presence of epigenetic uranium-bearing asphaltite, radium-bearing brines, and gamma-ray anomalies in these rocks indicates that migration of petroleum and associated waters through them has resulted in redistribution and concentration of uranium, thereby creating a favorable condition for accumulation of large quantities of helium in the natural gas traps.

An analysis of data published by the US Bureau of Mines[2] shows that the helium content of natural hydrocarbon gases increases with the age of the gas-producing reservoir. A summary of these data is shown below. The results indicate that the major part of the helium has accumulated in the gas fields subsequent to migration and accumulation of the major part of the associated hydrocarbons.

The US Bureau of Mines data also show that there is a parallel enrichment of nitrogen with helium. The mean ratio of nitrogen to helium is 30 with a standard deviation of ± 10. Virtually none of the gases analyzed had N/He ratios of less than 6; many of the gases sampled from shallow wells have excessively high proportions of nitrogen, probably the result of atmospheric contamination. Somewhat higher N/He ratios are found in solution gases produced from petroleum compared to dry natural gases.

Hydrogen, which many experiments[11,12] have shown to be the major reaction product of the irradiation of organic materials, is present among the gases of the Panhandle Field. The hydrogen is about one-twentieth as abundant as the helium.[13]

The average ratio of He^3 to He^4 in the Panhandle Field is about 1.5×10^{-7} compared to an average of 1.7×10^{-7} for the helium in all the natural gases that have been investigated,[14] a calculated ratio of 2×10^{-7} for helium originating from nuclear reactions in rocks of the composition of the earth's crust,[15] and a ratio of 12×10^{-7} in helium in the atmosphere.

Argon is also present in the gases of the Panhandle Field.[16] The ratio of helium to argon is approximately 10, which is close to the calculated ratio of He^4 and A^{40} resulting from decay of the amounts of uranium, thorium, and potassium-40 present in the rocks of the composition of the earth's crust. This ratio has been calculated as between 8 and 12, depending on the value that is assumed for the branching ratio of potassium-40.

The close agreement between the measured and calculated amounts of argon, helium-3, and helium-4 that should be present in rocks indicates that the major part of the helium in the gases of the Panhandle Field is of radiogenic origin.

Studies on the quantitative distribution of asphal-

Age of reservoir rock	*Number of gas fields*	*Per cent of gas fields having indicated per cent helium*				
		(per cent) <0.001	*(per cent) 0.001–0.01*	*(per cent) 0.01–0.1*	*(per cent) 0.1–1.0*	*(per cent) 1.0–10.0*
Tertiary	178	45	38	15	2	0
Mesozoic	183	12	16	51	19	2
Paleozoic	609	1	4	23	61	11

tite in the Panhandle Field have indicated that the helium contained in the gases of one of the smaller gas reservoirs can be entirely accounted for by the decay of the uranium present in the asphaltites of the gas-producing rocks.

CONCLUSIONS

Uranium has been redistributed and concentrated within the interstices of rocks through which petroleum has migrated or in which it has accumulated. The concentration and redistribution of uranium has been associated in time with structural and diagenetic events including recrystallization, solution, cementation, and adsorption of metalliferous surface-active fractions of migrating petroleum. The result has been to make uranium and its daughter products easily accessible to fluids and gases.

It is believed that a large part of the helium present in natural gases may have been derived from the radioelements that have been distributed in this manner. More information about the geochemistry of uranium in petroleum and petroleum waters, however, is necessary to a complete understanding of the genesis of the helium and the associated uraniferous asphaltites.

REFERENCES

1. Cady, H. P. and McFarland, D. F., *On the occurrence of helium in natural gas,* Proceedings American Chemical Society, Minutes 33rd General Meeting (1906).
2. Anderson, C. C. and Hinson, H. H., *Helium-bearing natural gases of the United States,* US Bureau of Mines Bulletin 486 (1951).
3. Erickson, R. L., Meyers, A. T. and Horr, C. A., *Association of uranium and other metals with crude oil, asphalt, and petroliferous rock,* Bulletin American Association Petroleum Geologists, v. 38, no. 10, p. 2200–2218 (1954).
4. Davidson, C. F. and Bowie, S. H. U., *On thucolite and related hydrocarbon-uraninite complexes,* Bulletin Geological Survey of Great Britain, no. 3, p. 1–19 (1951).
5. Grip, E. and Odman, O. H., *On thucolite and natural gas from Boliden,* Arsbok Sveriges Geological Undersok, v. 38, no. 6, Stockholm (1944).
6. Young, R. B., *The Banket,* London (1917).
7. Vernadsky, W. and Khlopin, V. G., *Radium investigations of oil fields of the USSR,* Doklady Akademii Nauk, SSSR (1932).
8. Gott, G. B. and Hill, J. W., *Radioactivity in some oil fields of Southeastern Kansas,* US Geological Survey Bulletin 988–E (1953).
9. Faul, H. *et al., Radon and helium in natural gas,* Comptes Rendue 19e Congrès Géologique International, Alger, Section 9, p. 339–348 (1954).
10. Botset, H. G., *Radon content of soil gas,* Physics, v. 2, p. 376–385 (1932).
11. Lind, S. C., *Chemical effects of alpha particles and electrons,* Chemical Catalog Company, New York (1928).
12. Sheppard, C. W. and Whitehead, W. L., *Formation of hydrocarbons from fatty acids by alpha particle bombardment,* Bulletin American Association Petroleum Geologists, v. 30, p. 32–51 (1946).
13. Brewer, A. K. and Dibeler, V. H., *Mass spectrometric analysis of hydrocarbon and gas mixtures,* Journal of Research, US Bureau of Standards, v. 35, p. 125–139 (1945).
14. Aldrich, L. T. and Nier, A. O., *The occurrence of helium-3 in natural sources of helium,* The Physical Review, v. 74, p. 1590–1594 (1948).
15. Morrison, P. and Beard, D. B., *Helium-3 and the origin of terrestrial helium,* The Physical Review, v. 75, p. 1332–1333 (1949).
16. Faul, H., *Nuclear Geology,* John Wiley and Sons, New York and Chapman and Hall, Ltd., London, chapter 4, section 4.1a, p. 135 (1954).

Uranium in Phosphate Rock

By V. E. McKelvey,* USA

Uranium and phosphate are associated in many different kinds of deposits and minerals. About one-sixth of the ninety-odd minerals[1] in which uranium is one of the major, essential constituents are phosphates; uranium occurs also as a frequent minor constituent of xenotime (YPO_4), monazite ((Ca, La, Th) Po_4), crandallite ($CaAl_3(PO_4)_2(OH)_5 H_2O$) and apatite ($Ca_5(PO_4)_3(F, Cl, OH)$). Because of their greater abundance, the latter two minerals are the chief source of phosphate and, potentially, the greatest source of uranium from the uraniferous phosphates. The phosphate minerals in which uranium is a major essential constituent occur mainly as secondary minerals formed during the weathering of ore deposits. Locally they provide clues to the presence of uranium ores, and two uranium phosphates, autunite and torbernite, are the dominant minerals in a few uranium ores. As a group, however, the uranium phosphates are quantitatively unimportant as carriers of uranium in either an economic or a geochemical sense. Monazite and xenotime are widespread accessory minerals in silicic igneous rocks, pegmatites, and migmatites, and are locally concentrated in placers. They are the chief sources of rare earths, and monazite is at present the chief source of thorium. Some uranium may be recovered from monazite and xenotime as a byproduct, but these minerals are not as important potential sources of uranium as are the apatite and crandallite deposits. This review of uranium in phosphates therefore will be concerned chiefly with the distribution of uranium in deposits valued primarily for their phosphate content.

MINERALOGY

The principal minerals in the commercially valuable phosphate deposits are calcium phosphates, mainly those of the apatite group, and aluminum phosphates, chiefly crandallite and wavellite ($Al_3(OH_3 (PO_4)_2 \cdot 5H_2O$). The structural complexity of apatite favors many isomorphous substitutions. Thus, small amounts of VO_4, AsO_4 SiO_4, SO_4, and CO_3 or CO_4 may substitute for PO_4. The fluorine position is generally occupied by fluorine, forming fluorapatite, but may also be occupied by Cl (chlorapatite) or OH (hydroxy-apatite). Fluorapatite and hydroxyapatite may be CO_3-bearing; these varieties are called carbonate-hydroxyapatite and carbonate-fluorapatite. These anionic substitutions for PO_4 are electrostatically compensated by cationic substitutions of Mg, Mn, Sr, Pb, Na, U, or rare earths.[2,3,4] In crandallite, Ba, Sr, rare earths, and U may substitute for Ca, and OH for PO_4 (Ref. 4, p. 834); in wavellite, F may substitute to a small extent for OH; Fe^{+3}, Cr^{+3}, Ga, and perhaps Ca and Mg for Al; and SiO_4 for PO_4.[2,4]

From this account it may be seen that uranium in the phosphate deposits occurs mainly in apatite or crandallite. The uranium is in acid-soluble form, is tetravalent, and is believed to isomorphously substitute for calcium.[5] Although uranium has been reported in wavellite deposits,[6] and in other aluminum phosphates, notably turquoise,[6] evansite, and fischerite (Ref. 1, p. 206), Altschuler[7] considers it probable that the uranium associated with aluminum phosphates in Florida is in crandallite rather than wavellite. Moreover, several specimens of pure turquoise analyzed by Davidson and Atkin[6] contain 0.002 per cent eU (equivalent uranium) or less. In view of these observations, as well as the improbability of the substitution of the large uranium ion for the much smaller aluminum ion, the occurrence of uranium in the aluminum phosphate minerals seems doubtful.

TYPES OF PHOSPHATE DEPOSITS

Phosphate in minable quantities is concentrated by igneous, sedimentary, weathering, and biologic processes and hence is found in a wide variety of deposits.[2] Chief among these are igneous apatites, marine phosphorites, residual phosphorites, river pebble deposits, phosphatized rocks, guano, and fossil bone. Only the main features of these deposits that may aid in the search for or appraisal of uraniferous phosphates are described here. The reader is referred elsewhere for a fuller account of their characteristics[2] and for information on the uranium content of individual deposits.[8]

Apatite of igneous origin is found as an accessory mineral in many igneous rocks, and it is concentrated in deposits of minable size in certain intrusives associated with alkalic igneous rocks, like those of the Kola Peninsula (USSR); in pegmatites; in hydrothermal veins or disseminated replacements; and in marginal differentiations along or near the boundaries of instrusions. The apatite in most of these deposits is fluorapatite. It may contain as much as several per cent rare earths[8] (Ref. 4, p. 883), but it rarely

* US Geological Survey, Menlo Park, Calif.

contains more than 0.005 per cent U.[5,9] A recently discovered exception is apatite from a magnetite ore body in New York; 14 samples of this apatite average 0.032 per cent U, 0.15 per cent Th, and 11.14 per cent rare earth oxides.[8] Some of the igneous apatite deposits contain enormous reserves of phosphate, but they are not promising sources of uranium, compared to the marine phosphorites. Because much of the uranium in igneous rocks is concentrated in apatite, however, it is probable that much of the uranium in the earth's crust is present in this mineral.

Most of the world's production of phosphate comes from marine phosphorites. They generally contain 0.005 to 0.03 per cent uranium, and most high-grade deposits (ie., those containing more than 30 per cent P_2O_5) contain more than 0.01 per cent. Despite their low uranium content as compared to other ores, they are a promising source of uranium as a by-product of the manufacture of triple-superphosphate.[10]

The marine phosphorites are composed mainly of carbonate-fluorapatite[11] in the form of fine crystals (unaggregated), structureless pellets, oolites, pisolites, nodules (either structureless or composed of one or more of the other types of grains), and fossil remains, including those originally phosphatic, such as fish scales, teeth, and linguloid brachiopod shells, and those that were originally calcareous and have since been phosphatized. These various types of grains may be present in the same beds but one or two types generally predominate in a given layer. Other constituents associated with the carbonate-fluorapatite are quartz, chert, hydromica, and other silicates, carbonaceous matter, carbonates, and glauconite. The phosphorite formations as a group are thin compared to the period of geologic time required for their accumulation; they form only in the absence of significant deposition of clastics or carbonates.

Despite the similarities in the phosphorites, there are some systematic differences. As a rule, the most phosphatic deposits, in terms of total phosphate in the section as well as thickness of high-grade beds, are fine grained, pelletal or oolitic; they are associated in vertical sections with carbonaceous mudstones and cherts. The thinner, less phosphatic deposits are coarse grained and bioclastic in many places; they contain appreciable quantities of carbonate, quartz sand, glauconite and carbonaceous matter and are associated in vertical sections with rocks composed largely of these constituents.[12] Many of these assemblages are lateral equivalents. Because the deposits of the first assemblage are generally present in geosynclines (recognizable not only by their thicker sections but by complexity of structure) and the second is typically developed on cratons or platforms, Kasokov[13] termed them geosynclinal and platform facies, respectively. Neither is a polar type in a strict sense; vertical sections include some petrographic types common to both the geosynclinal and platform facies but the assemblages are nevertheless contrasting in the aggregate.

The uranium content of phosphorites in both geosynclinal and platform facies is variable but is generally higher in the geosynclinal facies, in part because the uranium content of phosphorites increases roughly with increasing phosphate content—as geosynclinal phosphorites are more phosphatic than platform types, they are bound to be more uraniferous. In addition, phosphorites in the geosynclinal facies of the Phosphoria formation are more uraniferous than those of equivalent phosphate content on the platform. An exception to this rule is found in moderately or highly uraniferous phosphatic nodules in Pennsylvanian black shales in Kansas and Oklahoma.[14,15] Not all such nodules are appreciably uraniferous, however; for example, those at the top of the Devonian and Mississippian Chattanooga shale in Tennessee contain less than 0.005 per cent U.

In addition to the gross differences in the uranium content of the phosphorites of the geosynclinal and platform facies, variations in the uranium content of phosphorites in the Phosphoria formation have been related to specific textural and chemical properties. These are discussed more fully in a companion paper[16] and it will suffice to say here that uranium appears to be lower in bioclastic than in pellet phosphorites, in weathered than in fresh rocks, and in rocks that contain less than 3 or 4 per cent P_2O_5.

The uranium in marine phosphorites is believed to be derived from sea water or later percolating solutions.[15] Its removal from these source solutions and its emplacement in carbonate-fluorapatite is hindered by the abundance of calcium, carbonate, and hydroxyl ions,[17] but it is influenced also by the length of time the phosphate grains are exposed to the source solutions, by the uranium content of the source solutions, by the size of the phosphate grains, and by the permeability of the phosphatic beds. These relationships may explain the lower uranium content of the more calcareous phosphorites and the bioclastic phosphorites (which are commonly rather dense) as well as some of the variations in the uranium content of otherwise similar phosphorites.

Apatite is a more resistant mineral to weathering than carbonates, carbonaceous matter, and other minerals with which it is commonly associated. Weathering, therefore, generally leads to the enrichment of P_2O_5, even in a high-grade phosphorite; and it may lead to the formation of a minable phosphate deposit from a phosphatic limestone, too weakly phosphatic to be workable in its unweathered state. More prolonged weathering of phosphorites, or of residues derived from phosphatic carbonate rocks, may partially destroy the apatite and some silicates and form crandallite, wavellite, or other aluminum phosphates.

The phosphatic limestone residues, of which the brown-rock deposits of Tennessee[18] are examples, are composed of phosphatic particles of the same texture as those in the source rock, in a matrix of sand and clay. They often lie on a highly irregular, deeply etched limestone surface. The phosphate minerals in these deposits are of the same type as those

found in the parent deposits—generally carbonate-fluorapatite—though soluble impurities may have been leached out. The uranium content of these deposits is generally less than 0.005 per cent, partly because phosphatic particles in carbonatic rocks, which are the source for such residues, are generally weakly uraniferous, and partly because some uranium is differentially leached from carbonate-fluorapatite during weathering.

The aluminum phosphate deposits, of which those in Florida,[19] Senegal,[20,21] and Nigeria,[6] are examples, consist of crandallite, wavellite or other aluminum-bearing phosphate minerals, kaolin, quartz sand, and perhaps some relatively unweathered remnants of the unaltered minerals of the original deposits. The rock may be firm and vesicular, or soft and clayey; in either case, most of the phosphate is clay sized and is separable from the sand by washing. The uranium content of aluminum phosphate deposits derived directly from phosphatic limestones is negligible. In deposits derived from high-grade phosphorites the uranium content is generally in the range of 0.01 to 0.03 per cent, but it may be much higher locally.

Weathered phosphates may contain secondary uranium minerals. Tyuyamunite has been found in weathered deposits in the Phosphoria formation, tyuyamunite or ferghanite in the phosphates of Morocco,[22] and autunite in the Florida deposits.[23] None of these occurrences, however, is of more than academic interest.

RIVER PEBBLE DEPOSITS

Detrital phosphates derived from the erosion of phosphatic residues have been mined from fluvial deposits in both Florida and South Carolina.[2] These deposits, called river pebble, are essentially apatite placers. The deposits in Florida and South Carolina seem to contain less phosphate than those in the formations from which they are derived, presumably as the result of leaching in the stream. Their uranium content has not been tested but, judging from the phosphate content, is probably low.

GUANO

Guano deposits, formed from the accumulation of sea-fowl and bat droppings, are rich in nitrogenous materials and phosphates. Their mineralogy is complex; slightly decomposed deposits consist of soluble ammonium and alkali oxalates, sulfates, and nitrates, and a variety of magnesium phosphates and ammonium-magnesium phosphates. Largely decomposed guano consists essentially of calcium phosphates. Guanos tested by both US Geological Survey and Davidson and Atkin[6] contain only negligible amounts of uranium.

PHOSPHATIZED ROCK

Some of the phosphate leached during the weathering of phosphorites or in the decomposition of guano is reprecipitated after traveling only a short distance, particularly if the phosphatic solutions encounter aluminous or iron-bearing rock in a different chemical environment. These deposits, of which the white-rock deposits of Tennessee[18] and some of the insular deposits[24] are examples, consist of encrustations on joint surfaces or in cavities or of irregular replacements of bedrock or residual boulders. The minerals formed reflect the composition of the host rock, and thus range from iron and aluminum phosphate minerals to calcium phosphates. As far as known, none of these deposits contain significant amounts of uranium.

FOSSIL BONE

Bone consists mainly of nonuraniferous carbonate-apatite at the time of its formation, but fossil bones show an increasing content of both fluorine[25] and uranium[26] with increasing age. The uranium content of fossil bone associated with phosphorite deposits is of the same order of magnitude as that of the phosphorites themselves—0.005 to 0.03 per cent—but isolated specimens in pervious rocks may contain much more. The maximum uranium content in bone that does not contain a discrete uranium mineral is 0.55 per cent (eU), reported by Davidson and Atkin[6] from the Old Red Sandstone, but on the Colorado Plateau and elsewhere fossil bone is commonly replaced, either partly or completely, by uranium minerals.

Fossil bone piles have been mined in the past as a source of phosphate, but known reserves are too small to be of significance now. For this reason, fossil bone is not likely to be an important source of uranium, except as it is a constituent of marine phosphorites, but it is of scientific interest in showing that apatite acquires uranium from percolating solutions.

CONCLUSIONS

Although the uranium content of phosphatic rocks varies widely, some criteria may be listed as helpful in appraising the potential of unsampled deposits. No known guanos, no phosphatic limestones or residual deposits derived directly from them, no phosphatized rocks, and few igneous apatite deposits contain as much as 0.01 per cent U. As a rule, the high-grade marine phosphorites and residual deposits derived from them contain 0.01 per cent U or more. Their uranium content is variable but generally increases with increasing phosphate content, judged not only by the phosphate content of individual beds but by the phosphate content of the section as a whole. Amongst less phosphatic deposits, most, but not all of those consisting of phosphatic nodules in black shale contain more than 0.01 per cent U. Phosphates in sand or other unconsolidated materials amenable to mechanical separation are unlikely to yield a concentrate containing as much as 0.01 per cent U if the matrix is highly calcareous or if the phosphatic particles themselves contain less than 25 per cent P_2O_5. Residual deposits reworked by marine waters may also contain uranium. Thus the phosphorite particles in the Miocene Hawthorn limestone in Florida contain 0.005 to 0.008 per cent U, but those in the over-

lying Pliocene Bone Valley formation, derived in large part from marine reworked Hawthorn residuum, contain 0.01 to 0.02 per cent U.

Though these and other generalizations that may be made concerning the uranium content of phosphorites hold good for most known deposits, the fact that uranium can be emplaced or displaced from the structure of apatite and perhaps other phosphate minerals introduces a large element of uncertainty in any predictions concerning the uranium content of unsampled deposits, particularly those whose geologic history is also unknown.

REFERENCES

1. Frondel, J. W. and Fleischer, M., *Glossary of Uranium- and Thorium-bearing Minerals,* US Geological Survey Bulletin 1009–F (1955).
2. McKelvey, V. E., Cathcart, J. B., Altschuler, Z. S., Swanson, R. W. and Buck K. L., *Domestic Phosphate Deposits,* in Pierre, W. H. and Norman, A. G., Soil and Fertilizer Phosphorus, Agronomy IV, Academic Press, Inc., 11: 347–372, New York (1953).
3. McConnell, D., *Radioactivity of Phosphatic Sediments,* Economic Geology 48: 147–148 (1953).
4. Palache, C., Berman, H. and Frondel, C., *Dana's System of Mineralogy,* John Wiley & Sons, Inc., 2, New York (1951).
5. Altschuler, Z. S., Clarke, R. S., Jr. and Young, E. J., *Uranium in Apatite,* (abstract) Geological Society of America Bulletin 65: 1225 (1954).
6. Davidson, C. F. and Atkin, D., *On the Occurrence of Uranium in Phosphate Rock,* 19th International Geological Congress Compte Rendu 11: 13–31, Algiers (1953).
7. Altschuler, Z. S., oral communication.
8. McKeown, F. A. and Klemic, H., *Rare-earth-bearing Apatite at Mineville, Essex County, New York,* US Geological Survey Bulletin, in press.
9. Larsen, E. S., Jr. and Phair, George, *The Distribution of Uranium in Thorium and Igneous Rocks,* in Faul, H., Nuclear Geology, John Wiley & Sons, Inc., 75–89, New York (1954).
10. Ruch, J. W., *Status of Uranium Recovery from Low-grade Sources,* Mines Magazine 44: no. 3, 105 (1954).
11. Altschuler, Z. S., Cisney, E. A. and Barlow, I. H., *X-ray Evidence of the Nature of Carbonate-apatite,* 19th International Geological Congress Compte Rendu 11: 9, Algiers (1953).
12. McKelvey, V. E., Swanson, R. W. and Sheldon, R. P., *The Permian Phosphorite Deposits of Western United States,* 19th International Geological Congress Compte Rendu 11: 45–64, Algiers (1953).
13. Kazakov, A. V., *The Phosphorite Facies and the Genesis of Phosphorites,* in Geological Investigations of Agricultural Ores, Scientific Institute of Fertilizers and Insecto-Fungicides Transactions (published for the 17th International Geological Congress) 142: 8–21, Leningrad (1937).
14. Runnels, R. T., Schleicher, J. A. and Van Nortwick, H. S., *Composition of Some Uranium-bearing Phosphate Nodules from Kansas Shales,* Kansas Geological Survey Bulletin 102: 93–104 (1953).
15. McKelvey, V. E. and Nelson, J. M., *The Characteristics of Marine Uranium-bearing Sedimentary Rocks,* Economic Geology 45: 35–53 (1950).
16. McKelvey, V. E. and Carswell, L. D., P/291, *Uranium in the Phosphoria Formation,* Vol. 6, Session 6B, these Proceedings.
17. Neuman, W. F., Neuman, M. W., Main, E. R. and Mulryan, B. J., *The Deposition of Uranium in Bone, VI, Ion Competition Studies,* Journal of Biological Chemistry 179: 341–348 (1949).
18. Smith, R. W. and Whitlatch, G. I., *The Phosphate Resources of Tennessee,* Tennessee Department of Conservation Division Geological Bulletin 48 (1940).
19. Cathcart, J. B., Blade, L. V., Davidson, D. F. and Ketner, K. B., *The Geology of the Florida Land-pebble Phosphate Deposits* 19th International Geological Congress Compte Rendu 11: 77–91, Algiers (1953).
20. Guntz, A. A. and Arene, M., *Sur la présence de l'uranium dans les phosphates Africains,* 19th International Geological Congress Compte Rendu 11: 11, Algiers (1953).
21. Capdecomme, L., *Etude minéralogique des gites de phosphates alumineux de la région de Thiès (Sénégal),* 19th International Geological Congress Compte Rendu 11: 103–118, Algiers (1953).
22. Arambourg, C. and Orcel, J., *Observations préliminaires sur la présence d'un vanadate d'urane dans les gisements de phosphates du Maroc,* Académie des Sciences Compte Rendu 233: 1635, Paris (1951).
23. Altschuler, Z. S. and Boudreau, written communication.
24. Rodgers, J., *Phosphate Deposits of Former Japanese Islands in the Pacific; a Reconnaisance Report,* Economic Geology 43: 400–407 (1948).
25. Oakley, K. P., *Relative Dating of the Piltdown Skull,* Advancement of Science 6: 24 (1950).
26. Jaffe, E. B. and Sherwood, A. M., *Physical and Chemical Comparison of Modern and Fossil Tooth and Bone Material,* US Geological Survey TEM–149, US Atomic Energy Commission, Technical Information Service, Oak Ridge, Tennessee (1951).

Uranium in the Phosphoria Formation

By V. E. McKelvey and L. D. Carswell,* USA

The Permian Phosphoria formation and its close stratigraphic correlatives contain marine phosphorite beds over an area of about 135,000 square miles in Montana, Idaho, Wyoming, Utah and Nevada. The phosphorites contain 0.005 to 0.03 per cent uranium[1] and locally, in very thin layers, as much as 0.06 per cent U.[2] The occurrence of uranium in these rocks will be described in the following pages, but we will preface this description with a brief account of the stratigraphy of the Phosphoria rocks and the distribution of the phosphorites themselves.

STRATIGRAPHY

The Phosphoria formation ranges from about 200 to 1500 feet in thickness. It consists of two overlapping couplets, each composed of a carbonaceous, phosphatic shale member overlain by a chert member. The lower couplet is thickest (400 to 1300 feet) in southeastern Idaho and closely adjacent parts of southwestern Wyoming and Utah; the upper couplet is thickest (100 to 300 feet) in northwestern Wyoming and Montana. Eastward and southward from these areas the phosphatic and cherty rocks thin and interfinger with sandy and carbonatic rocks, which in turn tongue out into redbeds and evaporites along the fringe of the phosphate field.[3,4] The lateral sequence of facies is carbonaceous mudstone and phosphorite, chert, carbonate rock and sandstone, and redbeds and evaporites. The lateral sequence is reproduced, in whole or in part, in the same and in reverse order in vertical sections.[5] The lateral sequence is interpreted as the product of deposition on a shelving bottom. The vertical sequence from carbonaceous mudstone to evaporites is interpreted as the product of deposition on a rising bottom, and vice versa. The rocks of the Phosphoria thus record nearly two cycles of transgression and regression in depositional environment.

DISTRIBUTION AND COMPOSITION OF PHOSPHATE DEPOSITS

The phosphate content of the Phosphoria formation and its correlatives is greatest in southeastern Idaho and decreases rather steadily away from this area to the fringe of the phosphate field (Fig. 1). The phosphate content of individual beds also diminishes in the same direction; thus there are no beds in west-central Wyoming and eastern Utah that contain as much as 30 per cent P_2O_5, whereas many beds in southeastern Idaho contain 30 to 36 per cent P_2O_5 (Ref. 6, p. 13). The most phosphatic rocks are typically near the base and top, or only near the top, of the phosphatic shale members. The greatest concentration of phosphate is in the lower phosphatic shale member in southeastern Idaho. There the member is 175 to 225 feet thick, and the whole thickness of the phosphatic shale member averages 11 to 12 per cent P_2O_5; beds 5 to 10 feet thick near the base and top contain 25 to 33 per cent P_2O_5. The lower bed and the upper bed are respectively overlain and underlain by a phosphatic zone, each of which is 10 to 25 feet thick and contains 15 to 25 per cent P_2O_5. The phosphate content of the lower phosphatic shale member as a whole, and of most individual beds as well, decreases progressively in all directions away from southeastern Idaho. The upper phosphatic shale member is most phosphatic in southwestern Montana,[7] where it is 50 to 80 feet thick and averages 9 to 11 per cent P_2O_5. It contains no high-grade beds of minable thickness in the area where it is thickest, but in some of the surrounding area where it is 3 to 20 feet thick it contains 3 to 6 feet of phosphate rock averaging 30 per cent P_2O_5, or more.

Most of the phosphate beds consist of submicrocrystalline carbonate-fluorapatite, generally aggregated into fine-grained structureless pellets,[8] and varying amounts of quartz, silicates, carbonates and carbonaceous matter. In some beds, the phosphatic grains are oolitic or pisolitic, and in others they consist mainly of fragments of phosphatic brachiopods, of fish scales, or of phosphatic casts of small gastropods. Generally speaking, the phosphorites in the areas where the phosphatic members are thickest are composed of fine-grained structureless pellets; coarse-grained, oolitic or pisolitic and bioclastic phosphorites are more common in the fringe areas.

The phosphorites are hard and dark brown or black in color where fresh, but in weathered sections they are often friable and range in color from brown to light gray, buff, or pink. Comparison of fresh and highly weathered rocks shows that phosphate is enriched on weathering at the expense of carbonaceous matter, carbonates, minor metals, and possibly iron sulfides and alkalies.

URANIUM IN THE PHOSPHORITES

Although the phosphatic shale members of the Phosphoria formation contain some black shale beds

* US Geological Survey.

that resemble the uraniferous black shales of certain other formations, only the phosphatic beds are appreciably uraniferous. Thin coatings of tyuyamunite have been found along joints in the phosphate mines in the Crawford Mountains, Rich County, Utah, but most of the uranium is in dispersed form. It is acid soluble, tetravalent, and, as shown by autoradiographs, mainly concentrated in the carbonate-fluorapatite grains, where it is presumed to substitute isomorphously for calcium.[9]

As a general rule, the uranium content of the phosphatic beds increases roughly with increasing P_2O_5 content, but there are many exceptions (Fig. 2). The reasons for the lack of a constant relationship between uranium and phosphate are not fully understood, but at least several factors seem contributory. Uranium is believed to enter carbonate-fluorapatite either at the time of its precipitation or after burial;[1] the amount of uranium in the apatite might thus be a function of the uranium content of the source solutions and the length of time apatite was exposed to them. Beyond this possibility, however, variations in the uranium content seem correlatable with certain differences in the rocks themselves. Thompson (Ref. 2, p. 62) found that the uranium-P_2O_5 correlation is stronger in groups of samples that have a high average eU (equivalent uranium) content than

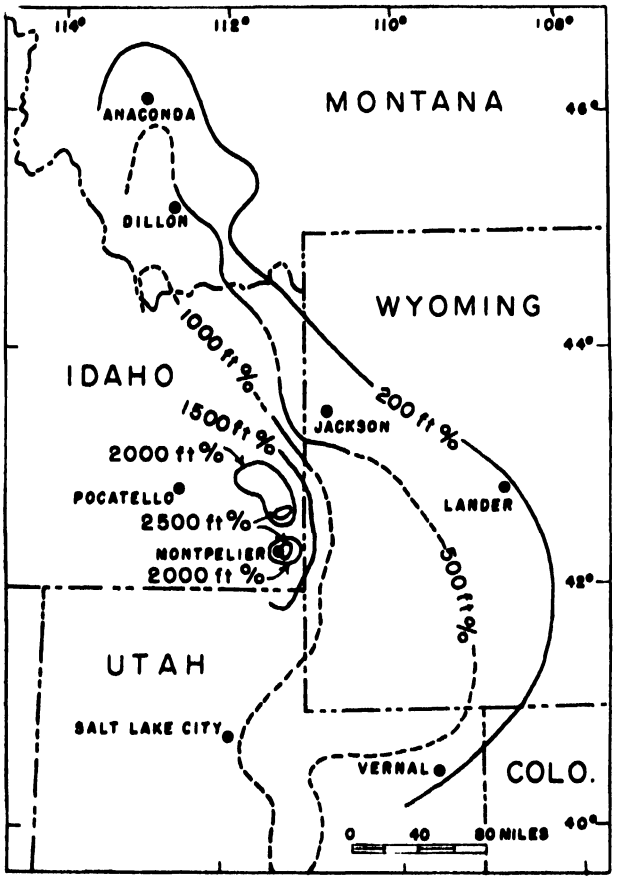


Figure 1. Total phosphate (in feet times per cent P_2O_5) in phosphatic portions of the Phosphoria formation and its stratigraphic correlatives

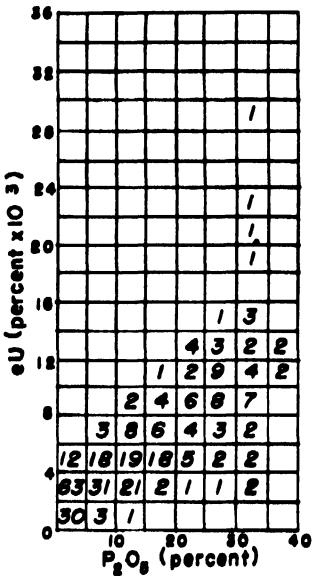


Figure 2. Comparison of P_2O_5 and eU content of all samples from the phosphatic shale member of the Phosphoria formation at Mabie Canyon and the 300-level of the Conda mine, Idaho. Numbers within graph refer to number of samples falling within each block

in groups that have a low average eU content. Thompson also found that groups of samples with a high average eU content show a strong negative correlation between eU and per cent organic matter and that this negative correlation shifts gradually to a positive correlation with decreasing average uranium content. In the one group of samples that show a positive correlation of uranium and organic matter, a better correlation exists between uranium and the product of the organic matter and P_2O_5 contents than with either alone. These relationships suggest that small amounts of uranium are present in organic matter, and possibly other constituents as well as apatite, but that higher amounts are only concentrated in apatite. Increasing amounts of organic matter and other constituents serve only to dilute the uranium present in apatite and therefore yield an inverse correlation with uranium. The uranium content also varies inversely with the CO_2 content (Fig. 3). This relationship seems to be more than that expected if CO_2 were acting only as a diluent, for few samples that contain more than 0.01 per cent uranium also contain more than 3 to 4 per cent CO_2.

The relation between uranium content and texture of Phosphoria rocks has not been much investigated, but it is possible that some of the variations in uranium content may be related to textural differences. For example, phosphorites composed of well-cemented fish scales and shell fragments are generally less uraniferous than pellet phosphates of the same P_2O_5 content. Thompson (Ref. 10, p. 120) found a moderate positive correlation between uranium content and the modal diameter of pellets at two localities.

Part of the variation in uranium content observed in phosphatic rocks of the Phosphoria is due to the effects of weathering. Because carbonate-fluorapatite resists decomposition in this climate, weathered sec-

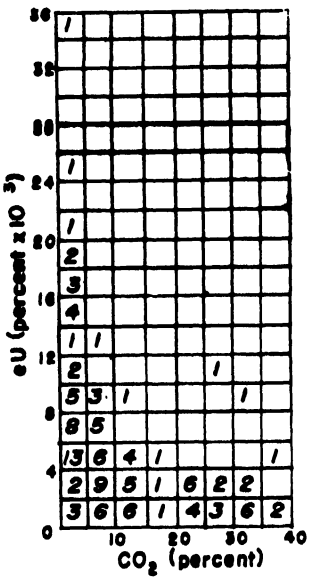


Figure 3. Comparison of CO_2 and eU content of all samples from the phosphatic shale member of the Phosphoria formation at Coal Canyon, Wyoming. Numbers within graph refer to number of samples falling within each block

tions are enriched in phosphate; in fact, data from the Conda mine in southeastern Idaho suggest that the lower phosphate bed contains only about 29 per cent P_2O_5 at depths of a few hundred feet whereas in trenches and open-pit mines throughout southeastern Idaho it contains 32 to 34 per cent P_2O_5. Uranium, on the other hand, seems to be slightly impoverished in weathered sections, suggesting that it may be differentially leached from the apatite. Evidence of the migration of uranium leached from the apatite on weathering is the presence of tyuyamunite in the phosphate mines in the north Crawford Mountains, where the phosphate rocks near the surface are weathered to an advanced degree. Additional evidence of the migration of leached uranium is the presence of as much as 0.022 ppm uranium in certain mine waters, compared to the 0.001 ppm, or less, common in ordinary surface and ground waters. The effects of weathering are also seen in the progressively lower P_2O_5 and higher U content of the upper phosphate zone at successively lower elevations in Sublette Ridge, Lincoln County, Wyoming, as shown in the table at the bottom of this page.

The beds in this area lie on the east limb of a northward-plunging anticline (the decrease in thickness from Layland Canyon to Raymond Canyon probably is a function of increasing dip of the beds) that was truncated by an erosion surface prior to the deposition of the Eocene Wasatch formation. Elsewhere in the region beds immediately below this surface are bleached and leached to an advanced degree; although the outcrop of the Phosphoria formation has been reduced below the pre-Wasatch surface by subsequent erosion, it seems likely that the enrichment of phosphate and impoverishment of uranium were accomplished by weathering related to the pre-Wasatch surface rather than to the present topography.

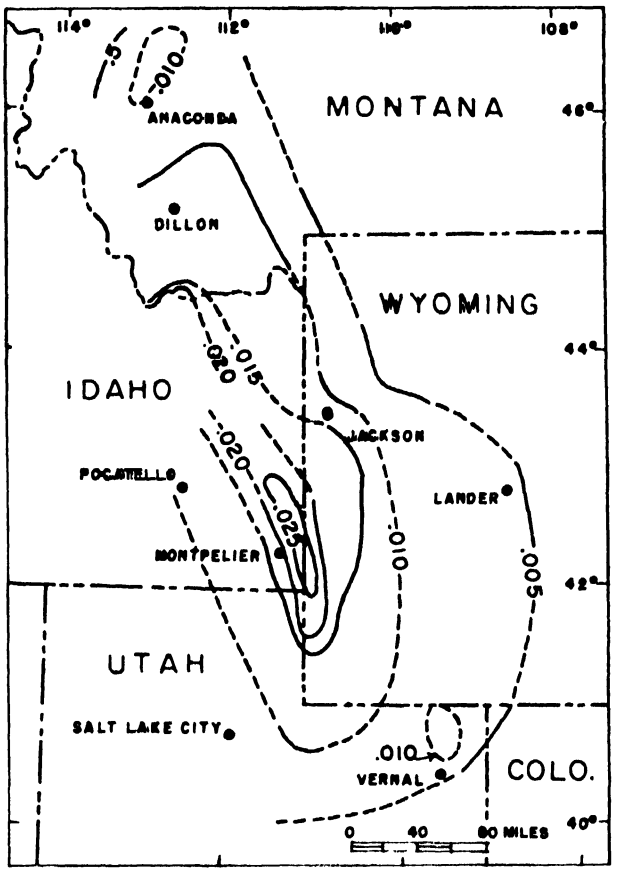


Figure 4. Generalized maximum eU content (per cent) of rocks of the Phosphoria formation and stratigraphic correlatives

The uranium content also varies areally (Fig. 4) in much the same way as does the total phosphate content of the formation (Fig. 1). The westward increase in the maximum uranium content of individual beds is partly related to the increase in maximum phosphate content of individual beds in the same direction (Ref. 6, p. 13–15), but it is partly due to other causes, for the uranium content of beds of the same P_2O_5 content increases as the total phosphate content of the phosphatic members increases. This is shown in the tabulation of the eU content of all beds containing 20 to 25 per cent P_2O_5 in several districts across the field, listed in east to west order at the top of the next page.

Bed numbers	*Lot number**	*Locality*	*Elevation (feet)*	*Thickness (feet)*	P_2O_5	*eU (per cent)*	*U*
95–97	1202	Layland Canyon	7000	6.8	30.5	0.016	0.010
92–98	1201	Coal Canyon	6850	6.7	29.2	0.020	0.018
6–11	1312	Raymond Canyon	6400	6.4	22.8	0.022	

* Refer to 11, 12 for descriptions of the localities and beds.

Locality	Feet × per cent P_2O_5 in Phosphoria formation or equivalents	eU content (per cent) of beds containing 20–25 per cent P_2O_5	
		Average eU	Range in eU
Lander, Wyoming	260	0.0035	0.001–0.007
Wyoming Range, Wyoming	500–700	0.0065	0.004–0.010
Sublette Ridge, Wyoming	1400	0.0075	0.004–0.017
Aspen Range, Idaho	2000–2600	0.0080	0.002–0.018
Fort Hall, Idaho	1100–1200	0.007	0.004–0.009
Mud Springs, Idaho	800	0.005	0.004–0.006

The reasons for these areal variations are not understood—they might have to do with differences in the composition of sea water (perhaps content of carbonate ion) at the time of deposition or with compositional or textural differences in the phosphate beds that might affect the amount of uranium they could take up from sea water or from later percolating solutions.

Thickening or thinning, caused either by deformation or sedimentation, of layers of either very high or very low uranium content may affect the uranium content of beds that appear homogeneous. Thus Thompson (Ref. 2, p. 46, 56) found that the eU content of a layer only 0.5 feet thick at Coal Canyon, Wyoming, ranged from 0.006 to 0.025 in the lower half and from 0.039 to 0.065 in the upper half; thinning or elimination by faulting (a common occurrence in these rocks) of the upper half of this layer would have a marked effect on the uranium content of the upper phosphate bed as a whole. Similarly, the lower phosphate bed in southeastern Idaho may be divided into three parts on the basis of uranium content, though it is mined and often sampled as one homogeneous unit. For example, at five sections where no faulting is evident, the middle part contains 0.018 to 0.027 per cent eU, compared to 0.008 to 0.014 per cent eU for the upper and lower parts. The relative variations in thickness of the middle part, however, are such that it makes up 15 to 27 per cent of the thickness of the bed as a whole.

Although the variations in uranium content of the phosporites of the Phosphoria are thus diverse in origin, they are not large in absolute values. Beds of minable thickness that contain more than 31 per cent P_2O_5 generally contain about 0.01 to 0.02 per cent uranium at or near the surface. It is possible that zones of slight secondary enrichment may be found locally below highly weathered zones, but the prospects of finding minable thicknesses and tonnages of phosphate rock that contain more than 0.03 per cent do not appear bright.

REFERENCES

1. McKelvey, V. E. and Nelson, J. M., *The Characteristics of Marine Uranium-Bearing Sedimentary Rocks,* Economic Geology 45: 35–53 (1950).
2. Thompson, M. E., *Distribution of Uranium in Rich Phosphate Beds of the Phosphoria Formation,* US Geological Survey Bulletin 998-D (1953).
3. McKelvey, V. E., Swanson, R. W. and Sheldon, R. P., *The Permian Phosphorite Deposits of Western United States,* 19th International Geological Congress Compte Rendu 11: 45–64, Algiers (1953).
4. Cheney, T. M., *Facies and Oil Possibilities of the Phosphoria Formation and Correlative Upper Two Members of the Park City Formation in Eastern Utah and Southwestern Wyoming,* Wyoming Geological Association Guidebook (in press).
5. Sheldon, R. P., *Physical Stratigraphy of the Phosphoria Formation in Northwestern Wyoming,* US Geological Survey Bulletin (in press).
6. Swanson, R. W., McKelvey, V. E. and Sheldon, R. P., *Progress Report on Investigations of Western Phosphate Deposits,* US Geological Survey Circular 297 (1953).
7. Cressman, E. R., *Physical Stratigraphy of the Phosphoria Formation in Part of Southwestern Montana,* US Geological Survey Bulletin (in press).
8. Altschuler, Z. S., Cisney, E. A. and Barlow, I. H., *X-ray Evidence of the Nature of Carbonate-Apatite,* 19th International Congress Compte Rendu 11: 9, Algiers (1953).
9. Altschuler, Z. S., Clarke, R. S., Jr. and Young, E. J., *Uranium in Apatite [abstract],* Geological Society of America Bulletin 65: 1225 (1954).
10. Thompson, M. E., *Further Studies of the Distribution of Uranium in Rich Phosphate Beds of the Phosphoria Formation,* US Geological Survey Bulletin 1009-D (1954).
11. McKelvey, V. E. et al., *Stratigraphic Sections of the Phosphoria Formation in Wyoming, 1947–48,* US Geological Survey Circular 210 (1953).
12. Sheldon, R. P., Waring, R. G., Warner, M. A. and Smart, R. A., *Stratigraphic Sections of the Phosphoria Formation in Wyoming, 1949–50,* US Geological Survey Circular 307 (1953).

The Aluminum Phosphate Zone of the Bone Valley Formation and its Uranium Deposits

By Z. S. Altschuler, E. B. Jaffe and F. Cuttitta,* USA

In the upper part of the Bone Valley formation, Florida, a discontinuous zone of alteration containing aluminum phosphate overlies the commercially mined apatite which constitutes the Land Pebble phosphates. This aluminum phosphate zone has been known for many years. In 1949, however, during the US Geological Survey's exploration studies for uranium, it was found to be fairly widespread and enriched in uranium, thus greatly enhancing its value as a potential resource not alone of uranium, but also of alumina and phosphate. The aluminum phosphate deposits result from the lateritic alteration of the Bone Valley formation by ground water and represent the progressive replacement of clay and apatite in a paragenetic sequence which has recently been reported from other similarly altered phosphate deposits—those of Nigeria[1] and Senegal.[2] Thus, the aluminum phosphate zone is intrinsically interesting as it represents a general type of alteration in the particular petrogenetic domain of phosphorites.

GENERAL GEOLOGY AND STRATIGRAPHY

The Bone Valley formation of Pliocene age[3] underlies 2600 square miles in west-central peninsular Florida, east of the Tampa Bay region, in Polk and Hillsboro Counties and extending into adjoining counties. The region is generally flat and exposures are limited to the phosphate mines and to a few spots in the banks of the Alafia and Peace Rivers, which drain the area. A low north-trending ridge of subdued karst topography divides the Peace and Alafia drainages in the center of the region. The Bone Valley unconformably overlies the Hawthorn formation of early and middle Miocene age[4] and is covered by a mantle of loose quartz sand.

The Hawthorn formation consists mainly of quartzose and slightly phosphatic limestone and marl. Its upper part has been irregularly altered to dolomite, and its clay, normally montmorillonite, has been transformed to attapulgite. The Hawthorn's surface is irregular, its rock is solution-pitted, and it contains many small slumps, and locally large ones, within which the overlying Bone Valley thickens.[5] In addition the Bone Valley strata drape over irregularities of the Hawthorn surface due to post-depositional solution and slumping. Apparently the Hawthorn was exposed and weathered during late Miocene time, developed an irregular karst topography, and accumulations of phosphatic residuum. Marine transgression during the Pliocene dolomitized and weathered limestone and reworked the clastic residuum and phosphatized limestone into the Bone Valley formation, at the same time adding unknown amounts of quartz, clay, and phosphate. Later uplift, continuing in the Recent, induced new subterranean solution and slumping and is responsible for the present karst topography.

The Bone Valley formation is a pebbly and clayey sand of quartz and phosphate. Much of its clastic material is transgressively reworked Hawthorn residue. The formation is normally 25 to 30 feet thick and is characteristically graded-bedded in its lower two-thirds which is the pebbly phase that is mined and known commercially as matrix (Fig. 1). The materials in the graded-bedded phase range through pebbly sand, sand, clayey sand, and clay. In the upper third of the Bone Valley the graded-bedded deposits change rapidly to massive-bedded clayey quartz sand containing only minor amounts of clastic phosphate. This upper zone and the overlying quartz sand are discarded as overburden during mining.

The Bone Valley is composed of approximately equal amounts of quartz, clay, and phosphate minerals. The distribution of these is uneven, however, as the upper part of the Bone Valley contains from 60 to 70 per cent of quartz sand in a groundmass of clayey cement, and the lower part of the Bone Valley is correspondingly higher in phosphate particles and lower in quartz.

The phosphate in Hawthorn and unaltered Bone Valley rock occurs primarily as nodules and pebbles of carbonate-fluorapatite.[6] The clay in the lower Bone Valley is an iron-rich montmorillonite, and in the upper, massive-bedded Bone Valley it is a kaolinite. The change from montmorillonite to kaolinite is a post-depositional alteration and does not conform precisely to the boundary between the upper and lower Bone Valley.

Generally the Bone Valley formation is compact although not indurated and it is gray or greenish gray owing to the ever present clay. In places red-brown or orange color is superimposed irregularly by oxidative weathering of clay. In the mines of

*US Geological Survey. Including work by Z. S. Altschuler, J. B. Cathcart, F. Cuttitta, E. B. Jaffe, and E. J. Young.

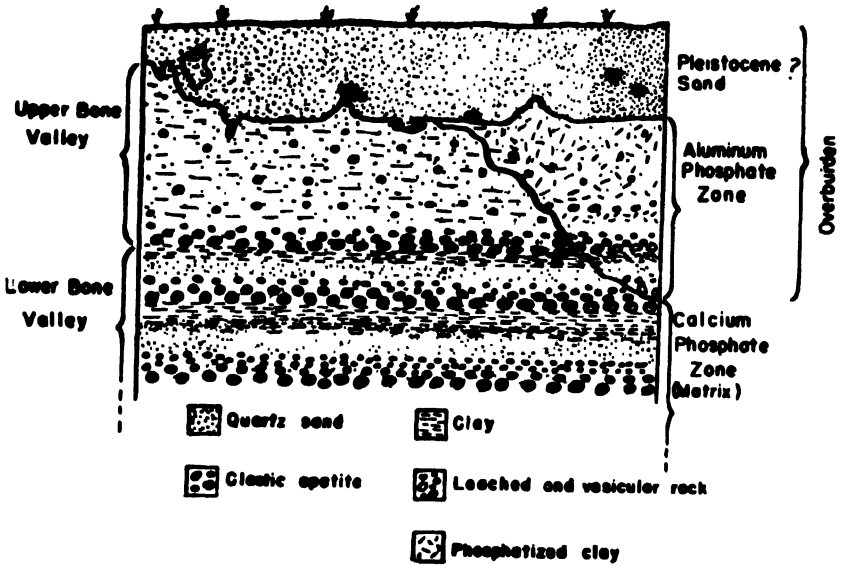


Figure 1. Stratigraphic relations in the aluminum phosphate zone

the Peace and Alafia drainage basins a white-colored zone of leaching and alteration irregularly transgresses the upper part of the section (Fig. 1). This is the aluminum phosphate zone. Its rock is vesicular, friable, and light weight and composed of quartz sand cemented and indurated by the secondary minerals wavellite, crandallite, and locally, millisite. In the aluminum phosphate zone, therefore, the lithology of the section as previously outlined has been modified by leaching, secondary precipitation, and replacement. These modifications, as well as the chemical characteristics and uranium contents of the rock depend greatly on whether only the upper or both of the primary lithologic zones of the Bone Valley formation have been altered. Thus, coarsely vesicular rock is confined to originally pebbly strata (Fig. 1) and as these were the apatite-rich layers, the calcium-aluminum phosphates—crandallite and millisite—are prominent in such rock. Where the alteration is restricted to the upper part of the Bone Valley, however, the aluminum phosphate wavellite is the dominant mineral, the porosity is more uniform, and the rock is finely vesicular.

Secondary precipitates underlie the aluminum phosphate zone in the form of irregular discontinuous seams of horizontal hardpan which cement layers of sand and encrust upper surfaces of clay. The cement consists of dark-colored apatite and, subordinately, of limonite and chert. The chert represents silica released during the phosphatization of clay to wavellite and crandallite. Silica seams can be seen closely associated with clay in process of such alteration higher in the section. The hardpans are formed by material leached from above and redeposited at the ground-water table during the early stages of leaching; hence apatite, rather than secondary phosphate, prevails.

Pebbles of apatite at the base of the leached zone record the onset of alteration. They are softened, highly porous, and rimmed by a bleached and whitened zone of crandallite and wavellite. Within the next two feet the pebbles are completely altered and white, and, finally, cavities occur that are comparable in size and sorting to the pebbles in the adjoining rock. Where the leaching is most intense, holes coalesce and all parts of the rock are affected. Higher in the section uniformly porous phosphatic sandstone prevails in rock that was originally well-sorted clayey sand.

Another important modification within the aluminum phosphate zone is the fine-grained secondary cement that coats most fractures and cavities. Much of it is layered and built up from the floors of the cavities in concave lenslike masses that are devoid of silt. The secondary cement is a mixture of kaolinite, apatite, and aluminum phosphates. Its habit implies deposition from descending solutions from which phosphate minerals have precipitated; kaolinite, either reforming from solution or carried in suspension, has been deposited synchronously. From bottom to top of the section the composition of the secondary cements shows the same change from calcium to aluminum phosphates as does the zone as a whole. Thus, apatite drops out as crandallite and wavellite become successively most prominent. Microscopic examination reveals wavellite needles discordantly replacing the previously deposited mixtures, thus representing not merely the precipitation of a later phase but progressive alteration.

The precipitation of secondary cement is dependent both on degree of leaching and stratigraphic position. At the base of the aluminum phosphate zone cavity fillings are microscopic and secondary cements occur only as fracture fillings and coatings around partly leached grains. In the middle of the zone where leaching is more pronounced secondary cements may constitute 10 per cent of the rock, mainly in the form of layered cavity fillings. Toward the top of the section leaching has been most pronounced; however,

eluviation predominates and secondary cements diminish again.

DESCRIPTIVE MINERALOGY

The principal minerals of the aluminum phosphate zone are apatite, crandallite, millisite, and wavellite. Of these, crandallite and wavellite are the most typical, as apatite is generally confined to the basal part of the zone and millisite is important only locally.

Carbonate-Fluorapatite

The fine-grained apatite in the aluminum phosphate zone, like that in the rest of the Bone Valley formation and other marine phosphorites, is characterized by a deficiency in P_2O_5 content of 3 to 6 per cent, an excess of F or $(F + OH)_2$ of 0.5 to 1 per cent, and the presence of approximately 3 per cent of carbonate.[6,7] In addition, the apatite is demonstrably smaller in unit-cell dimensions than igneous fluorapatite.[6] The structural differences revealed by the characteristically smaller cell dimensions are best explained by the chemical deviations. These latter can be expressed in the formula $Ca_{10}(PO_4CO_3)_6 F_{2\ 3}$.

The apatite invariably occurs as aggregates of submicroscopic crystals Its index of refraction ranges from 1.575 to 1.625 and is typically about 1.605. It is generally isotropic but fibrous varieties show birefringence of about 0.003, positive elongation, and parallel extinction. The specific gravity of the pure apatite nodules is 2.96–2.99.

Crandallite $CaAl_3(PO_4)_2(OH)_5 \cdot H_2O$

Crandallites[8] in the aluminum phosphate zone is entirely secondary. It replaces either apatite or kaolinite and is intimately mixed with them. It inherits their fine-grained textures and is predominantly isotropic. It may also be associated with the secondary minerals millisite, wavellite, and goethite. Depending on the amount of intermixed minerals, the index of refraction of crandallite ranges from 1.590 to 1.630. Purest varieties are least birefringent and have an index of 1.615. Crandallite is white to pale gray in reflected light and colorless to brown in transmitted light. The composition of crandallite departs from the ideal formula in having 11 to 12 per cent CaO instead of 13.55. The specific gravity of this crandallite is approximately 2.75–2.78.

Millisite $(NaK)CaAl_8(PO_4)_4(OH)_9 \cdot 3H_2O$

Millisite[8] is known to occur as a major component of the aluminum phosphate zone within the area of several square miles and is present only in minor or trace amounts elsewhere. Like crandallite, with which it occurs as a microcrystalline intergrowth, millisite is fine-grained and virtually isotropic. The presence of millisite was demonstrated in X-ray studies of Owens and Berman. Its mass index of refraction is 1.630 and it is pale greenish white. The specific gravity of millisite in the aluminum phosphate zone is the same as that of crandallite.

Millisite requires alkalies; hence its restricted occurrence, in contrast to crandallite, is probably related to the distribution of montmorillonite. In most areas montmorillonite had been transformed to kaolinite prior to the phosphatization of clay, and crandallite developed.

Wavellite $Al_3(PO_4)_2(OH)_3 \cdot 5H_2O$

Wavellite[8] occurs in the aluminum phosphate zone in two ways: as bands of cryptocrystalline fibrous material of low birefringence, index of refraction of 1.580, and as euhedral, white, bladed crystals, crystal aggregates, and spherulites. The euhedral material is most common and can be readily identified by its optical properties and mode of occurrence. Its indices of refraction are: α 1.52 to 1.53, β 1.535, and γ 1.546. Its specific gravity is between 2.30 and 2.33. The wavellite occurs as druses and vein fillings, as spherules in cavities, or replacing clay and apatite. The cryptocrystalline variety is primarily a clay replacement.

PETROLOGY

The nature of the alteration in the aluminum phosphate zone is shown in Table I, a series of chemical analyses from the Homeland mine of the Virginia-Carolina Chemical Corporation at Homeland, Florida. These samples are representative of the thickest section of the aluminum phosphate zone in Fig. 1. Sample Ho 20 is from the basal part of the zone and Ho 25 is a sample of the uppermost material. Quartz and clay as reflected by SiO_2 content are higher on the average in the upper part of the section and CaO, CO_2, and F, all of which reflect apatite, drop off sharply from bottom to top. The relative changes as shown in Fig. 2 where the major oxides are recomputed and plotted on a silica-free basis according to their stratigraphic position. As very little clay remains in this particular section, this is equivalent to removal of quartz, which, being relatively inert, is unaffected by the alteration.

It can be seen in Fig. 2A that CaO and Al_2O_3 have a complementary relation in the aluminum phosphate zone, but that P_2O_5 shows a slight, though steady decline toward the top of the section, reflecting general leaching of phosphate minerals. The abrupt drop in P_2O_5 in sample Ho 22 and the corresponding peak in Al_2O_3 are due to the presence of kaolinite in an originally thick clay layer. Otherwise, the respective upward and downward trends of the Al_2O_3 and CaO curves correspond almost exactly to a gradual replacement of apatite (3.3 CaO:1 P_2O_5) by crandallite and wavellite (both $3Al_2O_3$: $2P_2O_5$). Thus Al_2O_3 increases half as rapidly as CaO falls, because Al_2O_3 in crandallite and wavellite requires approximately twice as much P_2O_5 as does CaO in apatite.

The mineral composition at Homeland is reflected in the ratios of CaO to P_2O_5 and Al_2O_3 to P_2O_5 in Fig. 2B. Apatite is not found in any samples above Ho 21. Crandallite is a major mineral only in sample Ho 21 and Ho 22. From this point to the top of the section crandallite is of minor importance, and the ratio of CaO to P_2O_5 declines sharply above Ho 21 and remains small thereafter. Wavellite is a major

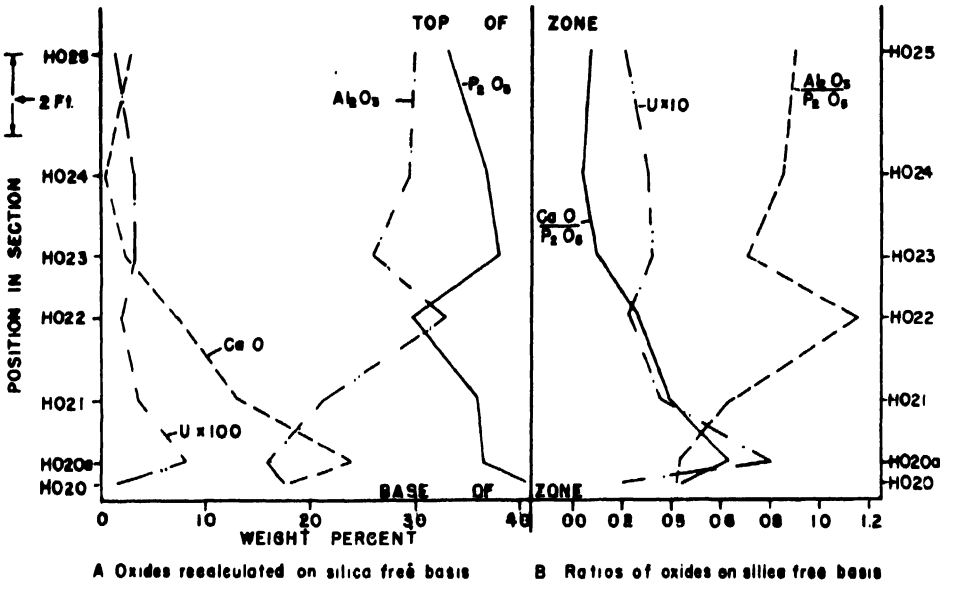


Figure 2. Chemical variations with stratigraphy in the aluminum phosphate zone

component throughout the section, and the ratio of Al_2O_3 to P_2O_5 is large initially and increases upward.

Experiments by Warrenton, cited by DuToit,[9] have shown that calcium phosphates in the presence of carbonated water can be dissolved by aluminum hydroxides with the formation of aluminum phosphates. Laboratory and soil fertilization studies indicate that clays may be transformed to Ca-Al- and Al-phosphates in acid conditions. Field and microscope evidence for such reactions in the aluminum phosphate zone have been described above, namely, the progressive replacement of clays and apatite by crandallite and wavellite and the occurrence of chert seams adjacent to wavellitized clay. We may state that these reactions proceed from the top of the section downward and are still incomplete at the base. This is evident from the vertical sequence. Thus the most acid phase, wavellite, dominates at the top and the less stable, more basic phases crandallite and apatite are successively more prominent downward. Also, wavellite needles can be seen replacing earlier deposited secondary cements at the base.

URANIUM DISTRIBUTION IN THE ALUMINUM PHOSPHATE ZONE

The uranium in the Bone Valley formation, and indeed in most other phosphorites, is associated intimately and almost entirely with the phosphate minerals. A single trace occurrence of autunite, $Ca(UO_2)_2(PO_4)_2 \cdot 12H_2O$, was found by the authors in 1949 in the aluminum phosphate zone, and others[10,11] have reported trace occurrences of uranite-group minerals in Moroccan phosphates. These occurrences are quantitatively insignificant. In laboratory experiments uranium is not differentially leached from apatite or aluminum phosphate rock with complexing or noncomplexing acids. Further, the clays, quartz, carbonates, and other minerals associated with apatite in phosphorites invariably contain less than 0.001 per cent uranium.

Unaltered phosphorite in the lower part of the Bone Valley formation averages 0.008 per cent uranium and contains from 10 to 15 per cent P_2O_5; apparently unaltered clayey sand from the upper part of the Bone Valley contains only minor amounts of P_2O_5 and approximately 0.002–0.003 per cent uranium. In contrast, typical rock from well-developed sections of the aluminum phosphate zone has 8–12 per cent P_2O_5 and approximately 0.012 per cent uranium. Furthermore the rock in the aluminum phosphate zone generally contains from 60 to 70 per cent quartz and 5 to 10 per cent kaolinite, both relatively nonuraniferous diluents. The aluminum phosphate zone has thus had two to fourfold enrichment in uranium, even in contrast to the matrix.

Although there is much and expected variation in the composition and uranium content of the aluminum phosphate zone, the distribution of uranium within it generally exhibits the pattern illustrated in Fig. 2 and reflects the mineral, chemical, and stratigraphic relations. As shown in Fig. 2A the uranium content increases sharply just above the base of the zone, declines gradually in the middle, and is relatively low in the upper half. Moreover the distributions of uranium and CaO are strikingly similar. Analyses for uranium in pebbles, cements, and mineral concentrates show that the apatite pebbles are the most enriched of the aluminum phosphate zone components and that the pebbles in the base of the zone are richer than those in the middle. Individual pebbles from the base of the zone commonly have tenths of a per cent of uranium, although pebbles from the same strata outside the zone of alteration contain only 0.02 per cent of uranium. Concentrates of crandallite and millisite generally contain 0.03 to 0.04 per cent uranium. In contrast, pure wavellite contains only 0.002 to 0.004 per cent uranium. Despite the low uranium content of wavellite, the upper part of the aluminum phosphate zone (Table I and Fig. 2A)

Table I. Chemical Analyses of Seven Samples from the Aluminum Phosphate Zone
(Analyst, F. Cuttitta)

Constituent	*Ho-20*	*Ho-20A*	*Ho-21*	*Ho-22*	*Ho-23*	*Ho-24*	*Ho-25*
SiO_2	51.48	62.60	40.92	57.24	69.46	68.08	51.32
Al_2O_3	8.26	5.98	12.48	14.17	8.16	9.40	14.91
Fe_2O_3[a]	2.76	2.86	2.61	2.17	1.32	1.33	2.19
MnO	0.70	0.53	2.14	0.16	0.16	0.14	0.13
MgO	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CaO	8.98	8.25	8.00	3.10	0.90	0.20	1.20
Na_2O	0.23	0.13	0.12	0.15	0.06	0.04	0.03
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TiO_2	0.37	0.40	0.63	0.63	0.31	0.42	0.65
P_2O_5	19.72	13.60	20.79	12.79	11.61	11.32	16.35
Loss on ignition[b]	6.76	6.09	11.72	9.96	7.91	9.18	13.24
CO_2	0.80	0.24	0.26	0.05	0.02	0.02	0.05
F	1.15	0.52	0.63	0.59	0.51	0.70	0.53
Cl	0.03	0.02	0.04	0.01	0.03	0.02	0.01
SO_3[c]	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cr_2O_3	0.01	0.01	0.01	0.01	0.01	0.01	0.01
V_2O_5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
U[d]	0.01	0.03	0.02	0.01	0.01	0.01	0.01
Total	101.28	101.28	100.39	101.06	100.49	100.89	100.65
Less F = O	0.48	0.22	0.27	0.25	0.22	0.30	0.22
Less Cl = O	0.01	0.01	0.01	0.00	0.01	0.01	0.00
Corrected total	100.79	101.05	100.11	100.81	100.26	100.58	100.43
H_2O (110°C)	0.35	0.49	1.13	0.64	0.73	0.39	0.88

(*a*) This represents total iron, some of which may be present as ferrous iron.
(*b*) The figure for loss on ignition include adsorbed water (H_2O) and exclude CO_2.
(*c*) This represents total sulfur; no sulfides were found.
(*d*) Uranium is reported as a metal, as its valence state was not determined.

generally contains about 0.01 per cent uranium; however, this is attributable to minor amounts of crandallite.

Thus uranium associates most strongly with the more calcic phases, preferentially with apatite; when apatite is depleted uranium is enriched in crandallite. This is clearly demonstrated by the virtual identity between the curves for uranium and Ca/P_2O_5 (Fig. 2B) for samples Ho 20 to Ho 22. Ho 22 is the first sample in which apatite is missing and the CaO/P_2O_5 drops accordingly as the remaining lime is fixed in crandallite. At this point the uranium curve abruptly departs from the CaO/P_2O_5 curve although it generally parallels its trend through the remainder of the section.

The correspondence between CaO and uranium and the basal enrichment of uranium in apatite suggest that uranium substitutes for calcium in the apatite structure. This is plausable on crystallochemical grounds as the ionic radii of quadrivalent uranium (1.05 Å)[12] and bivalent calcium (1.06 Å)[12] are virtually identical, and both McKelvey[13] and Goldschmidt[12] have proposed the substitution. Recent work[14] demonstrating that much of the uranium in apatite is quadrivalent essentially establishes the proof. Considering the fact that uranium occurs in apatite in amounts of one atom per several thousand unit cells, the excess charge involved in the substitution of uranium for calcium can easily be balanced by a number of substitutions known to occur in apatite or by excess fluorine. The replacements of calcium by sodium and of phosphate by silicate are both of far greater magnitude than the replacement of calcium by uranium. The sexivalent uranium in apatite can usually be explained by post-depositional weathering or by oxidation incident to radioactive decay. Thus a mechanism is supplied for explaining the zone of basal enrichment within the aluminum phosphate zone. The amount and manner of enrichment in the entire zone are discussed below.

ORIGIN OF THE ALUMINUM PHOSPHATE ZONE AND ITS URANIUM ENRICHMENT

The distinctive features of the aluminum phosphate zone are: (1) it transgresses the stratigraphy and always extends downward from the top of the Bone Valley formation; (2) it is commonly underlain by hardpans reflecting old ground-water levels; (3) its mineralogic and textural changes progress vertically through the section and diminish downward; and (4) it is characterized by leaching and reprecipitation involving the depletion of CaO, Na_2O, silicate silica, and some phosphate and a complementary increase in Al_2O_3 coordinated as acid aluminum phosphates which yield downward to basic calcium phosphates.

This combination of features implies post-depositional lateritic alteration by acid ground water. It also implies downward percolation controlled by the ground-water table. The ground water of the region was probably rich in humic "acids" derived from

Pleistocene soils, bogs, and ground-water podzols; fossil and current examples of these occur in the area. One of the first changes is the transformation of montmorillonite to kaolinite. The apparently unaltered clayey sand is kaolinitic, however, the change from montmorillonite to kaolinite transgressed the primary stratigraphic change from pebbly graded beds to massive clayey sands. Moreover, minor amounts of montmorillonite are found in many sections of the kaolinitic clayey sand, and discrete residual patches of montmorillonite containing appreciable apatite sand have been found in one section of otherwise fresh-looking kaolinitic sand containing only minor amounts of apatite.

Coincident with the alteration of montmorillonite to kaolinite, or shortly thereafter, clay and apatite were dissolved, and the phosphoric acid thus generated reacted with clay to produce crandallite and wavellite. Aluminum hydroxides reacted with apatite and also produced crandallite and wavellite. Further, crandallite was precipitated as a secondary cement from acid solutions which percolated downward and were neutralized in the more basic zone containing apatite. During early stages of leaching calcium is more abundant and crandallite is the main secondary phase. With additional acid ground-water percolation the more stable end-product, wavellite, gradually replaces the intermediate phase, crandallite.

The picture of downward leaching and redeposition accords well with the pattern of uranium distribution. Uranium is liberated during the leaching of apatite pebbles in the upper part of the zone. It is kept soluble in the descending acid waters, probably as complexed uranyl and uranous ions, and it is secondarily enriched[14] in the porous partly leached apatite pebbles at the base of the zone by structural replacement of calcium. Work by Baes[15] demonstrates that sexivalent uranium can be reduced to quadrivalent uranium by the oxidation of ferrous iron in acid solutions and that this reaction is furthered by the presence of fluorine and phosphate. Thus some uranous uranium could persist after release from apatite and be available for uptake in the manner proposed. It is necessary to postulate the presence of uranyl phosphate because of the thermodynamic relations favoring the transformation of U^{4+} to UO_2^{++},[16] and also because of the trace occurrence of autunite which indicates local concentration of UO_2^{++}.

Presumably only uranous uranium would be fixed by diadochy, and uranium could also be adsorbed by apatite as uranyl phosphate. Experimental evidence has shown that apatite can fix appreciably uranyl uranium.[17,18] Valence analysis of the uranium in apatite from the base of the leached zone has shown that the ratio of quadrivalent to sexivalent uranium is lower than in comparable unenriched apatite; however the total amount of quadrivalent uranium may be higher. This indicates that the apatite in the aluminum phosphate zone may have taken up both uranous and uranyl uranium. It is equally possible that the initial uptake was largely of uranous uranium and that continual weathering and decomposition of the host apatite have caused oxidation to the uranyl state.

The mode of occurrence of uranium in crandallite and wavellite is not known. It is assumed to be intimately associated as uranyl phosphate. The downward secondary enrichment of uranium is based on the properties of the entire aluminum phosphate zone, however, and applies equally to these minerals. Capdecomme[19] also reports uraniferous crandallite deposits that are more radioactive in the basal zone.

The theory presented of supergene enrichment of uranium demands the original presence of two or three times more apatite than now occurs in the aluminum phosphate zone. Although the initial content of apatite in the zone was undoubtedly higher than the amount remaining, it is not possible to assume a two- to threefold increase in view of the primary stratigraphic change to a less phosphatic clayey sand that can be observed in relatively unaltered outcrops. It is known from field and laboratory evidence, however, that an originally thicker section was available for leaching of apatite to provide the present enrichment in uranium. Briefly, the contacts between the loose sands and the upper Bone Valley are gradational in detail, and the sands of both zones are virtually identical in size, sorting, and heavy-mineral content. Therefore, part of the loose sand mantle is a blanket of lateritically weathered and eluviated upper Bone Valley and hence not a Pleistocene deposit, and the present contact is a lowered one.

Cathcart mapped the regional occurrence of the aluminum phosphate zone and established the fact that its isopach and isograde contours generally conform to the topography of the river valleys. The zone is thickest and richest in uranium under the outer slopes of the flood plains and the changes in grade and thickness migrate upstream in most of the tributaries and toward the master streams on all the interfluves.

The degree of accord between equivalent uranium and chemically determined uranium in the aluminum phosphate zone indicates that the zone and its distribution and grade patterns originated in Pleistocene time and are probably preglacial. Precise ages cannot be proposed at this time.

The relation of the aluminum phosphate zone both to the ground-water table and to the stream valleys indicates that the weathering and leaching are related to stream incision and a lowering of the ground-water table, probably caused by slight regional uplift during Pleistocene time. The down-cutting and the adjustment in the ground-water system would have been most pronounced in the lower reaches of the rivers, and the resultant ground-water leaching and deposition are therefore most profound on the slopes of the master stream valleys. The post-depositional subterranean solution and collapse which reflect in the present topography and cause supratenuous fold-

ing in the Bone Valley are related to this initial uplift as well as to later movement.

ECONOMIC GEOLOGY

The aluminum phosphate zone underlies several hundred square miles in the valleys of the Peace and Alafia Rivers, and it averages 6 to 7 feet in thickness. Known reserves exceed 800 million tons.[20] Several million tons of aluminum phosphate zone rock are stripped annually in mining the calcium phosphate deposits. The aluminum phosphate zone generally averages 0.01 to 0.02 per cent uranium and is therefore a potential source of tens of thousands of tons of uranium.

The average content of phosphate minerals in the aluminum phosphate zone is 20 to 30 per cent. The potential reserves of alumina and phosphates with which uranium is associated are thus hundreds of millions of tons.

Certain petrographic features of the aluminum phosphate zone are particularly auspicious for economic exploitation. The rock is a friable phosphatic sandstone. More than 60 per cent of the rock is quartz that is coarser than 150 mesh (0.1 mm). Virtually all of the phosphatic material is finer than the quartz or can be reduced to finer size during disaggregation. Thus by a separation into appropriate coarse and fine fractions, a two- to threefold concentration of the phosphate, alumina, and uranium can be obtained with moderately high recovery. Furthermore, because of its characteristic basal enrichment in uranium the aluminum phosphate zone can be easily delimited in prospecting by shallow radioactivity logging.

In view of the auspices under which these discussions are assembled it is appropriate to emphasize not only the inherent geologic interest of the aluminum phosphate zone but also the benefits that would result from its utilization. The added stimulus of great quantities of recoverable uranium makes possible the exploitation of vast deposits of alumina and phosphate which would normally be lost or unused, and much research is currently in progress in the United States on the extraction of uranium and the production of alumina and phosphate fertilizer from the aluminum phosphate zone.

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REFERENCES

1. Russ, W., *The Phosphate Deposits of Abeokuto Province,* Bulletin of the Geological Survey of Nigeria 7 (1924).
2. Capdecomme, L., *Etude Mineralogique des Gites de Phosphates Alumineux de la Region de Thies (Senegal),* Comptes rendus, 19th International Geologic Congress, section 11: 103–117 (1953).
3. Cathcart, J. B., Blade, L. V., Davidson, D. F. and Ketner, K. B., *The Geology of the Florida Land-Pebble Phosphate Deposits,* Comptes rendus, 19th International Geologic Congress, section 11: 77–91 (1953).
4. MacNeil, F. S., *Correlation Chart for the Outcropping Tertiary Formations of the Eastern Gulf Coastal Plain,* US Geological Survey Oil and Gas Investigations Preliminary Chart 29 (1947).
5. Cathcart, J. B., *Notes on the Land-Pebble Phosphate Deposit of Florida, in Mineral Resources of Southeastern United States,* University of Tennessee Press, Knoxville, 131–151 (1950).
6. Altschuler, Z. S., Cisney, E. A. and Barlow, I. H., *X-ray Evidence of the Nature of the Carbonate-Apatites* (Abstract), Comptes rendus, 19th International Geologic Congress, section 11: 9 (1953).
7. Jacob, K. D., *The Composition and Distribution of Phosphate Rock with Special Reference to the US,* US Department of Agriculture Technical Bulletin 364 (1933).
8. Palache, C., Berman, H. and Frondel, C., *Dana's System of Mineralogy,* 7th edition, Volume 2, John Wiley and Sons, New York (1951).
9. DuToit, A. L., *The Phosphates of Suldanha Bay,* South African Geological Survey, Memoir 10 (1918).
10. Arambourg, C. and Orcel, J., *Observations Preliminaires sur la Présence d'un Vanadate d'Urane dans les Gisements de Phosphate du Moroc,* Comptes rendus, Academy of Science of Paris 233: 1635 (1951).
11. Guntz, A. A., *Sur la Présence d'Uranium dans les Phosphates Nord-Africains,* Comptes rendus, Academy of Science of Paris 234: 868 (1952).
12. Goldschmidt, V. M., *Geochemistry,* Clarendon Press, Oxford (1954).
13. McKelvey, V. E. and Nelson, J. M., *Characteristics of Marine Uranium-Bearing Sedimentary Rocks,* Economic Geology 45: 35–53 (1950).
14. Altschuler, Z. S., Clarke, R. S. and Young, E. J., *Uranium in Apatite* (Abstract), Bulletin of the Geological Society of America 65: 1539 (1954).
15. Baes, C. F., Jr., *The Production of U^{4+} by Ferrous Ion in Phosphoric Acid Solution: The Formal Electrode Potential of the U^{4+}—U^{6+} Couple,* US Atomic Energy Commission ORNL–1581 (1954).
16. Garrels, R. M., *Some Thermodynamic Relations among the Uranium Oxides and their Relations to the Oxidation States of the Uranium Ores of the Colorado Plateaus,* American Mineralogist (in press).
17. Neuman, W. F., Neuman, M. W., Main, F. R. and Mulryan, B. J., *The Deposition of Uranium In Bone, V. Ion Exchange Studies,* Journal of Biological Chemistry 179: 335–340 (1949).
18. Moore, G. W., *Extraction of Uranium from Aqueous Solution by Coal and Other Materials,* Economic Geology 49: 652–659 (1954).
19. Capdecomme, L. and Pulou, R., *Sur la Radioactivité des Phosphates de la Region de Thies,* Comptes rendus, Academy of Science of Paris 239: 288–290 (1954).
20. McKelvey, V. E., Cathcart, J. B., Altschuler, Z. S., Swanson, R. W. and Lutz, K., *Domestic Phosphate Deposits in Soil and Fertilizer Phosphorus in Crop Nutrition,* Agronomy, Volume 4, Academic Press, New York, 347–376 (1953).

Distribution and Occurrence of Uranium in the Calcium Phosphate Zone of the Land-Pebble Phosphate District of Florida

By J. B. Cathcart,* USA

The Florida land-pebble phosphate district covers more than 1000 square miles in west-central peninsular Florida. The district has been divided on the basis of phosphate content and recoverable tonnage into a northern, high-grade part in Polk and Hillsborough Counties and a southern, lower grade part in Hardee and Manatee Counties (Fig. 1).

Mining of the deposits started in 1888, and production has increased steadily. In 1954, over 9 million long tons of phosphate rock was produced. Mining has been confined to the northern part of the district.

During this study the cooperation of the mine owners and operators of the district has been wholehearted, and much of the analytical data on which this report is based were furnished by companies. The writer also wishes to thank L. J. McGreevy and A. M. Coleman of the Geological Survey for their assistance in computing and compiling data.

GENERAL GEOLOGY

The land-pebble phosphate district is a part of the Gulf Coastal plain. King[1] points out that the geology of peninsular Florida differs from that of the remainder of the coastal plain in that Florida was a positive, relatively stable area during a large part of Mesozoic and Cenozoic time, and because of its distance from the main part of the North American continent, it received relatively small amounts of land-derived sediment.

The rocks in the land-pebble phosphate district are the lower Miocene Tampa limestone, lower and middle Miocene Hawthorn formation, middle Pliocene Bone Valley formation, and Pleistocene terrace sands.[2,3]

The Tampa and Hawthorn formations dip very gently to the south and east. The Tampa limestone is exposed only in pits in the northernmost part of the district where the Hawthorn formation is absent owing to erosion. The Hawthorn formation underlies the rest of the district. The Bone Valley formation overlies the Hawthorn throughout the district, except along the Peace and Alafia rivers, where the Hawthorn formation is exposed. Quartz sands, generally assigned to the Pleistocene[3] overlie the Bone Valley formation in most of the district.

Phosphate nodules are present in the Tampa, Hawthorn, and Bone Valley formations. According to Altschuler and Cisney,[4] the phosphate mineral is a carbonate fluorapatite.

STRATIGRAPHY AND DISTRIBUTION OF URANIUM

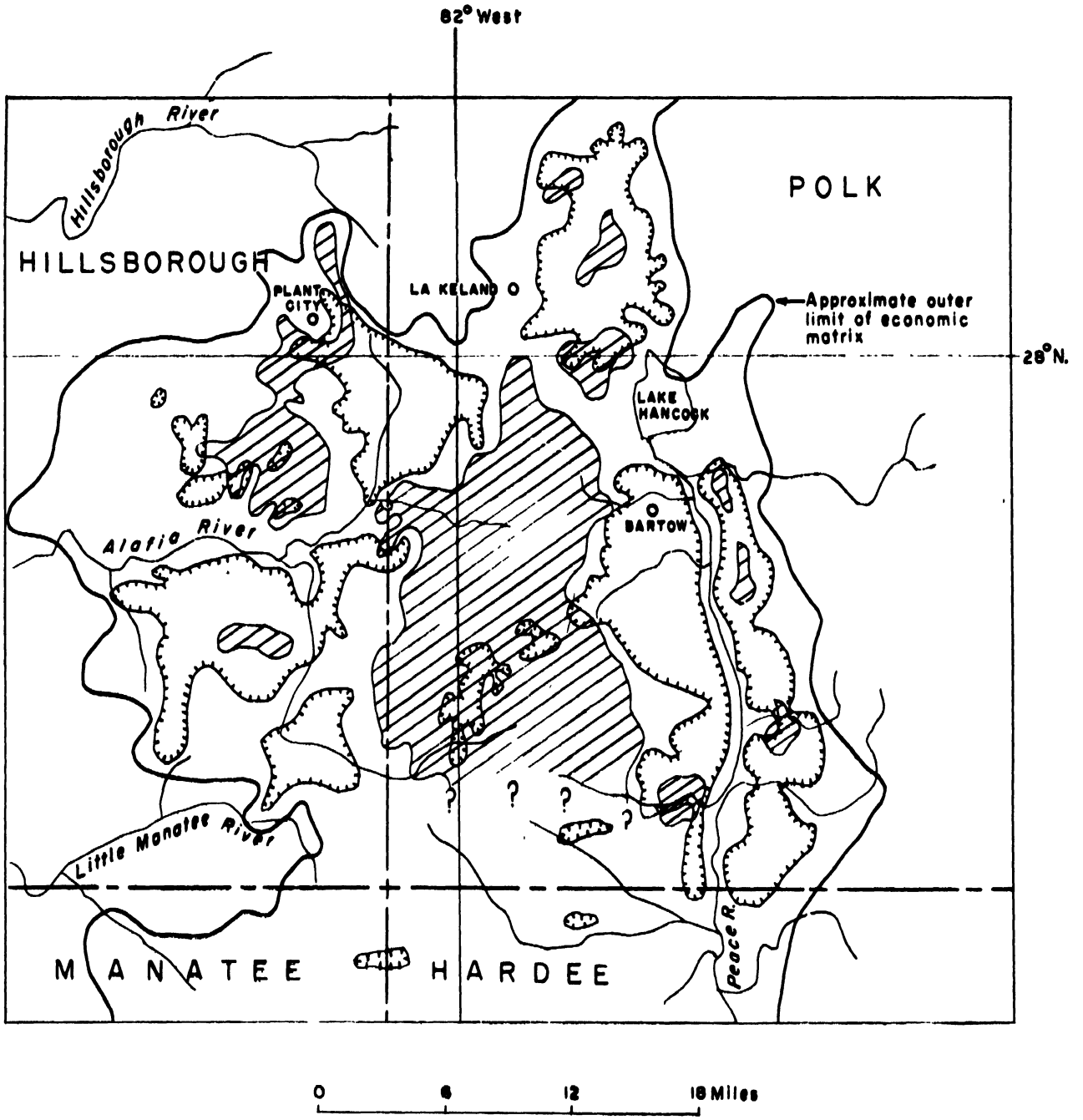
Stratigraphic relations, mining terminology, mineralogy, and average uranium content are summarized in Fig. 2.

The Tampa limestone (lower Miocene) is exposed in only one pit but may form the so-called bedrock in some drill holes in the northernmost part of the district. Only a few feet are exposed at any one locality, but drill records indicate a total thickness of about 70 feet in Hillsborough County. The Tampa is an impure limestone or a calcareous clayey sand, containing traces of phosphate nodules. Carr and Alverson[5] report that 16 samples of Tampa limestone contain an average of 0.3% P_2O_5. The uranium content of the formation is also very low, probably averaging less than 0.001%.

The Hawthorn formation (lower and middle Miocene)[6] conformably overlies the Tampa limestone in some places, but elsewhere the contact is apparently unconformable.[7] The Hawthorn formation ranges from a feather edge in the northern part of the land-pebble district to several hundred feet in thickness in the south and east. Where exposed in the pits, the Hawthorn formation is a soft, buff to yellow, sandy, clayey phosphate-bearing dolomite. In studying cuttings from a deep well, Robert Berman[8] found an abrupt change at 80 feet from a dolomite to a sandy limestone containing some phosphate. The change from dolomite to limestone may be significant, and it is believed that the upper dolomitic zone may be a replacement of the limestone.

"Bedrock," the term used for material too hard to penetrate with the hand-auger method of drilling, is generally the hard dolomite of the Hawthorn formation. Although few samples have been analyzed, the bedrock is typically low in both phosphate and uranium, probably averaging less than 5.0% P_2O_5 and about 0.001% U_3O_8. Apatite nodules in the bedrock are also low in both phosphate and uranium. Although individual samples of nodules may contain as much as 32% P_2O_5, and 0.010% U_3O_8, most are much lower. The average P_2O_5 content of apatite

* US Geological Survey.



EXPLANATION

Hachures point to areas where ratio of coarse to fine phosphate is less than one

Areas where uranium content of phosphate particles is highest (average more than 0.015 percent

Figure 1. Map of the land-pebble phosphate district, Florida

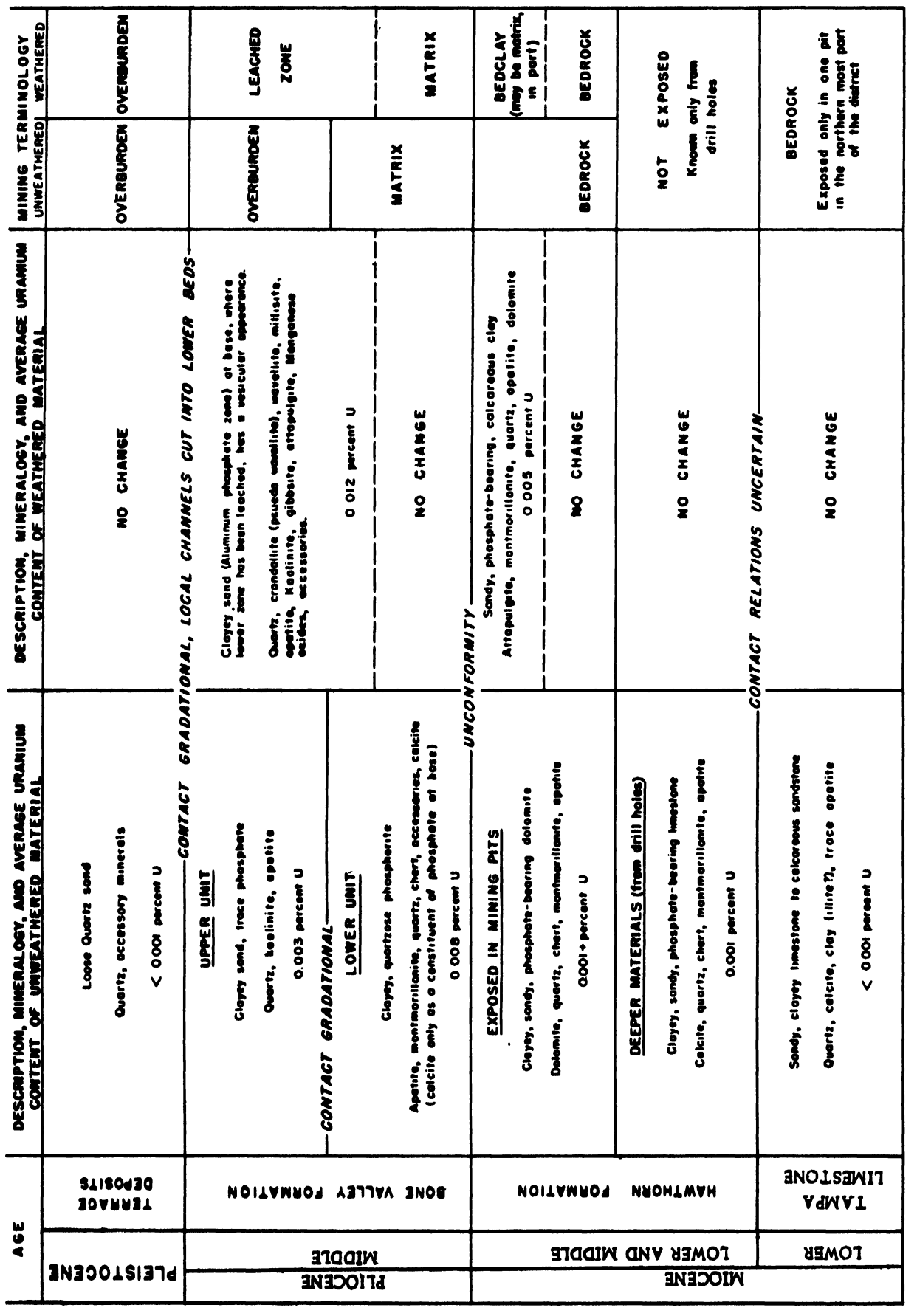


Figure 2. Correlation of stratigraphy, mineralogy, average uranium content and mining terminology, land-pebble phosphate district, Florida

nodules in the bedrock is probably less than 20%, and the average uranium content is less than 0.005%. The remainder of the minerals that make up the bedrock (dolomite, quartz, and montmorillonite) contain practically no uranium.

A thin, discontinuous deposit of soft, water-saturated, plastic sandy clay overlies the dolomite of the Hawthorn formation. This clay is gradational with the material below, and is unconformably overlain by bedded phosphorite deposits, and apparently was derived from the hard dolomite beneath by carbonate leaching. This material, called "bedclay," is mined when the residual concentration of phosphate particles and the P_2O_5 content of the particles is significant, economically. The bedclay often has more uranium than the minable material (matrix) directly above it, but most of the uranium is concentrated in the slime (—150 mesh) fraction. The matrix above the bedclay contains a higher percentage of recoverable phosphate nodules and usually less clay. The bedclay ranges from 7 to about 28% P_2O_5 and from 0.002 to 0.015% U_3O_8 but averages only about 8% P_2O_5 and about 0.005% U_3O_8. Most of the uranium is concentrated in the phosphate minerals of the bedclay; the other minerals, attapulgite, montmorillonite, quartz, and dolomite contain practically no uranium.

The Bone Valley formation is generally regarded as Pliocene in age on the basis of land vertebrates,[9] although it may be uppermost Miocene. Bergendahl[10] shows an interfingering of his "undifferentiated phosphate," in part equivalent to the Bone Valley formation, with a sand containing marine invertebrates that have been regarded as very late Miocene in age. At present, this apparent discrepancy in age assignment has not been resolved.

The Bone Valley formation unconformably overlies the Hawthorn formation. In the northern part of the land-pebble district the Bone Valley formation may be divided into a lower and an upper unit. The lower unit, which ranges from a feather edge to 50 feet in thickness, is about 20 feet in average thickness. The lower unit is a pebbly, clayey, phosphate sand, characterized by crude graded bedding, but in places it is laminated and crossbedded. The unit consists essentially of quartz, apatite, and montmorillonite. Individual beds may range from nearly pure clay or quartz sand to apatite sand or conglomerate. The base of the lower unit is marked by a persistent phosphate conglomerate or sand below which Pliocene land mammals have not been found.

The upper unit of the Bone Valley formation is composed essentially of quartz and montmorillonite clay, with only trace amounts of apatite. The unit ranges in composition from a clayey sand to a sandy clay.

The contact between the upper and lower unit is graduational over a few inches to a foot or more. The basal part of the upper unit contains a small percentage of phosphate nodules, but the upper part of the unit contains little, if any, clastic phosphate.

The lower part of the Bone Valley formation plus the part of the residual Hawthorn that is economic is the calcium phosphate zone or matrix in the district. Although both lithology and thickness vary greatly, the material as mined consists of nearly equal amounts of quartz sand, slime (—150 mesh material), and recoverable apatite nodules. Average matrix contains slightly less than 20% P_2O_5 and about 0.008% U_3O_8. After disintegration, the matrix is washed over a 14-mesh screen. The oversize, a product called pebble, contains between 29 and 34% P_2O_5, and between 0.008 and 0.050% U_3O_8. The undersize is treated in a hydroseparator, the overflow, usually slime, is a waste product. The slime fraction contains an average of about 15% P_2O_5 and 0.005% U_3O_8. The underflow of the hydroseparator is the flotation feed. It is treated in a froth flotation mill, where the quartz and apatite sands are separated. The quartz sands, or tails, a waste product, contain less than 4.0% P_2O_5, and less than 0.001% U_3O_8. The apatite sands, or concentrate, contain between 32 and 37% P_2O_5, and between 0.004 and 0.030% U_3O_8. Because of the loss of P_2O_5 in the slime fraction, about ⅔ of the total phosphate in the matrix is recovered.

The Bone Valley formation has been altered by downward percolating acid ground water, and this zone of alteration is called the leached or aluminum phosphate zone by the mining companies. The leached zone is not a stratigraphic unit, but may effect either the upper unit, or the lower unit, or both. The zone is characterized by the presence of aluminum phosphate minerals, and by a relatively high uranium content. The leached zone ranges from a knife edge to almost 50 feet in thickness, and averages about 8 feet thick, about half the average thickness of the matrix. The uranium and phosphate contents of the zone vary widely, depending on whether the upper or lower parts of the Bone Valley formation were leached. The average composition of the zone is difficult to estimate, but it may contain about 0.012% U_3O_8 and less than 10% P_2O_5.

The uranium content of the Bone Valley formation is closely associated with the phosphate minerals. Clay minerals, montmorillonite in the unleached material, and kaolinite in the leached zone, contain practically no uranium, the quartz sand is essentially barren, and while accessory heavy minerals may contain small amounts of uranium, they are usually not present in more than trace amounts.

Loose quartz sands overlying the Bone Valley formation have been called Pleistocene and have been divided into terraces by several writers.[2,3] With the exception of the 30-foot terrace, which contains abundant invertebrate fossils, only a few horse teeth of Pleistocene age have been found in these sands. The contact with the underlying clayey sands of the upper unit of the Bone Valley formation is commonly gradational, but disconformable relations (channel cutting and filling) have been seen in a few of the mines. The terrace sands commonly contain less than 0.001% U_3O_8, and less than 0.5% P_2O_5.

OCCURRENCE OF URANIUM

Uranium is associated with the phosphate minerals in the land-pebble field. No uranium minerals have been found, except in one locality in the leached zone, where small amounts of autunite were identified by Z. S. Altschuler of the Geological Survey. The highest uranium contents in the field are associated with a bed of soft, white phosphate nodules, at the base of the leached zone. The highest uranium contents seem to be associated with the calcium phosphate minerals. Spherulites of wavellite found in the leached zone contain practically no uranium.[11]

Several hundred samples of the leached zone were chemically analyzed for uranium, phosphate, alumina, iron, fluorine, calcium, and silica. Each sample was of the total thickness of the zone as determined from a gamma-ray log. Table I shows the coefficients of correlation[12] for these samples.

Table 1. Coefficients of Correlation, Leached Zone

Uranium/phosphate	+0.68
Uranium/fluorine	+0.48
Uranium/calcium	+0.47
Uranium/aluminum	+0.24
Uranium/iron	+0.16
Uranium/silica	−0.48

The coefficients of correlation show that the uranium is associated with apatite and not particularly with the aluminum phosphate mineral. The negative correlation of uranium and silica is expected, because silica, in the form of quartz sand, is the principal diluent in the leached zone.

Uranium in the matrix occurs almost exclusively with apatite. Samples of coarse apatite nodules in the matrix are, in general, higher in uranium content, but lower phosphate content than the finer nodules. Many of the finer nodules are primary granules, reworked, at least in part, from the Hawthorn formation, while the coarser nodules are phosphatized limestone. Many coarse nodules contain fossils of Hawthorn age, or apatite pseudomorphs after calcite. Figure 3A is a scatter diagram of U_3O_8 plotted against P_2O_5 for both coarse- and fine-grained samples. Each point on the scatter diagram is a weighted average of the phosphate and uranium content of apatite nodules from many drill holes and each sample represents from 1×10^5 to 1×10^7 long tons of phosphate. The samples are from all the mining companies and are representative of the district. The coefficient of correlation (r) is −0.64, a strong negative correlation, which shows that for all nodules, as the uranium content increases, the phosphate content decreases.

To find the variation of uranium and phosphate content with nodule size, analytical results were tabulated from deposits with different characteristics. Phosphate deposits in the district can be divided into three classes, based on phosphate content and particle size: (*a*) low-grade deposits, predominantly coarse pebble, (*b*) medium-grade deposits of mixed pebble and concentrate (apatite sands), and (c) high-

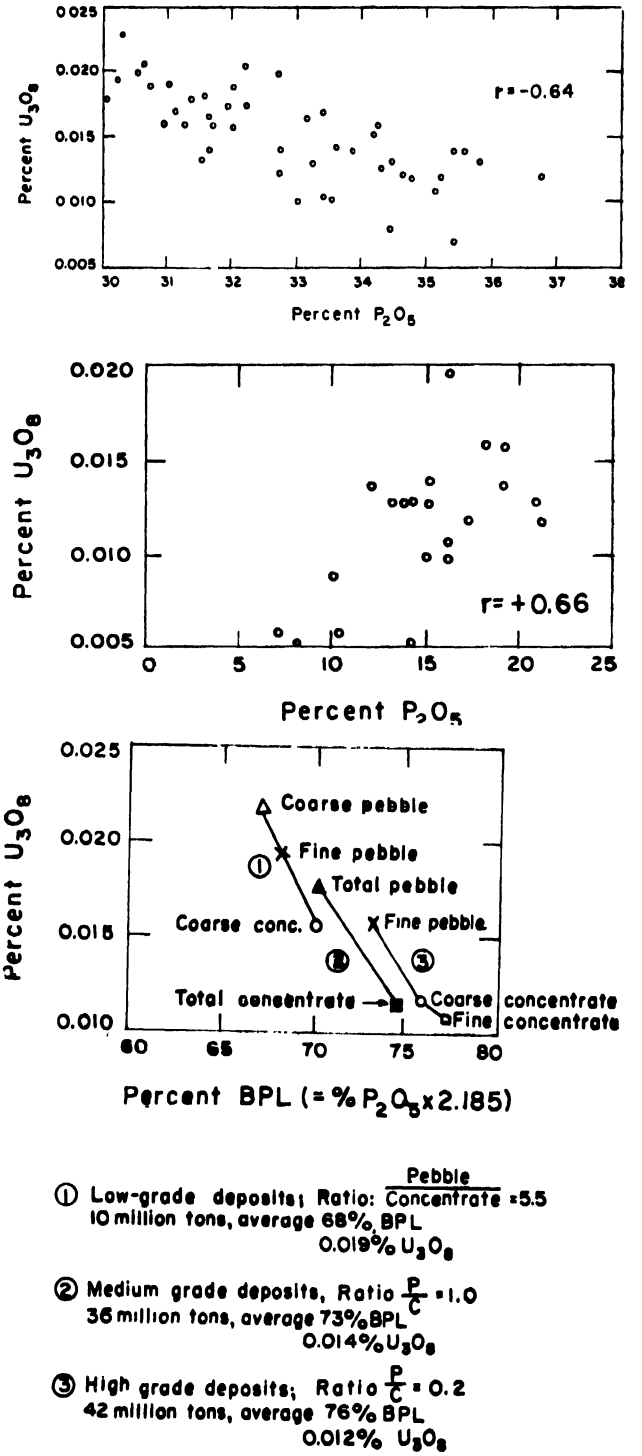


Figure 3. Diagram showing relations of U_3O_8 and P_2O_5 land-pebble phosphate district. Top (A): scatter diagram for apatite nodules, +150 mesh; center (B): scatter diagrams for slime samples, −150 mesh; bottom (C): diagram showing variation in U_3O_8 and P_2O_5 content with nodule size

grade deposits, predominantly concentrate. Weighted averages of hundreds of samples for each of the types of deposit are shown on Fig. 3C. This diagram clearly shows that the phosphate content increases as the size of the nodules decrease, but the uranium content of the nodules decreases as the nodule size decreases. The total uranium content of

the high phosphate deposits is shown to be less than the total uranium content of the lower grade phosphate deposits. Coefficients of correlation were computed for nodules of the same size and from the same deposits, but the results are not conclusive. In general, there is a slight tendency for the sized fractions of apatite nodules to show a small positive correlation, but the coefficients of correlation range from +0.60 through no correlation (close to zero) to —0.26. The slime fractions from these samples, however, did not vary nearly as much, and the average for all samples of slime is +0.66, a good positive correlation (Fig. 3B). In summary, a definite negative correlation is shown between uranium and phosphate content for apatite nodules of all sizes, and an equally definite positive correlation is shown between uranium and phosphate in the slime fraction of the matrix, but the coefficient of correlation within a size grade for the apatite nodules is not as good, and in individual groups of samples may be either positive or negative.

Variations in grain size, and consequent phosphate and uranium content of the apatite nodules in the matrix have been mapped (Fig. 1). Deposits dominantly composed of coarse rock occupy the central portion of the northern part of the land-pebble district, the deposits of finer grained material occupy peripheral areas in the drainage of the Peace and Alafia Rivers. The same figure also shows the higher grade uranium areas, which coincide with the areas of coarser rock and are lowest in phosphate content.

CONCLUSIONS

Davidson[13] has pointed out that in general throughout any single sample, there is a constant U_3O_8/P_2O_5 ratio, and that on acidulation of phosphate rock, the uranium taken into solution is directly proportional to the phosphate dissolved. In addition, abundant evidence from chemical work shows that uranium, which has about the same ionic radius as calcium, proxies for calcium in the apatite of bone.[14] An ionic replacement of this type is a satisfactory explanation for the radioactivity of phosphate deposits. In the land-pebble phosphate deposits of Florida the highest radioactivity is associated with calcium phosphate minerals, and, although the aluminum phosphate minerals do contain higher than average amounts of uranium, at least some of the samples collected contain practically no uranium. This indicates that although uranium probably shows a preference for calcium phosphate, it is present, in some way different than ionic replacement, in aluminum phosphates.

The inverse relation between grain size of the apatite nodules and their uranium content is constant throughout the district. This relation precludes downward percolation of ground waters as a source for the uranium, because the relation holds even in deposits that contain more than 95% of fine-grained apatite nodules. Any downward movement of uranium-bearing solutions through this type of deposit would almost certainly enrich the finer grained nodules. In addition, the nodules in the Hawthorn formation contain less uranium than do those in the Bone Valley formation. These relations can best be explained by assuming that the uranium in these deposits is syngenetic, and was absorbed by the phosphate particles as they formed on the sea floor. The period of weathering that followed the deposition of the Hawthorn formation resulted in the development of a residuum, and this material was available for reworking into the Bone Valley. Thus, phosphate particles originally formed in the Hawthorn sea were exposed a second time to the action of sea water, and are consequently higher in uranium content. In addition, the explanation for the higher uranium content of the coarser particles may be that the coarser particles were exposed for a longer time to the action of sea water by virtue of their size and consequent slower burial.

REFERENCES

1. King, P. B., *The Tectonics of Middle North America; Middle North America East of the Cordilleran System*, Princeton University Press (1951).
2. Cooke, C. W., *Geology of Florida*, Florida Geological Survey Bulletin 29 (1945).
3. MacNeil, F. S., *Pleistocene Shore Lines in Florida and Georgia*, US Geological Survey Professional Paper 221–F (1950).
4. Altschuler, Z. S. and Cisney, E. A., *X-ray Evidence of the Nature of Carbonate-Apatite* [abstract], Geological Society of America Bulletin 63: (1952).
5. Carr, W. J. and Alverson, D. C., in *Geologic Investigations of Radioactive Deposits—Semiannual Progress Report, December 1, 1953 to May 31, 1954*, US Geological Survey TEI–440, US Atomic Energy Commission, Technical Information Service, Oak Ridge, Tennessee, 156 (1954).
6. MacNeil, F. S., *Correlation Chart for the Outcropping Tertiary Formations of the Eastern Gulf Region*, US Geological Survey, Oil and Gas Investigations Preliminary Chart 29 (1947).
7. Carr, W. J. and Alverson, D. C., in *Geologic Investigations of Radioactive Deposits—Semiannual Progress Report*, June 1 to November 30, 1953: US Geological survey TEI–390, US Atomic Energy Commission, Technical Information Service, Oak Ridge, Tennessee, 182 (1953).
8. Berman, Robert, unpublished report.
9. Simpson, G. G., *The Extinct Land-Mammals of Florida*, Florida Geological Survey 20th Annual Report: 257–260 (1929).
10. Bergendahl, M. H., *Stratigraphy of Parts of DeSoto and Hardee Counties, Florida* (in preparation).
11. Bergendahl, M. H., *Wavellite Spherulites in the Bone Valley Formation of Central Florida [abstract]*, Nuclear Science Abstracts: 7, 375 (1952).
12. Snedecor, G. W., *Statistical Methods Applied to Experiments in Agriculture and Biology*, Iowa State College Press, Ames, 138 (1946).
13. Davidson, C. F. and Atkin, D., *On the Occurrence of Uranium in Phosphate Rock*, in Origine des Gisements des Phosphates des Chaux. Comptes Rendus de la XIX Session. Congres-Geologique International, Algiers, 13–31 (1953).
14. Neuman, W. F. *et al.*, *The Deposition of Uranium in Bone*, Journal of Biological Chemistry: 175 and 179 (1948 and 1949).

Uranium in Precipitates and Evaporites

By Kenneth G. Bell,* USA

Chemical sediments generally contain only trace amounts of syngenetically deposited uranium and are not commonly favorable host rocks for epigenetic deposits of this element. The syngenetic uranium content of these rocks tends to be rather uniformly distributed within individual strata but may vary considerably between adjacent strata. Epigenetic uranium deposits in these rocks are generally small, erratic in shape and grade, and most of them have been found at shallow depths within the zone of oxidation.

Most precipitates and evaporites contain less than 4 ppm syngenetic uranium. These low contents result from the chemical environments of deposition. Many chemical sediments are deposited in oxidizing environments where the uranium content of the waters is held in soluble uranyl and uranate ions. Other sediments are deposited from waters containing high carbonate and bicarbonate ion concentrations which inhibit precipitation and adsorption of uranium. Exceptions are found in some marine phosphatic sediments which may contain up to a few hundred parts per million uranium. This uranium appears to be present in isomorphous substitution for calcium in calcium phosphate minerals, and it may not be entirely syngenetic in origin.

Most chemical sediments do not form good host rocks for epigenetic uranium deposits. Low porosities and permeabilities characteristic of many limestones and stratified evaporites do not permit circulation of mineralizing solutions. Many of these rocks, in addition to limestones and dolomites, contain substantial amounts of carbonates which inhibit precipitation of uranium. It is probable that uranium is deposited epigenetically in such rocks only where slightly acid uraniferous groundwaters or hydrothermal solutions are neutralized and only prior to the build-up of significant carbonate or bicarbonate ion concentrations.

Precipitates and evaporites rarely contain enough syngenetic uranium to make these materials valuable as ores under present conditions except as by-products. Many occurrences of epigenetically deposited uranium minerals in these rocks are known, but the deposits are generally small and low grade. The conditions which cause deposition of uranium in the most abundant types of precipitates and evaporites are discussed in the following paragraphs, and brief comments are made concerning a few typical deposits.

* US Geological Survey.

CARBONATE ROCKS

The syngenetic uranium contents of carbonate rocks and sediments are among the lowest of all the rocks of the earth's crust. Marine limestones and dolomites have uranium contents ranging from almost nil to about 4 ppm. Data pertaining to spot samples taken from typical marine calcareous sediments, limestones, and dolomites in the United States are presented in Table I.

The low uranium contents of the carbonate rocks are attributed to two factors: deposition of the sediments in oxidizing environments, and the inhibitory effects of high carbonate and bicarbonate ion concentrations on precipitation and adsorption of uranium.

Some carbonate sediments are precipitated from marine and other waters as a result of changing conditions which reduce the dissolved carbon dioxide content. Conditions of changing temperature and turbulence at rather shallow depths are most effective. Shallow, turbulent waters contain substantial amounts of dissolved oxygen and therefore generally form oxidizing environments unfavorable for the precipitation of uranium. Other carbonate sediments are deposited by biologic process and consist wholly or in part of shells and other skeletal parts of organisms. The organisms live in oxygen-rich environments, and their remains generally accumulate on bottoms where conditions are oxidizing rather than reducing.

It has been known for many years that uranium in the oxidized state is soluble in the presence of high concentrates of carbonate and bicarbonate ions, and this property is utilized in making quantitative separations of uranium from several other elements.[1,2,3] The fact that carbonate and bicarbonate ions are efficient agents for keeping uranium in solution during geochemical processes is made evident by the low syngentic uranium contents of carbonate rocks and by the negative relationship between carbonate and uranium in black shales and phosphatic sediments.[4] Uranium may be deposited epigenetically in carbonate rocks by ground and surface waters containing uranium leached from other rocks, by hydrothermal solutions, and by petroliferous fluids. Most of these deposits are small or consist of low-grade material, but some provide substantial amounts of high-grade ore. Ground and surface waters may leach uranium from mineral deposits and slightly uraniferous rocks and subsequently deposit it else-

Table I. Uranium Contents of Typical Marine Limestones and Dolomites

Formation	Age	Locality	Uranium in ppm
Lomita, bioclastic ls. stratum[a]	Pleistocene	Los Angeles County, Calif.	3.8
Topanga, coquina stratum[a]	Miocene	Los Angeles County, Calif.	3.8
Moenkopi, Sinbad ls. mem.[c]	Early and Middle (?) Triassic	Emery County, Utah	2.0
Moenkopi, Virgin ls. mem.[b]	Early and Middle (?) Triassic	Washington County, Utah	1.7
Redwall[b]	Mississippian	Grand Canyon National Park, Ariz.	0.7
Bright Angel, dolomite stratum[b]	Middle Cambrian	Grand Canyon National Park, Ariz.	1.6
Tomstown, dolomite[b]	Early Cambrian	Jefferson County, W. Va.	0.7
Bass ls.[b]	Precambrian	Grand Canyon National Park, Ariz.	2.4
Altyn ls., dolomite stratum[a]	Precambrian	Glacier National Park, Mont.	1.1
Missoula group[a]	Precambrian	Glacier National Park, Mont.	2.1
Siyeh ls., algal stratum[a]	Precambrian	Glacier National Park, Mont.	0.7

a Samples collected by George Neuerburg, US Geological Survey.
b Samples collected by R. L. Cannon, US Geological Survey.
c Sample collected by R. L. Erickson, US Geological Survey.

where. This action appears to be common in areas characterized by abundant pyroclastic debris. Deposition occurs in materials which readily adsorb uranium, such as carbonaceous rocks and clay, in rocks which can quickly change the chemical character of solutions moving through them, such as limestones and dolomites, and wherever evaporation causes solutions to reach saturation.

Deposits of secondary uranium minerals occur in Tertiary limestones of Wyoming and Utah. Some of the Mesozoic and Tertiary formations of these states include large amounts of pyroclastic material as beds of nearly pure volcanic ash or as debris distributed in other sediments. It is probable that weathering and alteration of the pyroclastics release a part of the uranium which is then leached by slightly acid ground waters. Deposition in the limestones probably occurs mainly as a result of neutralization of the slightly acid waters and consequent lowering of the solubility of uranium. It must occur prior to the build-up of a significant carbonate ion concentration. Evaporation at or near outcrops causes additional deposition of uranium and probably plays a major role in forming the higher grade parts of the deposits.

In the Miller Hills area, Carbon County, Wyoming, there are small uraniferous deposits in a limestone member of the Pliocene(?) North Park(?) formation. This formation consists principally of water-laid pyroclastic debris and includes several fresh-water limestone beds. Uranophane is the only uranium-bearing mineral that has been identified. It coats fracture surfaces and partially fills vugs. Small amounts of uranium are contained in opal and chalcedony which also coat fracture surfaces and partially fill vugs. The uranium is believed to have been leached from thick porous beds of tuffaceous sandstone by ground-water solutions and deposited as secondary concentrations in the limestone. These deposits are small and erratic. The higher grade parts of the deposits occur in brecciated zones in the limestone, especially where these zones are exposed on outcrops or lie under very thin cover.[5]

In the Split Rock area, Fremont and Natrona Counties, Wyoming, uraniferous tufa and travertine recently have been deposited upon a terrane underlain by a thick series of tuffaceous shale, sandstone, and pumicite strata of Pliocene(?) age. The stratified rocks contain up to 60 ppm uranium, and the spring deposits contain up to three times this amount.[6] It is probable that groundwater solutions leached uranium from the tuffaceous material. Deposition at sites of springs probably was caused principally by evaporation because it appears that the flow of water was small, and no significant drainage channels exist in the immediate vicinity of the deposits. There are no visible uranium minerals in the deposits.

The outcrops of some thin limestone beds in the upper part of the Green River formation, near Myton in the Uinta Basin, Utah, are uraniferous. The limestones contain a small amount of tuffaceous material and are interbedded with tuffaceous shales and siltstones. The uranium content of the limestone is as much as 180 ppm; the content of the shales and siltstones has not been determined but is indicated by portable scintillometers to be much lower.

Hydrothermal solutions sometimes deposit uranium in carbonate rocks although the environment appears unfavorable. Deposition probably occurs as acid solutions are neutralized and before the carbonate ion concentration reaches significant proportions. Primary uranium minerals, which may be of hydrothermal origin, are found in the Jurassic Todilto limestone near Grants, McKinley County, New

Mexico. Uraninite and uraniferous fluorite accompanied by pyrite and barite form disseminated deposits in the limestone. The richest uranium deposits contain a large proportion of secondary minerals principally concentrated on fracture surfaces and in vugs. The processes involved in the deposition of the primary uranium-bearing minerals are obscure, and the origin of the mineralizing solutions is a controversial subject. The limestone is petroliferous and fetid. It is possible that acidic solutions were neutralized by contact with the limestone, and the uranium was precipated in a reducing environment caused by the organic material and sulphides. The secondary minerals appear to have been formed in part by alteration of primary uranium minerals and to a greater extent by deposition from solutions which leached uranium from other nearby uraniferous formations.

Heavy petroliferous residues, "dead oil" stains, and asphalt, which remain in rocks after the passage of liquid hydrocarbons, often contain substantial amounts of uranium and other metals. These heavy hydrocarbon residues have been found in all kinds of rocks, but not all of them are uraniferous, and no explanation can be offered to account for this difference. It has been shown that metals contained in crude oils are concentrated in the asphaltic fraction[7,8,9] and that the heavier asphaltic fractions are adsorbed on the surfaces of some sediments.[10] The residues represent a small fraction of the original crude oil, but they may contain a large proportion of the metals originally present in the oil.

Solid asphaltite residues and pellets occur in the lower Permian dolomites of the Panhandle gas field, Texas, and in dolomites of the Seven Rivers gypsiferous member of the Chalk Bluff formation which crop out near Carlsbad, New Mexico. The pellets generally are botryoidal masses less than a millimeter in diameter, but some exceed a centimeter in diameter. The asphaltite appears to replace carbonate minerals rather than fill vugs. Pellets are most abundant near open fractures and may be distributed throughout the remainder of the rock in an apparently random manner. Solid asphaltite also may coat fracture surfaces and form stylolite-like structures. In some localities all of this asphaltite appears to be uraniferous; in other localities apparently similar asphaltite is not appreciably uraniferous. Asphaltite pellets from the Permian dolomites of the Panhandle gas field have been found to contain as much as 1.6 per cent uranium.[11] Even though the asphaltite itself contains significant quantities of uranium, no deposit has been found which contains enough of this material to permit its utilization as ore.

PHOSPHATIC SEDIMENTS

All marine phosphatic sediments are believed to be uraniferous. Phosphatic nodules found in some marine black shales also are uraniferous. The uranium content of these sediments appears to be concentrated in calcium phosphate minerals. In a general way uranium content increases with phosphate content, but the ratio is not constant thereby suggesting that some uranium probably is attached to clay or organic material.[4] Most of the uranium can be separated from phosphates only by chemical methods. It is probable that the greater part of the uranium is present in isomorphous substitution for calcium.

Marine phosphatic sediments probably are deposited along the edges of continental shelves where ascending cold phosphate-rich waters are warmed and the partial pressure of carbon dioxide decreases.[4] A large portion of the uranium content, which may be as much as a few hundred parts per million, probably is truly syngenetic, but there is no reason to believe that adsorption of uranium ceases with precipitation of calcium phosphate. According to McKelvey and Nelson[4] there is a strongly negative relationship between uranium and carbonate in the phosphorites of the Phosphoria formation. This relationship appears to be characteristic of all phosphatic sediments.

The Phosphoria formation of the northwestern United States is a typical marine deposit in which thinly bedded uraniferous phosphate strata are separated by slightly phosphatic shales. The total uranium content increases westward from Wyoming into Idaho with corresponding increases in thickness and phosphate content of the formation. Although uranium content increases in a general way with increasing phosphate content, the most uraniferous beds are not the most phosphatic.[4] Phosphatic nodules enclosed in some black shales—as for example those at the top of the Checkerboard limestone and the Fort Scott limestone of Pennsylvanian age in Oklahoma—are uraniferous, and such nodules generally contain more uranium than the enclosing shale.[4]

EVAPORITES

Evaporites deposited during desiccation of large bodies of water appear to have very small uranium contents even though the ingredients may have been derived from terranes having higher than average amounts of uranium. The meager analytical data pertaining to anhydrite, halite, and saline potash minerals indicate that these materials commonly carry less than 1 ppm of uranium. The uranium contents of several samples of halite and sylvite collected from mines in the Carlsbad district, New Mexico, were found to be too small to be measured by routine chemical methods. Gentner and others[12] report a uranium content of about 0.1 ppm in sylvite from Baden, Germany. Gamma-ray logs of holes drilled through evaporite deposits show very low levels of radioactivity except when potassium-bearing minerals are present.

Waters in desiccating basins are likely to be shallow and subject to turbulence. The environment is oxidizing, and therefore uranium remains in solution. Calcium carbonate concentration reaches saturation during the early stages of desiccation and tends to be stabilized thereafter unless substantial dilution occurs. The carbonate ion concentration acts to hold uranium in solution. As a consequence uranium, unless adsorbed by clays and organic material, probably tends to concentrate in bitterns and is deposited dur-

ing the final stage of complete desiccation. Such uraniferous evaporites appear to be uncommon because desiccation of the basins is rarely complete, and the salts may be blown away by winds or be leached when other sediments are deposited.

A substantial portion of the uranium carried into desiccating basins may be adsorbed by clays and organic material and be deposited in clay or shale strata interspersed in the saline sequence. Analyses of 23 samples of clays and silt-stones taken from drill cores of the saline sections of the Salado formation, Delaware Basin, New Mexico, show uranium contents of as much as 30 ppm.[13] The uranium content of the saline minerals is too low to be determined by standard chemical procedures. Corresponding gamma-ray logs show the radioactivity of clay and silt strata to be substantially greater than that of saline strata except when the latter contain potassium minerals, and furthermore show that the radioactivity of anhydrite and halite strata contaminated with clay, but not potassium minerals, is significantly higher than that of essentially pure saline strata. According to Wengerd and others,[14] thin euxinic black shale lentils interbedded in the salt phase of the Paradox formation of Colorado and Utah can be correlated over wide areas by means of radioactivity logs. A probable concentration of uranium in the black shale is indicated.

Minor deposits of secondary uranium minerals which apparently are of epigenetic origin have been found in gypsum beds. Some small ore-grade deposits occur in the basal 25 feet of nonmarine gypsum and gypsiferous clay facies of the Brule formation of Oligocene age about 12 miles northeast of Chadron, Nebraska.[15] Uranium minerals present are: carnotite occurring as vague irregular veinlets, poorly defined pore fillings, and minute blebs in bedded gypsum; sabugalite $HAl(UO_2)_4 \cdot 16H_2O$ occurring in a similar manner in bedded gypsum; and autunite occurring as fracture coatings and granular aggregates in gypsiferous clay directly above and below bedded mineralized gypsum. The larger and higher grade deposits are in gypsiferous clay. Within bedded gypsum, uranium minerals are restricted to parts containing substantial amounts of carbonaceous material. It is believed that the uranium has been leached from overlying tuffaceous sediments by ground waters and has been carried downward and precipitated in the parts of the gypsiferous facies containing abundant carbonaceous material. Small amounts of secondary uranium minerals have been found in bedded gypsum of the Paradox in Gypsum Valley, San Miguel County, Colorado. This uranium probably has been leached from nearby deposits in sandstones.

CALICHE-TYPE DEPOSITS

Leaching of uraniferous volcanic ash, black shales, lignites, and mineral bodies by ground and surface waters in semi-arid to arid regions may result in extraction of uranium and its subsequent deposition in caliche-like deposits. Soluble minerals such as schroeckingerite and zippeite, and slightly soluble minerals such as carnotite may be deposited in soils and near surface portions of rock formations. These deposits are likely to be locally transient and move about with changing seasons and periods of precipitation. Generally they are small and the uranium content is too low to permit the material to be used as ore.

The best known uraniferous caliche-like deposits in the United States are the Lost Creek schroeckingerite deposits in Sweetwater County, Wyoming. According to Page[16] and Wyant and Sheridan[17] the schroeckingerite occurs as rounded aggregates as much as an inch in diameter in gently dipping clay and silt beds and as tiny flakes in sand or sandy clay. The mineralized part of each bed extends from the surface to a depth of about 8 feet, or a width of about 25 feet along the dip. The deposits appear to be associated with the Cyclone Rim fault which is a major structure of the area. This fault is believed to have been the channel-way for the uranium-bearing solutions. The source of the uranium may be uraniferous lignite beds lying between 300 and 500 feet below the surface or in primary vein material at depth along the Cyclone Rim fault zone. It appears probable that the schroeckingerite is an efflorescent salt formed only near the surface and does not extend to any great depth. It is being dissolved and redeposited currently, and some probably is being formed by the evaporation of ground water containing more uranium from the same source. The grade of the deposits varies considerably, and little of the material meets present specifications for uranium ore.

In some parts of the Colorado Plateau and Wyoming, yellow coatings of carnotite, bayleyite, schroeckingerite, zippeite, and other less common, slightly more or less soluble uranium-bearing minerals appear on walls of mine workings and outcrops where evaporation of ground water occurs. These minerals have been described by Weeks and others.[18] When these deposits appear on outcrops or other surfaces exposed to the weather they are likely to disappear during periods of precipitation and be followed by new deposits when evaporation is resumed. Such superficial deposits generally do not provide ore-grade material, but they demonstrate that significant leaching and redistribution of uranium occurs in zones of ground-water movement.

SILICEOUS PRECIPITATES

Chert, flint, chalcedony, and opal formed in or near uraniferous terranes and in the vicinity of uranium deposits leached by ground waters commonly contain small amounts of uranium. Siliceous precipitates and replacements occurring with secondary uranium deposits also are commonly uraniferous. These siliceous rocks are abundant in some terranes characterized by large amounts of devitrified, weathered, and altered tuffaceous sediments and also may be present in nearby formations. Large amounts of silica are liberated during conversion of vitreous

volcanic sediments to bentonitic clays,[19] and this silica is subsequently precipitated upon neutralization or evaporation of the ground-water solutions. If the tuffaceous sediments happen to be uraniferous some uranium is liberated during devitrification and alteration and is removed in ground-water solutions. Part of this uranium may be adsorbed by siliceous precipitates, the uranium content of which may be as much as about 200 ppm.

Large amounts of uraniferous residual flint and chert nodules lie on erosional surfaces of tuffaceous Tertiary formations in many parts of the Rocky Mountain region, and secondary uraniferous siliceous deposits within the tuffaceous formations and nearby rocks are locally abundant. In the Monument Valley district and elsewhere on the Colorado Plateau deposits of uraniferous secondary silica have formed in the vicinity of altered and leached uranium deposits in the Shinarump conglomerate. None of these siliceous materials are utilized as ores because of their low uranium contents and their refractory character.

Many siliceous precipitates formed on uraniferous terranes and in the vicinity of uranium deposits are fluorescent, whereas similar materials found in other areas may not be fluorescent. Fluorescence is useful in prospecting, but it does not necessarily indicate the presence of nearby minable ore bodies, and it does not always indicate uranium because other elements can cause fluorescence. Investigations by Lewis[20] show that secondary silica occurring distant from ore bodies in barren ground is nonfluorescent, that samples taken near ore contain larger amounts of uranium, and that the fluorescent color varies with increase in uranium content from a pale yellowish green to deep green. This property can be used as a guide in prospecting rim exposures and talus slopes and could be of value in the examinations of drill cores.

REFERENCES

1. Fresenius, R. and Huntz, E., Zeitschrift für analytische Chemie 34: 437 (1895).
2. Rodden, C. J., *Analytical Chemistry of the Manhattan Project,* McGraw-Hill Co., Inc., New York, 31–32 (1950).
3. Scott, W. W., *Standard Methods of Chemical Analysis,* 5th Edition, vol. 1, D. Van Nostrand Co., Inc., New York, 1020 (1952).
4. McKelvey, V. E. and Nelson, J. M., *Characteristics of Marine Uranium-bearing Sedimentary Rocks,* Economic Geology 45: 35–53 (1950).
5. Vine, J. D., written communication (1955).
6. Love, J. D., written communication (1952).
7. Shirey, W. B., *Metallic Constituents of Petroleum,* Industrial Engineering Chemistry 23: 1151 (1931).
8. Thomas, W. H., *Inorganic Constituents of Petroleum, Science of Petroleum,* vol. 2, Oxford University Press; 1053 (1938).
9. Bonham, L. C., *A Geochemical Investigation of Certain Crude Oils,* PhD. thesis, Washington University, St. Louis, Missouri (1950).
10. Nutting, P. G., *Some Physical and Chemical Properties of Reservoir Rocks Bearing on the Accumulation and Discharge of Oils: Problems of Petroleum Geology,* American Association of Petroleum Geologists, 825–832 (1934).
11. Erickson, R. L. *et al., Associations of Uranium and Other Metals with Crude Oil, Asphalt, and Petroliferous Rock,* American Association of Petroleum Geologists Bulletin 38: 2200–2218 (1954).
12. Gentner, W. *et al., Argonbestimmungen an Kalium-Mineralien, III: Verglieichende Messungen nach der Kalium-Argonund Uran-Helium-Methode,* Geochimica et Cosmochimica Acta 5: 124–133 (1954).
13. Jones, C. L., Bowles, C. G. and Bell, K. G., written communication (1955).
14. Wengerd, S. A. and Strickland, J. W., *Pennsylvania Stratigraphy of Paradox Salt Basin, Four Corners Region, Colorado and Utah,* American Association of Petroleum Geologists Bulletin 38: 2157–2199 (1954).
15. Dunham, R. J., written communication (1955).
16. Page, L. R., written communication (1950).
17. Wyant, D. G. and Sheridan, D. M., written communication (1951).
18. Weeks, A. D. and Thompson, M. E., *Identification and Occurrence of Uranium and Vanadium Minerals from the Colorado Plateaus,* US Geological Survey Bulletin 1009-B (1954).
19. Waters, A. C. and Granger, H. C., *Volcanic Debris in Uraniferous Sandstones, and its Possible Bearing on the Origin and Precipitation of Uranium,* US Geological Survey Circular 224 (1953).
20. Lewis, R. Q., written communication (1955).

Mineralogy and Oxidation of the Colorado Plateau Uranium Ores

By A. D. Weeks,* USA

Vanadiferous uranium ores were discovered in western Colorado in 1898, and carnotite, a yellow, secondary, uranyl vanadate mineral, was named the following year.[1,2] Except during short intervals the Colorado Plateau ores have been mined for more than fifty years—at first chiefly for radium,[3] later for vanadium,[4] and recently for uranium.[5] For many years the production was from oxidized ore in shallow mines, and the Plateau ores became charcterized as carnotite ores. Recent extensive exploration and deeper mining, in many places in the Plateau, have penetrated black, unoxidized, vanadiferous ore below or close to the water table and nonvanadiferous ores, both oxidized and unoxidized. Much of the present production is from unoxidized ore. The deposits are now generally referred to as sandstone-type uranium deposits rather than carnotite deposits.

Thanks are due many members of the Geological Survey who have advised or participated in this study, both in the field and the laboratory. Fischer's detailed study of the carnotite and roscoelite ores has contributed much to the knowledge of the oxidized deposits.[4] Coleman has contributed to the mineralogy of the primary ores through study of thin and polished sections and minor element content of sulfides. Thompson has worked on mineral identification by optical properties and X-ray diffraction powder patterns and contributed to the description of new minerals. Stieff and Stern, in connection with their age-determination studies,[6] have identified three new minerals.[7,8] Garrels[9,10] and Evans[11] have studied the chemistry of the ores and the crystal structure of the minerals. Chemists, spectrographers, and X-ray crystallographers have done much analytical work, and many field geologists have aided in the collection of samples.

CLASSIFICATION

The Plateau uranium ores are classified on the basis of whether or not vanadium is associated with the uranium.[12] The presence of vanadium has an important chemical and mineralogic control on the uranium during the oxidation of the ore. The nonvanadiferous uranium ore contains traces of several metals and locally as much as 1% of copper. The two main types may be subdivided into highly oxidized and relatively unoxidized ore. Mineralogically the types differ greatly because the affinity of vanadium for uranium tends to make the uranyl vanadates, carnotite and tyuyamunite, the chief uranium minerals in oxidized vanadiferous ore, whereas the oxidation of uraninite in nonvanadiferous ore produces a greater variety of secondary yellow and greenish-yellow uranyl minerals such as hydrated oxides, carbonates, sulfates, phosphates, arsenates, and silicates.

MINERALOGY OF THE PRIMARY ORES (UNOXIDIZED)

Vanadiferous Ores

The primary vanadium-uranium ores are characterized in general by their black color and by the presence of low-valent uranium and vanadium oxides; and copper, iron, lead and zinc sulfides, arsenides and selenides. These ores should not be confused with the blue-black or corvusite ores, which represent an intermediate stage of oxidation. The ores have a great range of vanadium content and for convenience in description they have been divided into groups on the basis of their vanadium-uranium ratios.

Vanadiferous ores with vanadium-uranium ratio greater than 15:1 are characterized by the dominance of vanadium silicates over vanadium oxides and the general lack of fossil wood. The unoxidized ores in the Entrada sandstone (Jurassic) of the Rifle and Placerville districts in western Colorado are representative of this group and appear to have a monotonous and simple mineralogy. Roscoelite is the dominant vanadium mineral occupying the intergranular areas as fine-grained micaceous aggregates. In roscoelite-rich stringers the quartz is strongly corroded, and in less heavily mineralized sandstone replacement of detrital quartz is not apparent. Montroseite[13] is interleaved with the roscoelite aggregates as small, discrete, crystalline rosettes. Paramontroseite may locally supersede montroseite where oxidation has commenced. Calcite or dolomite commonly accompanies the montroseite and roscoelite and appears to be contemporaneous with the vanadium mineralization. Minor but persistent are the sulfides galena and chalcopyrite accompanied by scarce pyrite and marcasite.

Ores with vanadium-uranium ratios ranging between 15:1 and 1:1 occur extensively in the Salt Wash sandstone member of the Morrison formation (Late Jurassic) and to a lesser extent in the Shinarump conglomerate and Chinle formation (Triassic)

* US Geological Survey.

and in other formations. The uranium is fixed in uraninite and coffinite and almost without exception is associated with coalified wood or other carbonaceous material. The latter includes the much misused term "asphaltite" which has not, as yet, been established as an abundant constituent of the Colorado Plateau ores. Uraninite replaces the cell walls of the wood structure in preference to the cell cavities. If the cavities are vacant, the uraninite also forms in this area. In some cases the cell cavities are filled by sulfides. Where the original wood structure was collapsed or vitrainized, or both, during diagenesis, the uraninite intimately impregnates or replaces the wood and faithfully retains the coaly structures. Uraninite deposited in the sandstone bordering fossil wood may show replacement of earlier sulfides, of detrital quartz, or be intimately intergrown with calcite or dolomite. Coffinite is always found within coalified wood where it fills the cell cavities. The vanadium is fixed as an oxide in only one primary mineral, montroseite, which is easily oxidized to the more commonly observed paramontroseite.[13,14] In places, montroseite impregnates the fossil wood by filling cell cavities, but the growth of its elongate crystals soon obscures the wood structure. Typically its strong crystallinity causes the formation of rosettes and bands of intricate and sinuous nature, either in contraction fractures in fossil wood or in interstitial areas of the sandstone. Pyrite and marcasite are the commonest sulfides associated with the primary ores, and two distinct generations of iron sulfides have been recognized. Sulfides formed during diagenesis impregnate or form pseudomorphs after wood or occur as nodules and are considered pre-ore. Euhedral and massive pyrite associated with uraninite and galena are considered penecontemporaneous with the mineralization. Detailed study of the iron sulfides shows that those associated with mineralization have been enriched in cobalt and nickel relative to the diagenetic sulfides. Galena is commonly present within the uraninite and as later vein material cutting uraninite, indicating two generations. Calcite-dolomite mixtures with a small amount of barite make up a large part of the gangue. Mines in the Jo Dandy area on the faulted margin of the Paradox salt anticline, Montrose County, Colorado, commonly contain gypsum that is a pre-ore intergranular cement. Minor amounts of selenides including clausthalite and eucairite are found in some mines, and as yet it is not entirely certain whether the selenium is derived from and restricted to certain seleniferous stratigraphic horizons.

Nonvanadiferous Ores

Deposits in which vanadium is negligible and uranium is the only ore of importance (except where copper may be locally of commercial importance) occur chiefly in the Shinarump conglomerate and basal sandstones in the Chinle formation (Triassic). The ore is found mainly in channels that contain carbonaceous material and mudstone beds; these channels are along the thin edge (pinch-out) of the conglomerate and sandstone beds that fill cuts in the underlying formation.[15] The Happy Jack mine,[16] San Juan County, and the Delta mine, Emery County, Utah, are good examples of this group. These ores do not have the intense black color of the vanadiferous ores because the black vanadium oxide, montroseite, is lacking. In the primary ores, uranium is contained chiefly in uraninite,[17] and coffinite is scarce or lacking. Fossil wood is again the main control of the uraninite deposition, and the wood is replaced in the same manner as described above. More sulfides are associated with uraninite in some of these ores and a more complicated mineralization sequence is evidenced by ambiguous relations between the uraninite and sulfides. Two generations of pyrite have also been established in these primary ores with the pyrite in the uraninite showing rims of unidentified nickel and cobalt minerals—further evidence of nickel-cobalt enrichment accompanying the uranium mineralization. Copper sulfides, including chalcopyrite, bornite, chalcocite, and covellite, are dominant in some mines, and lead, zinc, and iron sulfides dominate in others. Galena is commonly associated with uraninite either as early, euhedral cubes or as late vein material. Molybdenum sulfide(?) in trace amounts commonly occurs in mineralized wood. Silver has been noted in spectrographic analyses of sulfide concentrates, but no silver minerals have been identified. Some uraninite ores have very little accompanying sulfide; these ores are difficult to recognize in the field and must be prospected by careful search with a Geiger or scintillation counter.

OXIDATION SEQUENCE AND MINERALOGY OF VANADIFEROUS URANIUM ORES

Corvusite Ore, Partly Oxidized

The primary ores are stable in reducing environments after emplacement and generally retain their original minerals and texture if they are not exposed to oxidizing conditions. Those ores which have remained below the zone of oxidation, i.e., water table, retain their primary character. In the Colorado Plateau, various stages of oxidation may be found superimposed on the primary ores because the deposits occur in many different situations with respect to the water table and also because of variable water retention capacities of the pore space of the ore sandstones.

The numerous vanadium minerals are very sensitive to changes in oxidation and pH,[9,10,18] and therefore they serve as convenient indicators to the degree of oxidation and the pH of the environment during oxidation. Montroseite, VO(OH), oxidizes readily[14] to paramontroseite, VO_2, when exposed to air, as evidenced by the fact that most montroseite specimens in the laboratory alter in a few months' time. Four new vanadium(IV) minerals are currently being studied by members of the US Geological Survey. Uraninite is altered as uranium(IV) oxidizes to uranium(VI), although this may not be determined visually. The early oxidation of the primary uranium

minerals apparently disperses the uranium into an unknown phase that may be colloidal. The sulfides are still fresh and unaltered after oxidation of uraninite and montroseite has commenced.

Further oxidation of the ores causes a change in color from black to blue-black in ores of the corvusite stage. Some greenish-black and brown colors also appear at this stage. The vanadium(IV) minerals alter to a group of vanadium compounds containing various proportions of vanadium(IV) and (V) with some calcium and iron.

Vanadium(V) combines with all available uranium(VI) to form the ill-defined and sometimes inconspicuous mineral rauvite,[19] which may be dispersed in microscopic aggregates in massive corvusite or form glassy, gel-like coatings on quartz grains, pebbles, or contraction fractures in mineralized wood. Rauvite ranges in color from purplish black and brownish red in the gel-like varieties to orange-red in the powdered aggregates.

The best crystallized of the vanadium minerals is melanovanadite, for many years known only from the type locality in Peru and now recognized in several mines in the Plateau. Most of the vanadium(IV) and (V) material shows a very complex and intimate mixture of minerals quite similar in nature and generally referred to as corvusite. The molecular ratio of vanadium(V) to (IV) ranges from 6 in the corvusite originally described by Henderson and Hess[20] to somewhat lower values in other analyzed corvusite-like minerals.

By the time the corvusite stage is reached, some of the associated minerals begin also to show a response to the oxidizing conditions. The sulfides alter to oxides and sulfates, and selenides may alter to native selenium.[21] Depending on the relative abundance of calcite with respect to pyrite in the primary ore, part or all of the calcite gangue and cement in the sandstone may be dissolved, and the sandstone may be partly recemented by gypsum and iron oxides.

Carnotite Ore, Highly Oxidized

As oxidation progresses carnotite and tyuyamunite develop chiefly from rauvite, and some may form in other ways. Once crystallized, the carnotite is remarkably stable and fixes the uranium very effectively. The minerals containing vanadium(IV) and (V) of the corvusite stage oxidize to form vanadium(V) minerals. The specific ones formed depend closely on pH conditions,[18] on the presence of certain cations to combine with vanadium, and on several other factors. Vanadium fixes all available uranium in uranyl vanadates, and the excess vanadium forms the hydrated pentoxide, navajoite,[22] or more commonly combines with calcium, sodium, potassium, magnesium, aluminum, iron, or copper to form one or more of the vanadates—hewettite, pascoite,[23] rossite,[24] sodium vanadate,[12] hummerite,[12] steigerite,[25] fervanite,[26] volborthite, and calciovolborthite. These vanadates range in color from brown through red, orange, yellow, green to nearly colorless.

In the Colorado Plateau, carnotite is probably more abundant than tyuyamunite in the oxidized ores of the Uravan mineral belt of western Colorado and eastern Utah.[27] High calcium content of the sediments in the Grants district and Shiprock district of New Mexico causes local predominance of tyuyamunite. In areas where the vanadium-uranium ratio is low, small amounts of other uranium minerals may occur, as uranophane, near Grants, New Mexico, and autunite, andersonite, schroeckingerite, and zippeite in the Thompson district, Grand County, Utah.

MINERALOGY OF OXIDIZED NONVANADIFEROUS URANIUM ORES

Uranium Minerals

The nonvanadiferous uranium ores differ notably from the vanadiferous because oxidation of uraninite in the absence of vanadium produces a greater variety of secondary uranium minerals. These include hydrated oxides, carbonates, sulfates, phosphates, arsenates, and silicates. They are microcrystalline or massive and range in color from orange through yellow and greenish yellow to green. They fill pore spaces or minute fractures in sandstone, conglomerate, or fossil wood and coat joint surfaces and mine walls. Among these minerals, none is as predominant as is carnotite in the oxidized vanadiferous ore.[12] In general, these secondary minerals are close to unoxidized remnants of the primary minerals from which they developed. They do not form large deposits of oxidized ore as does carnotite, since their relative solubilities are much greater than that of carnotite.

The hydrated uranium oxides are rare and small in quantity because sulfate, carbonate, or some other anion is usually present to combine with uranium. Small amounts of becquerelite, schoepite, and fourmarierite are closely associated with oxidizing uraninite.

In the oxidation of sulfide-rich uraninite ore the most abundant secondary uranium minerals are the uranyl sulfates—johannite, uranopilite, zippeite, and other unidentified zippeite-like minerals. These green, yellowish-green, and deep-yellow minerals are beautifully developed on the walls of Happy Jack mine in White Canyon, San Juan County, Utah.[16]

The uranyl carbonates are commonly developed wherever the sulfide content of the ore is low, and the host, or gangue, contains sufficient carbonate, as at Shinarump No. 1 mine, Grand County, Utah.[28] Six uranyl carbonates have been found on the Colorado Plateau, including liebigite, rutherfordine, and schroeckingerite; and three new carbonates, bayleyite,[29] andersonite,[30] and rabbittite.[31] Most of these are readily soluble in water and would be washed away almost as rapidly as they develop were it not for the semi-arid climate of the Plateau.

The uranyl phosphates are rare in the Plateau because the sandstone host rock is low in phosphate except where fossil bones are preserved. Small amounts of autunite, phosphuranylite (possibly an

alteration product of autunite), torbernite, and bassetite have been found. Small amounts of uranyl arsenates are present: metazeunerite at several localities in Utah, and novacekite,[32] and abernathyite[33] at one locality each. The uranyl silicates, uranophane, sklodowskite, and cuprosklodowskite are rare in the Plateau. The unknown sulfates, phosphates, and silicates that are being studied probably include several new minerals.

Secondary Minerals of Copper and Other Metals

Copper, the chief associated metal in some of the nonvanadiferous ore, occurs in many secondary minerals, commonly as malachite, azurite, chalcanthite, antlerite, brochantite, and chrysocolla, and rarely as conichalcite, chalcoalumite, and volborthite. Several other metals are present and differ in abundance from one mine to another: iron and manganese in limonite and wad, cobalt in bieberite (commonly dehydrated), cobaltocalcite, erythrite, or cobaltoan pickeringite, molybdenum in ilsemannite or ferrimolybdite, and traces of lead, zinc, nickel, and silver.[12]

The presence of brightly colored copper, cobalt and molybdenum secondary minerals on the rock outcrop or on joint surfaces within a few feet of the cliff face is helpful to the prospector, but many small copper deposits on the Plateau do not contain uranium.

Clay lenses in the ore and mudstone or shale underlying ore are commonly bleached and altered by development of one or more of the following: kaolinite, jarosite, alunite, or gibbsite. Fluorescent uraniferous opal and allophane coat some joint surfaces.

RELATION OF OXIDATION TO WATER TABLE AND MOISTURE CONTENT OF ORE

Second in importance only to the range of primary composition of the Colorado Plateau uranium ores is their range in degree and depth of oxidation. Oxidation depends on access of air to the ore as in exposed rocks with no soil cover and where evaporation is high, in relatively continuous permeable sandstone beds high above the water table, and in strata truncated down dip by a canyon. Oxidation has been prevented or retarded where water is held in the pore space of the ore sandstone, as in strata protected by thick soil cover, in lenticular sandstone beds surrounded by clay, in strata above a perched water table, and in strata that dip away from the valley wall.

A good example of unoxidized ore below or close to the water table is at the Peanut mine, Montrose County, Colorado. The mine is wet because it is situated in a small basin along the axis of the syncline between Paradox and Gypsum salt anticlines.[34] The water is being tapped gradually by headward erosion of Bull Canyon. The wet, unoxidized ore consists of montroseite, uraninite, sulfides, and traces of selenides in lenticular sandstones and mudstones cemented by calcite. Close above the water table where oxidation has begun, the ore contains an unusual development of vanadium(IV) minerals.

The Corvusite mine on Beaver Mesa, Grand County, Utah, is a good example of partly oxidized ore with small remnants of unoxidized ore. The deposit was mined intermittently for more than 40 years and was the type locality for the mineral corvusite.[20] The mine is located on the updip side of the mesa toward the La Sal Mountains, and the ore is in richly mineralized fossil trees and relatively small sandstone lenses interbedded with thick clay that retains moisture in the ore. The mesa is more than 7500 feet above sea level, has considerable soil cover and vegetation, cool temperature, low evaporation, and possibly more rainfall than the lower parts of the Plateau. All these factors contribute to the continued dampness of the ore and have prevented more than partial oxidation although the mine is high above the main regional water table.

The dry mines with highly oxidized ore may be classified in three groups. Some carnotite deposits apparently have been oxidized in place with practically no movement of material. Some have been modified during the corvusite stage of oxidation, by migration of water-soluble vanadium down dip and by accentuation of the boundary of ore rolls[4] to form "breakaway surfaces." Ore sandstone directly at the surface of the ground probably has been leached of some uranium and vanadium by alkaline surface and ground water.

The Rattlesnake mine in the north end of Lisbon Valley, San Juan County, Utah, has highly oxidized ore in dry friable sandstone. The yellow and brown ore has a spotted and banded texture giving the appearance of oxidation in place. Many carnotite-rich logs found in various mines appear to be the oxidized product of fossil wood impregnated with montroseite and replaced by uraninite. The wood cell structure so commonly observed in polished sections of uraninite is destroyed by volume changes during oxidation, and carnotite "logs" show only the gross feature of the wood.

The Club Group of mines on the sandstone bench of the Salt Wash member of the Morrison formation above the San Miguel Canyon at Uravan, Montrose County, Colorado, are dry with chiefly oxidized ore and abundant ore rolls with "breakaway surfaces." The strata dip toward the canyon allowing water to drain through the more permeable sandstone beds. Higher on Club Mesa, a mine at a depth of 260 feet is also dry and has chiefly oxidized ore with well-developed ore rolls and a small amount of corvusite ore. Water seeping through the sandstone and evaporating on the mine walls forms pascoite. The small pockets of corvusite have barite that is coated with radioactive daughter products of recently oxidized primary ore minerals. Still higher on Club Mesa a mine at a depth of 500 feet is moderately dry although shale overlying the ore sandstone is wet. The ore is partly oxidized with a few remnants of coffinite and montroseite. This series of mines illustrates the gradation in oxidation and the leaching of water-soluble vanadium compounds where water

moves through partly oxidized ore. Another series of mines, called the Lower Group, near Slickrock in San Miguel County, Colorado, illustrates the same processes.

Where small dry mesas are capped by the ore sandstone as at the Eastside Carrizo mines, west of Shiprock, New Mexico, the chief vanadium mineral is vanadium hydromica or another vanadium clay mineral. The ore of light, even gray color is low in uranium which is present in thinly disseminated yellow grains of tyuyamunite in the sandstone or as a coating of tyuyamunite on the joint surfaces. Some uranium seems to have been leached from these surface deposits, probably by recent alkaline ground water. Hewettite, a common vanadium mineral in deeper mines, has probably been leached by alkaline ground water also.

Although many details of the oxidation history have not been investigated as yet, the oxidation studies are helping to clarify the problem of origin of the ore by eliminating from consideration those features formed during oxidation and the modifications made by recent ground water.

REFERENCES

1. Friedel, C. and Cumenge, E., *Sur une nouvelle espéce minérale, La Carnotite,* Comptes Rendus, 128: 532 (1899).
2. Hillebrand, W. F. and Ransome, F. L., *On Carnotite and Associated Vanadiferous Minerals in Western Colorado,* US Geological Survey Bulletin 262, 9–31 (1905).
3. Coffin, R. C., *Radium, Uranium, and Vanadium Deposits of Southwestern Colorado,* Colorado Geological Survey Bulletin 16 (1921).
4. Fischer, R. P., *Vanadium Deposits of Colorado and Utah,* US Geological Survey Bulletin 936–P, 363–394 (1942).
5. Fischer, R. P., *Uranium-bearing Sandstone Deposits of the Colorado Plateau,* Economic Geology, 45: 1–11 (1950).
6. Stieff, L. R., Stern, T. W. and Milkey, R. G., *A Preliminary Determination of the Ages of Some Uranium Ores of the Colorado Plateau by the Lead-Uranium Method,* US Geological Survey Circular 271 (1953).
7. Stieff, L. R., Stern, T. W. and Sherwood, A. M., *Preliminary Description of Coffinite—a New Uranium Mineral,* Science, 121: 608–609 (1955).
8. Stern, T. W. *et al.*, and Meyrowitz, R., *The Occurrence and Properties of Metatyuyamunite,* $Ca(UO_2)_2(VO_4)_2 \cdot 3\text{–}5H_2O$, American Mineralogist (in press).
9. Garrels, R. M., *Some Thermodynamic Relations Among the Vanadium Oxides and Their Relations to the Oxidation State of the Uranium Ores of the Colorado Plateaus,* American Mineralogist, 38: 1251–1265 (1953).
10. Garrels, R. M., *Thermodynamic Relations Among the Uranium Oxides, and Their Relation to the Oxidation States of the Uranium Ores of the Colorado Plateaus,* American Mineralogist, 40: 317 (1955).
11. Evans, H. T., Jr. and Block, S., *The Crystal Structure of Montroseite, a Vanadium Member of the Diaspore Group,* American Mineralogist, 38: 1242–1250 (1953).
12. Weeks, A. D. and Thompson, M. E., *Identification and Occurrence of Uranium and Vanadium Minerals from the Colorado Plateaus,* US Geological Survey Bulletin 1009–B (1954).
13. Weeks, A. D., Cisney, E. A. and Sherwood, A. M., *Montroseite, a New Vanadium Oxide from the Colorado Plateaus,* American Mineralogist, 38: 1235–1241 (1953).
14. Evans, H. T., Jr. and Mrose, M. E., *A Crystal Chemical Study of Montroseite and Paramontroseite,* American Mineralogist (in press).
15. Finch, W. I., *Preliminary Geologic Map Showing the Distribution of Uranium Deposits and Principal Ore-bearing Formations of the Colorado Plateau Region,* US Geological Survey Mineral Investigations Field Studies Map, MF16 (1955).
16. Trites, A. F., Jr. and Chew, R. T., III, *Geology of the Happy Jack Mine, White Canyon Area, San Juan County, Utah,* US Geological Survey Bulletin 1009–H (1955).
17. Rosenzweig, A., Gruner, J. W. and Gardner, L., *Widespread Occurrence and Character of Uraninite from the Triassic and Jurassic Sediments of the Colorado Plateau,* Economic Geology, 49: 351–361 (1954).
18. Marvin, R., *CaO — V_2O_5 — H_2O System (Abstract),* American Mineralogist, 40: 326 (1955).
19. Hess, F. L., *New and Known Minerals from the Utah-Colorado Carnotite Region,* US Geological Survey Bulletin 750, 63–78 (1925).
20. Henderson, E. P. and Hess, F. L., *Corvusite and Rilandite, New Minerals from the Utah-Colorado Carnotite Region,* American Mineralogist, 18: 195–205 (1933).
21. Thompson, M. E. *et al., New Occurrences of Native Selenium,* American Mineralogist (in press).
22. Weeks, A. D., Thompson, M. E. and Sherwood, A. M., *Navajoite, a New Vanadium Oxide from Arizona,* American Mineralogist, 40: 207–212 (1955).
23. Hillebrand, W. F., Merwin, H. E. and Wright, F. E., *Hewettite, Metahewettite, and Pascoite, Hydrous Calcium Vanadates,* Proceedings of the American Philosophical Society, 53: 31–54 (1914).
24. Foshag, W. F. and Hess, F. L., Rossite and Metarossite, *Two New Vanadates from Colorado,* Proceedings US National Museum, 72: 1–12 (1927).
25. Henderson, E. P., *Steigerite, a New Vanadium Mineral,* American Mineralogist, 20: 769–772 (1935).
26. Hess, F. L. and Henderson, E. P., *Fervanite, a Hydrous Ferric Vanadate,* American Mineralogist, 16: 273–277 (1931).
27. Fischer, R. P. and Hilpert, L. S., *Geology of the Uravan Mineral Belt,* US Geological Survey Bulletin 988–A, 1–13 (1952).
28. Finch, W. I., *Geology of the Shinarump No. 1 Mine, Seven Mile Canyon Area, Grand County, Utah,* US Geological Survey Circular 336 (1954).
29. Stern, T. W. and Weeks, A. D., *Second Occurrence of Bayleyite in the United States,* American Mineralogist, 37: 1058–1060 (1952).
30. Axelrod, J. M., Grimaldi, F. S., Milton, C. and Murata, K. J., *The Uranium Minerals from the Hillside Mine, Yavapai County, Arizona,* American Mineralogist, 36: 1–22 (1951).
31. Thompson, M. E., Weeks, A. D. and Sherwood, A. M., *Rabbittite, a New Uranyl Carbonate from Utah,* American Mineralogist, 40: 201–206 (1955).
32. Stern, T. W. and Annell, C. S., *A Second Locality of Novacekite,* American Mineralogist, 39: 675–676 (1954).
33. Thompson, M. E., Ingram, Blanche and Gross, E. B., *Abernathyite, a New Uranium Mineral of the Metatorbernite Group,* American Mineralogist (in press).
34. Cater, F. W., Jr., *Geology of Bull Canyon, Montrose and San Miguel Counties, Colorado,* US Geological Survey Geologic Quadrangle Map GQ 33 (1954).

A Comparison of Black Uranium Ores in Utah, New Mexico and Wyoming

By John W. Grunder*, USA

Most if not all of the uranium deposits in sedimentary rocks in the Western United States were originally deposited in the form of reduced uranium minerals, that is, in the uranous state (U^{4+}). Due to the easy oxidation of the two uranous minerals, uraninite and coffinite, to the uranyl state (UO_2^{++}), practically all deposits display yellow, orange and green minerals on their outcrops and often to considerable depths. Comparisons of the black ore of the Wind River Basin, Wyoming, with some of the black ores of the Colorado Plateau show some similarities in the mineralogy and texture as well as in processes which led to their origin.

For comparison, deposits in four localities, widely separated, were chosen: (1) in the Tertiary Wind River formation at the Gas Hills anticline, Fremont County, Wyoming; (2) in the Triassic Chinle formation at Lisbon Valley, San Juan County, Utah; (3) in the Moss Back member of the Triassic Chinle formation at Temple Mountain, Emery County, Utah and (4) in the Brushy Basin shale member of the Jurassic Morrison formation at Poison Canyon in Grant County, New Mexico.

Discussions with many geologists of the Atomic Energy Commission and the U.S. Geological Survey have been of aid in gaining a comprehension of the local and regional geology.

GEOLOGICAL SETTING

Except for age differences the rocks are on the whole similar fresh-water sediments in which volcanic tuffs are prominent constituents, particularly above the sandstones containing the deposits. The angularity of the grains and archosic character of the sandstones points to a similarity of source rock of pre-Cambrian granites which must have been close by. There is no difficulty in accounting for these granites as they crop out within ten to twenty miles of three of the localities. Only the Temple Mountain area is farther from recognized granitic outcrops at present.

One could suggest a genetic relation between these deposits and their uranium which could have been easily leached from weathered granite by ground water. It is, however, less speculative to think of the coarse archosic sandstones as easy channel ways for ground water circulation.

Paleostream channels have not been identified in any of the four areas as far as the writer is aware, but large structures such as the Lisbon anticline and San Rafael Swell are present. These could have guided ground waters. Poison Canyon lies on the north flank of the Zuni Uplift, but the dip on this flank toward the San Juan Basin is gentle. It alone cannot explain the location of the deposits. The same may be said for the Gas Hills anticline area where no single, distinctive structure can be made responsible for the position of the deposits. One explanation is that vast volumes of ground water containing uranium passed through carbonaceous material which was at a favorable stage of decay to absorb the metal. In its first phase this process could be compared with ion exchangers. There is no mineralogical indication that the waters were hotter than ordinary ground water under correspondingly thick sedimentary cover.

PARAGENESES

In the tabulation below, similarities and differences in the four deposits are pointed out. There are few differences which would suggest that the deposits are dissimilar in origin. The absence of vanadium in as large an area as the Wind River Basin is notable. It could be related to the relative scarcity of plant remains though analyses show considerable organic carbon. Or, perhaps, the Wind River formation as a whole is low in vanadium. The abundance of hydrocarbons as "dead" oil in the Temple Mountain area has not been thought genetically important by most observers.

Arsenic compounds have been noted here; they are also rather common in the Wind River Basin.

The more detailed genetic relations are obscure in all of the deposits because cross cutting of minerals does not mean much where we are dealing with extremely fine-grained aggregates. Besides, such minerals as calcite, gypsum, montroseite, and other vanadium minerals recrystallize easily, which may lead to erroneous interpretations of parageneses. In spite of these drawbacks the relations definitely show the same pattern for all four deposits as may be seen from the following comparisons:

Lisbon Anticline, Utah

Chinle formation (Triassic), at and near Mi Vida mine

1. Much shale and siltstone interstratified with sandstone and conglomerate

* University of Minnesota.

2. Red-colored rocks prominent above and below but not in deposits
3. Little sorting in sandstones
4. Largely archosic. Angular to subangular grains
5. Fine-grained sandstone to mud pebble conglomerates
6. The more irregular and disturbed the beds are, the better the ore
7. Clay fragments in matrix very common
8. Much carbonaceous plant material
9. Much calcite as cement. Detrital calcite around quartz. Most calcite recrystallized
10. Calcite replacing feldspars and probably other minerals
11. Considerable muscovite as large scales in some beds
12. Some secondary authigenic quartz
13. Pyrite and marcasite replacing all primary minerals
14. U as uraninite and coffinite. The latter microscopic
15. V in reduced state as montroseite, doloresite, etc.
16. Sphalerite, galena greenockite
17. Barite
18. *Paragenesis* (tentative). Deposition of archosic sandstone with clay minerals detrital calcite and plant remains. Calcite replacing feldspars and rims of quartz. Recrystallization of calcite. Part of wood is replaced by it. Wood started to and continued to decay through this whole geologic interval into the Tertiary and adsorbed any U and V that passed in solutions through the rocks. Pyrite and any other sulfides probably were contemporaneous with the decay of the wood which furnished either H_2S directly for precipitation of iron, or was instrumental in maintaining a reducing environment for the contemporaneous precipitation U and Fe. V-minerals (montroseite and doloresite) cut all the other minerals except the pyrite. This does not mean that V must have been late but that it recrystallized late.

Temple Mountain, San Rafael Swell, Utah
Moss Back sandstone (Triassic). Includes all black ore of Temple Mountain

1. Shale and siltstone interstratified with conglomerate and sandstone
2. Red-colored rocks prominent above and below but not in deposits
3. Some sorting in sandstones
4. Somewhat archosic. Rounded to angular
5. Fine-grained sandstone to mud conglomerate with 2" pebbles
6. The more irregular and disturbed the beds are, the better the ore
7. Clay fragments in matrix very common
8. Asphaltite and carbonaceous and silicified trees. "Dead" oil in many places
9. Little calcite except in underlying Moenkopi
10. No replacement by calcite observed
11. Little mica
12. Some secondary authigenic quartz. Quartz is replaced by asphaltite
13. Pyrite replacing other minerals (syngenetic with asphaltite)
14. U as uraninite (and metallo-organic compounds?) microscopic in size
15. V largely in asphaltite where unoxidized
16. Galena, sphalerite, realgar, sulfur, arsenic in pyrite nodules.
17. Alunite, variscite, mansfieldite. These are probably secondary
18. *Paragenesis* (tentative). Deposition of sandstone with clay minerals and plant remains. Wood gradually carbonized. Asphaltite of unknown origin filled the interstices between grains and possibly replaced part of the wood, certainly a part of the sandstone. Pyrite formed at the same time under these highly reducing conditions. U and V were adsorbed by the asphaltite as it formed. The amount of pyrite is large and extends into the Moenkopi in much of the San Rafael Swell. It could be a diagenetic product. The crude oil in these rocks may have been trapped in the monoclinal structure of the San Rafael Swell before the Tertiary erosion cycle set in. Whether it had any part in the concentration of U and V is unknown, since it does not contain these metals now except in traces.

Poison Canyon Mine near Grants, N. Mex.
Brushy Basin member of Morrison formation (Jurassic) includes Mesa Top mine

1. Much shale and silt above and below main ore horizon of sandstone and grit
2. Minor quantities of red-colored rocks near deposits
3. Some sorting in sandstones
4. Largely archosic sandstone and grit
5. Subangular to angular grains
6. Relatively little disturbance of bedding
7. Kaolinite as small white aggregates in black ore
8. Organic black material around sand grains also woody material. Some asphaltite.
9. Calcite as cement abundant in mine layers of lowest ore. All recrystallized. A little gypsum
10. Calcite replacing feldspars
11. Very little mica
12. A little authigenic quartz
13. Much pyrite in black ore as minute crystals
14. U as coffinite. Extremely fine grained
15. V—not yet identified in black ores
16. Galena
17. No sulfates except gypsum observed.
18. Paragenesis (tentative). Deposition of archosic sandstone and grit with plant remains. It is likely that kaolinite or the mineral from which it developed was deposited at the same time as it is fairly evenly distributed through the ore-bearing sands. These are largely crumbly and porous now while the underlying grits are well cemented with calcite suggesting that calcite cement has been leached out of much of the ore. Pyrite is associated with

black material which coats the grains with a thin skin which suggests a "dried-up" original hydrocarbon. Rich asphaltite as at Temple Mountain occurs as small lenses in the ore. Coffinite is associated with the black coatings as well as with the asphaltite lenses. No V minerals have been identified. It is difficult to make any particular orogenic event responsible for the circulation of the groundwater which concentrated the U. The rocks have only a relatively slight dip toward the San Juan basin. This structure may be of early Tertiary age.

Gas Hills Anticline Area, Fremont Co., Wyo.
Wind River formation (Eocene) largely Lucky Mac No. 20 mine and vicinity

1. Little shale and silt in the ores but probably below them
2. Very little if any red color in immediate vicinity of ore bodies
3. Very little sorting in sandstones
4. Coarse archosic sandstone and grits, conglomerates locally
5. Angular grains, large percentage of feldspars
6. Too few exposures to be sure of lack of disturbance
7. Some clay aggregates but more often somewhat altered feldspars
8. Analyses show 0.5–0.7% organic carbon. Carbonaceous material probably too fine grained to be visible
9. Little calcite but much "primary" gypsum (not due to weathering)
10. Calcite probably having replaced feldspars being in turn replaced by gypsum
11. Very little mica but some chlorite
12. No secondary quartz observed
13. Pyrite replacing all other minerals. Responsible for dark gray color of ore
14. U as uraninite. Microscopically fine grained
15. No V present
16. Much gypsum. Apatite as coatings on sand grains
17. Liebigite, a uranyl carbonate. It veins the black ore and is secondary. Scorodite as veinlets and nests in grit
18. Paragenesis (tentative). Deposition of archosic sandstone and grit with organic carbon and relatively rare wood. Dark gray color caused by very fine-grained pyrite which invades all other minerals and looks like the last mineral that formed. The uraninite is so finely divided that it cannot be visually related to the other minerals. Gypsum forms a part of the matrix. It either replaces feldspar directly or calcite which may have replaced feldspar at an earlier stage. At any rate, a case can be made for both replacements. Gypsum fills most cracks and fissures and forms thin layers of satine spar largely parallel to the bedding. As pyrite is found all through the gypsum, the latter must be earlier. In oxidized portions of the ore it is now impossible to tell late gypsum from early, except that the pyrite has disappeared and has made room for jurosite.

In some areas in the same type of rock (Stan Claims), the mineralization is associated with thin layers of carbonate or hydroxyapatite, which coat the sand grains. Since the U is in the structure of the apatite it must be in the uranous state (U^{4+}) in order to replace the Ca ions of similar radius. This means that the apatite precipitated in a reducing environment in spite of the fact that this rock is light colored. There is little indication that much pyrite ever was present in the strata which contain the apatite.

Paragenetic Studies of Uranium Deposits of the Colorado Plateau

By R. A. Laverty and E. B. Gross,* USA

Detailed studies have been made of the paragenesis of several uranium deposits of the Colorado Plateau: the Mi Vida Mine, Big Indian Wash, Utah; the mines near Cove School, Lukachukai Mountains, Arizona; Notch Mines at Elk Ridge, Utah, and mines in the Todilto limestone near Grants, New Mexico (Fig. 1). Less detailed studies have been made of the Delta Group and Temple Mountain deposits in the San Rafael Swell, Utah, the Cal Uranium and U&I Mines in Big Indian Wash, Utah, the copper-uranium mines in White Canyon, Utah, the Lockhart Canyon deposits in Utah, the Sanastee deposits in the Chuska Mountains of Arizona, and the Meeker deposits in northwestern Colorado.

The paragenetic sequence, when integrated with field observations, presents evidence for the deposition of the Colorado Plateau uranium ores by late Cretaceous or post-Cretaceous solutions and rules out syngenetic deposition in situ.

The composite paragenetic sequence is compared to that at Marysvale, Utah, which is the nearest uranium deposit of definite hydrothermal origin. Similarities found are: (*a*) early silicification or fluoritization; (*b*) close association of uranium and sulfide minerals in both time and space; (*c*) early U^{4+} minerals and late U^{6+} minerals.

INDIVIDUAL DEPOSITS

Mi Vida Mine

The unoxidized uranium-vanadium ore of the Mi Vida Mine, San Juan County, Utah (Figs. 2 and 4) occurs in poorly sorted fine-grained subangular calcareous dark gray mottled sandstones and conglomerates of the Triassic Chinle formation. Detrital constituents are mainly quartz, accessory feldspar, mica, siltstone fragments, limestone pellets, and plant remains.

Linearity in sedimentary fabric in some of the strata is due primarily to alligned mica flakes, less commonly to oriented elongate grains in quartz and feldspar or oval-shaped pellets of mudstone, siltstone, or limestone. Mudstone lenses within the ore horizon contain illite. Carbonized plant remains may show complete replacement by uraninite or coffinite and calcite. Sulfides—pyrite, chalcopyrite, galena, and greenockite—are most abundant within the replaced carbonaceous logs and branches of fossil plants. Many carbonized plant remains contain pyrite and calcite but no uranium.

Early cements are minor amounts of quartz in secondary overgrowths, barite plates, illite, and calcite, which is the principal cementing agent of the sandstones.

Preceding the intermediate cements, structural deformation fractured the quartz and feldspar grains and caused recrystallization of the calcite cement. When the later mineralizing solutions pervaded the fractured sandstones, uraninite and coffinite were precipitated by carbonaceous material. Vanadium hydromica and the vanadium oxides of lower valence were also deposited within the matrix of sandstones by replacement of calcite. Sulfides were deposited chiefly in carbonaceous material. Greenockite and much of the galena were later than the pyrite. Calcite was recrystallized, and a late generation of it replaced the ore minerals to a small extent.

A late generation of hematite, calcite, and the oxidized uranium and vanadium minerals has developed only in minor amounts.

In conclusion, replacement textures have shown that the precipitating agents have been primarily carbonaceous material and calcite cement. Structural deformation preceded the influx of ore solutions which were quite active, corroding the fractured quartz and feldspar grains. The vanadium hydromica and accompanying ore minerals of lower valence were precipitated contemporaneously with some base metal sulfides. Cellular structure has been preserved in most wood replacement. Lastly, the oxidized minerals, corvusite, pascoite, and metatyuyamunite have developed from weathering the intermediate cements.

Lukachukai Mountain

The ore occurs as cementing material in a fine-grained, subangular, fairly well-sorted sandstone. Quartz is the major detrital mineral with accessory feldspar, mudstone fragments, chert, and carbonized plant remains (Fig. 5). Many small lenses of mudstone, clay, and argillaceous limestone are included in the sandstone. Most of the clay in these lenses is illite, but some is kaolinite.

Early cements in the sandstones of the ore bodies in the Lukachukai Mines are quartz, chalcedony, hematite, goethite, and clay, probably of the illite group.

* US Atomic Energy Commission.

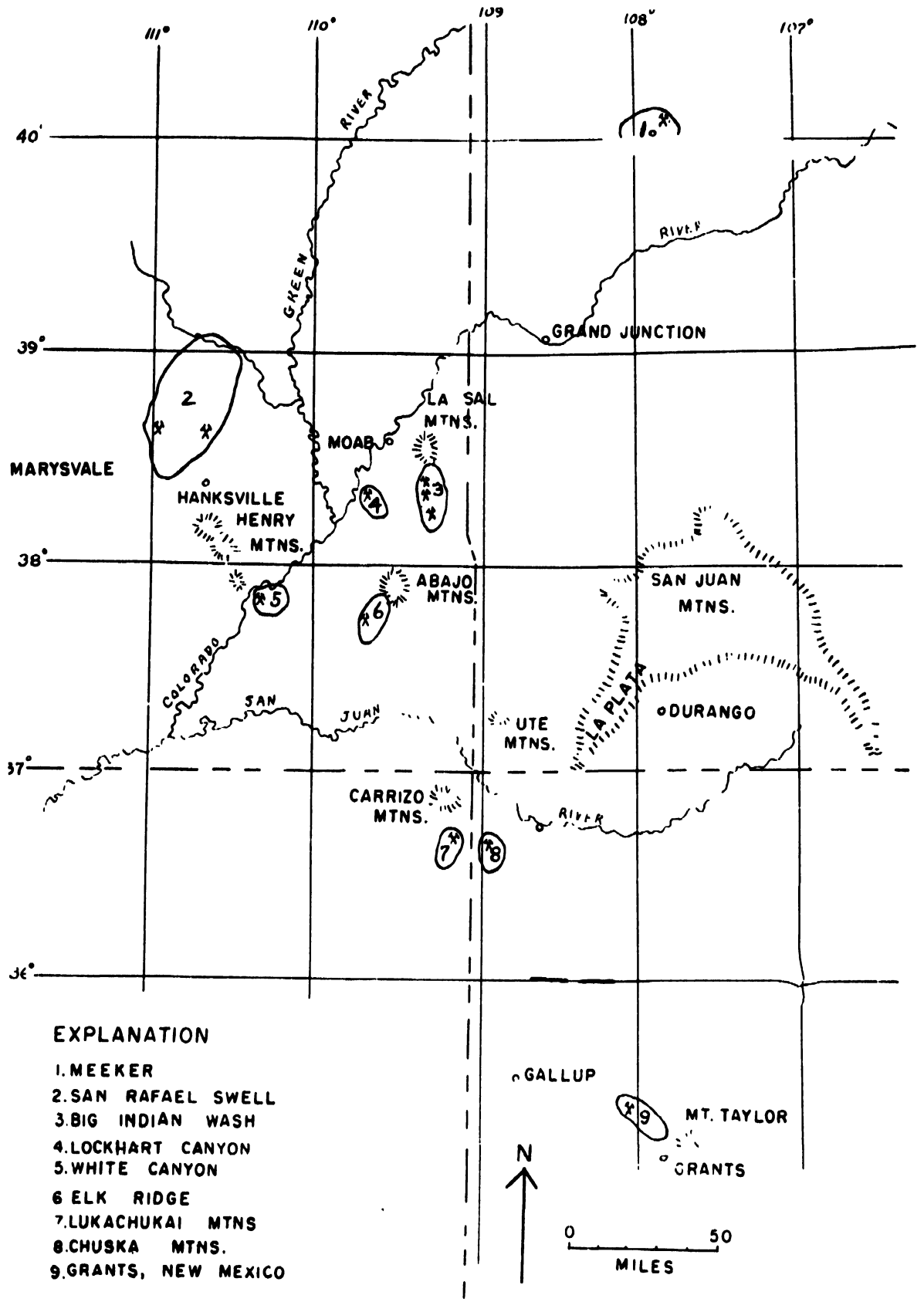


Figure 1. Index map of part of Colorado Plateau

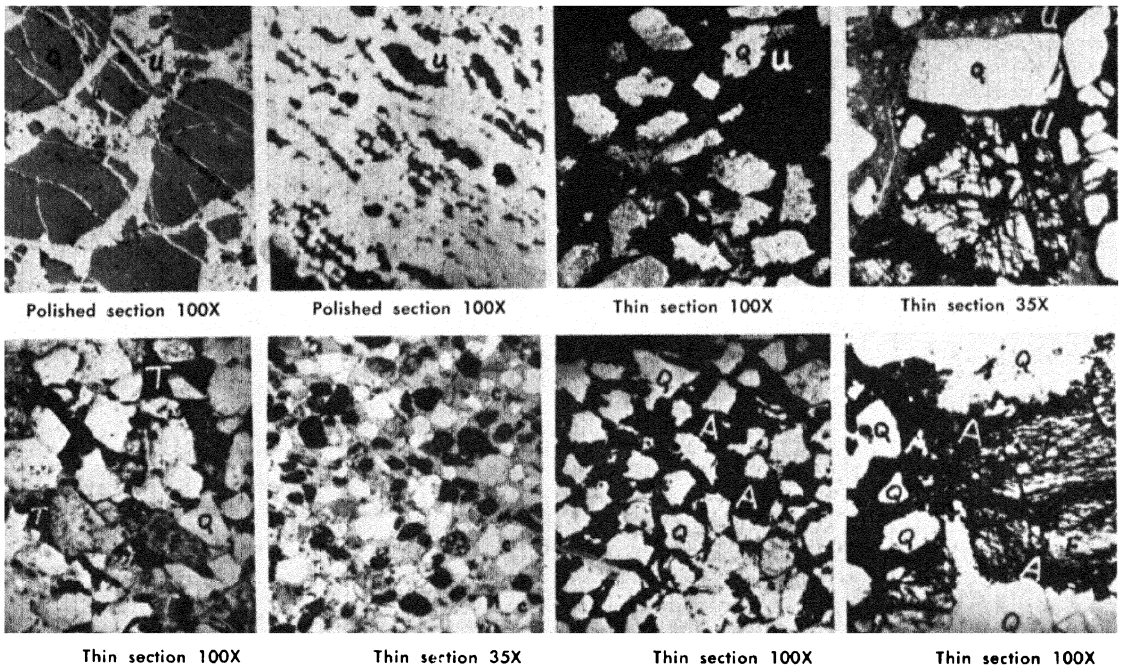


Figure 2. Sandstone ores. Top row: Mi Vida mine; two left photos, bottom row: Lukachukai Mountains; two right photos, bottom row: Elk Ridge

Intermediate cements of the sandstone are uraninite, hematite, goethite, illite, and coarsely granular calcite. Calcite occurs in large optically continuous masses up to two centimeters in diameter which may include 1000 detrital grains. Uraninite has been found as a replacement of carbonized wood and as interstitial cement which is almost entirely altered to tyuyamunite. Other minerals are the calcium vanadates—pascoite, hewettite and rossite.

In the group of late cements, coarsely granular calcite predominates but tyuyamunite cement is the principal ore mineral. The iron and vanadium oxides continue in deposition from the intermediate group to the end of the sequence.

Although the coarsely crystalline calcite and tyuyamunite overlap, there is no apparent replacement of calcite by tyuyamunite. Tyuyamunite, where it has been derived in situ from uraninite, is opaque due to dusty black inclusions. In contrast, tyuyamunite which precipitated at some distance from any preceding uranium mineral occurs in clear prismatic crystals.

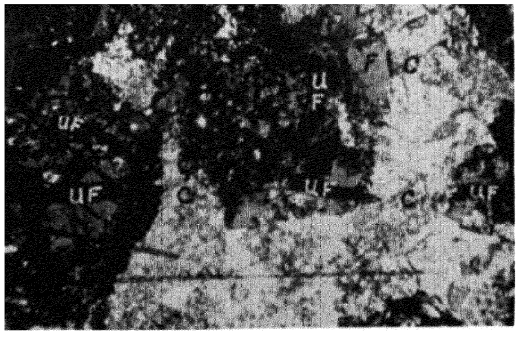


Figure 3. Limestone ore; U: uranite, F: fluorite, UF: uranite-fluorite intergrowth, C: calcite

In summary, the cement sequence at the uranium mines in the Lukachukai Mountains shows early silicification, then intermediate deposition of uraninite and coarsely crystalline calcite, followed by tyuyamunite. Iron oxide occurs throughout the sequence. In view of the large limestone content occurring as lenses in the sandstone, it is likely that the coarsely crystalline calcite of the intermediate and late parts of the sequence represents recrystallization of limestone rather than introduction of a new mineral.

Notch Mines, Elk Ridge

Uranium deposits on the Notch claims on Elk Ridge, southeastern Utah, occur mainly in fine-grained sandstone of the Moss Back member of the Triassic Chinle formation; with some mineralization extending downward into Moenkopi. A few mudstones and clay seams are found in the ore bodies. Quartz is the major detrital constituent with accessory feldspar, mica, magnetite, and carbonized organic remains (Fig. 6).

Early cements in the sandstones are calcite, hematite, goethite, and a clay which is probably a member of the kaolin group.

Intermediate cements include uraninite, asphaltite, pyrite, chalcopyrite, galena, and a black vanadium mineral, probably corvusite. Formation of calcite, hematite and goethite is continuous from the early cements.

In the late cements, calcite, hematite and goethite continue to the end of the sequence. Schroekingerite and meta-zeunerite are derived from the uraninite and uraniferous asphaltite. Malachite and volborthite

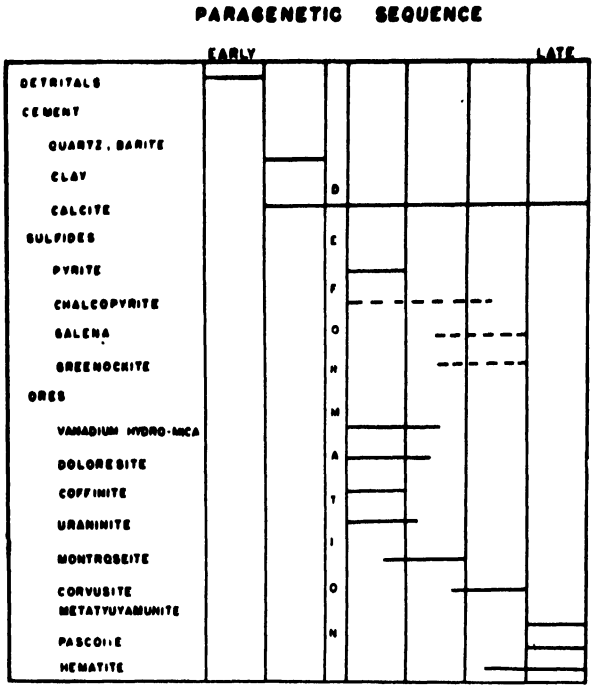


Figure 4. Mi Vida mine, San Juan County, Utah

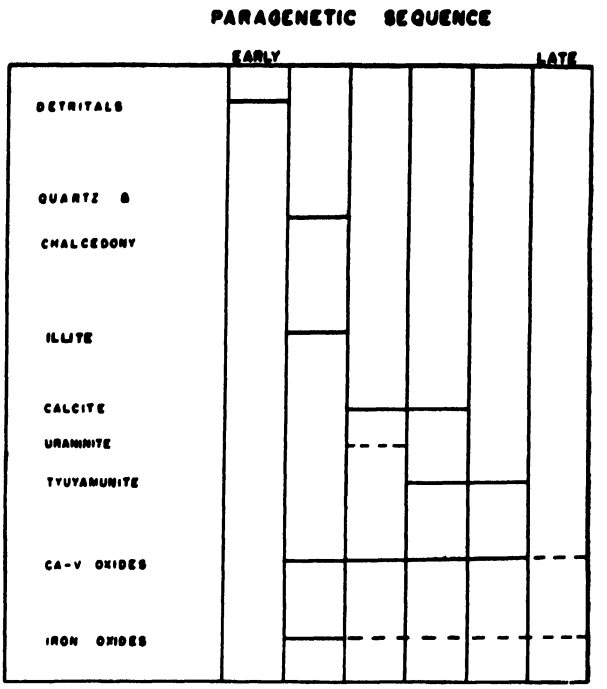


Figure 5. Kerr McGee mines, Lukachukai area, Arizona

are derived from the copper and vanadium minerals.

Carbonized organic remains appear to be the primary precipitant for the uranium minerals of the intermediate group, although a minor amount of uraninite has crystallized around earlier grains of chalcopyrite. There is some replacement of calcite by the uranium minerals. Uraniferous asphaltite is the principal uranium ore in the Notch area.

In summary, the cement sequence at Elk Ridge shows early kaolinization and slightly later silicification. The silicification is overlapped and followed by the uranium ores and the base metal sulfides. Oxidation of the intermediate cements resulted in uranium carbonates and arsenates, copper carbonates and hydrated vanadium oxides. Calcite and the iron oxides occur throughout the sequence.

Todilto Limestone Uranium Ores, Grants, New Mexico

The Jurassic Todilto formation is a thin-bedded limestone with a maximum thickness of about 25 feet. It is the principal ore horizon in the area northwest of Grants, New Mexico, and it is overlain and underlain by barren sandstones.

Thin silty streaks occur in the limestone near the contact with the overlying silty sandstone, but the silt grains constitute less than one percent of the total rock. The earliest black uranium ore is concentrated in these silty layers as a result of increased initial permeability along the layers. The effect of the silty layers is most obvious in those places where the ore is low grade. Where there has been intense mineralization, the limestone has been completely recrystallized and megascopic bedding obliterated. The intensity of mineralization increases in the vicinity of such tectonic features as small folds, faults, and joint swarms.

The calcite of the limestone itself appears to be the principal precipitant of the ore minerals. The limestone contains considerable organic matter and often has a fetid odor; the effect as a precipitant of organic matter is uncertain but since organic debris in other deposits was a certain precipitant of uranium, it is logical to assume that organic material in the Todilto had some effect.

Two types of black uranium ores occur in the Todilto limestone. One consists of extremely minute intergrowths of fluorite and uraninite (Fig. 3). Such fluorite crystals contain clear zones of pure fluorite alternating with opaque zones which are intergrowths of fluorite and uraninite on a submicroscopic scale, suggesting initial deposition of fluorite followed by coprecipitation of uraninite and fluorite. The other type of ore is finely granular uraninite occurring with finely granular pyrite along silty seams in the limestone. The two are not intermixed in a single deposit.

In non-fluoritic areas, deposition of limestone was followed by the introduction of pyrite as an accessory mineral, and this in turn was followed by the contemporaneous deposition of uraninite and pyrite. Recrystallized calcite was formed during this intermediate stage.

In the fluoritic deposits, deposition of calcite overlapped the latter part of the uraninite-fluorite mineralization which was followed by the introduction of barite, nontronite, and vanadium hydromica.

In all deposits in the Todilto limestone, tyuyamunite, carnotite, and uranophane are the principal oxidized uranium minerals. They occur as thin post-uraninite veinlets and as rims around the black uranium minerals.

Hematite occurs both as pseudomorphs after pyrite and disseminated in recrystallized limestone in and near the ore bodies.

In summary, the paragenetic sequence (Fig. 7) shows early fluorite in some places and early pyrite in others. The fluorite was followed by uraninite fluorite intergrowths, and the pyrite was overlapped by uraninite. As the fluorine, uranium, and iron content of the solutions decreased, the recrystallization of the limestone to pure calcite began and continued to the end of the sequence. After the calcite recrystallization was well started and after the uranium deposition was completed, the deposition of barite and clay minerals began. Oxidation of uranium and iron minerals completed the sequence.

Other Deposits

Less detailed studies of eight other Plateau uranium deposits also show similarities in paragenetic sequence (Fig. 8). These deposits are found at Meeker, the San Rafael Swell, Big Indian Wash, Lockhart Canyon, White Canyon, and Sanastee. All are in sandstones and conglomerates of Permian to upper Jurassic age with the major ore bodies occurring in the Shinarump and Morrison formations.

The detritals are primarily quartz, with minor feldspar, micas, limestone and siltstone pellets, and carbonized organic remains. Occasionally clay seams or mudstone pellets are present. Carbonized organic remains occur in all the deposits except the Lockhart Canyon ore body in the Permian Cutler formation.

Secondary silica overgrowths are common in sandstones of most of the deposits. Silica preceded the deposition of calcite cement in the sandstones. Calcite is the most abundant cementing agent. Clay is less common, and it is usually illite except in the Morrison deposits where it is kaolinite. Where the sandstone contains much silica cement, mineralization is meager.

Intermediate cements consisting of ores, sulfides, uraniferous asphaltite, and recrystallized calcite occur in variable amounts in most of the deposits. The uraninite is found replacing carbonaceous material only, whereas the vanadium hydromica observed in two deposits has replaced calcite cement of the matrix. Clay cements are usually less replaced than calcite cements. At Temple Mountain, uraniferous asphaltite is the principal ore material. Sulfides, chiefly pyrite, occur in all but the Meeker and Sanastee areas. Copper sulfides are associated with the uraninite at the Happy Jack Mine but are rarely observed elsewhere.

Late cements composed of oxidized uranium and vanadium minerals, hematite, and limonite are more common than the unoxidized intermediate cements except for the deposits of Big Indian Wash. The late uranium and vanadium cements have replaced calcite cement and in part the clay.

In conclusion, the paragenetic sequence of these eight uranium deposits are very similar. Detrital constituents are cemented by calcite, silica, or clay minerals. The ore-bearing solutions have corroded some grains and replaced cement. Calcite and carbonaceous material precipitated the uranium and sulfides. Subsequent oxidation of the intermediate cements formed secondary uranium and vanadium minerals.

Marysvale

The uranium deposits at Marysvale, Utah, have been studied and previous work summarized by Kerr *et al.*, who concluded that the ore was deposited from hydrothermal solutions. For comparative pur-

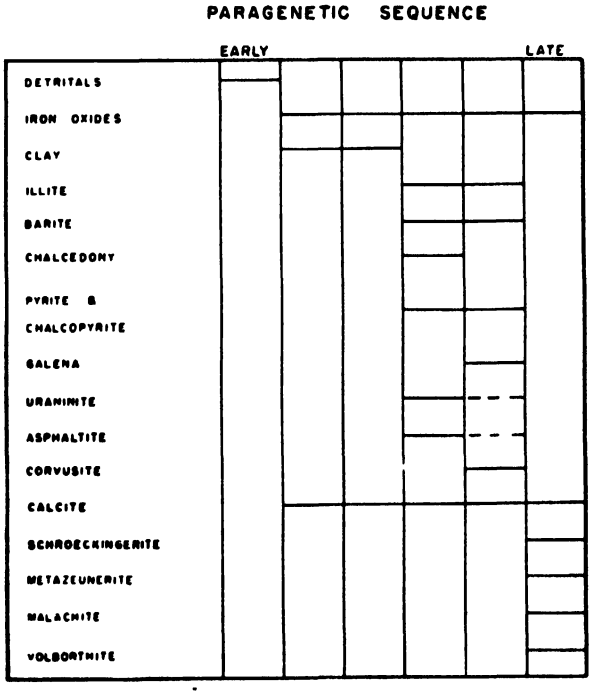


Figure 6. Notch mines, San Juan County, Utah

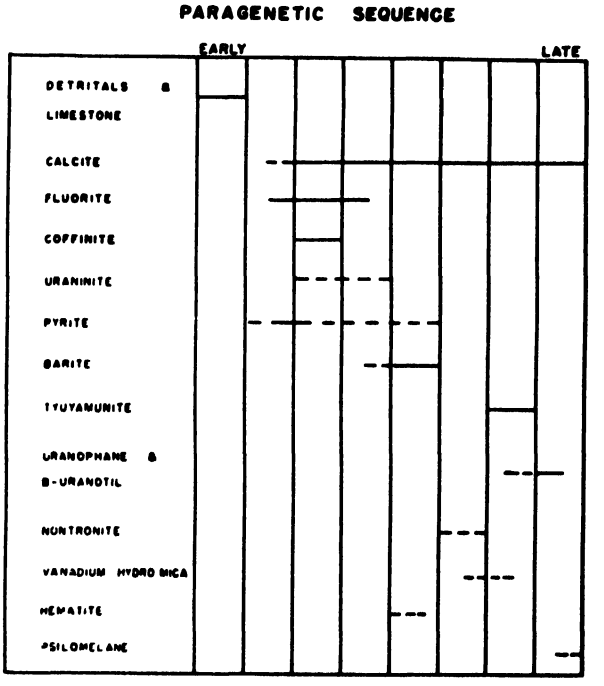


Figure 7. Todilto limestone ores, Grant, New Mexico

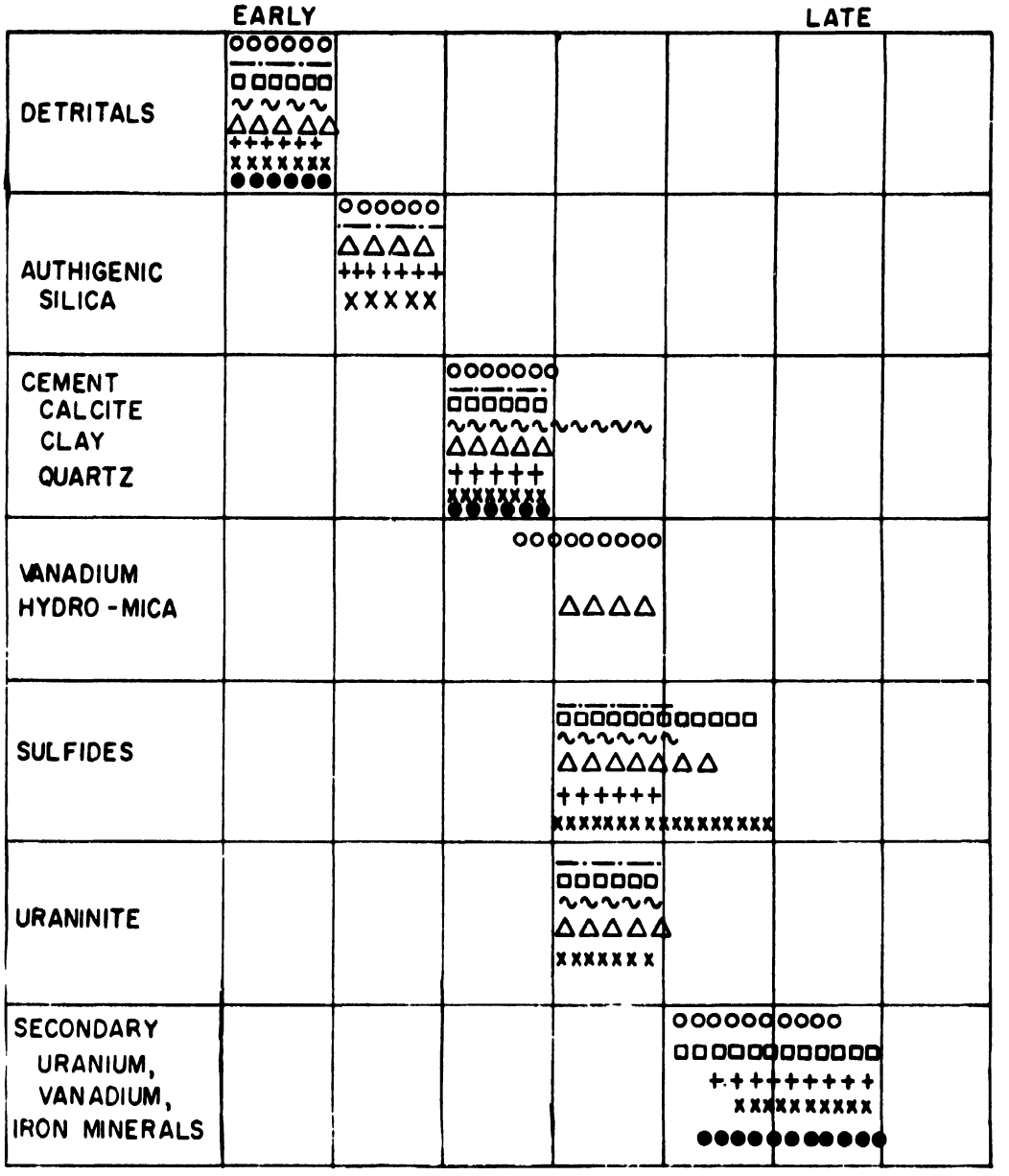


Figure 8. Composite paragenesis of eight uranium deposits

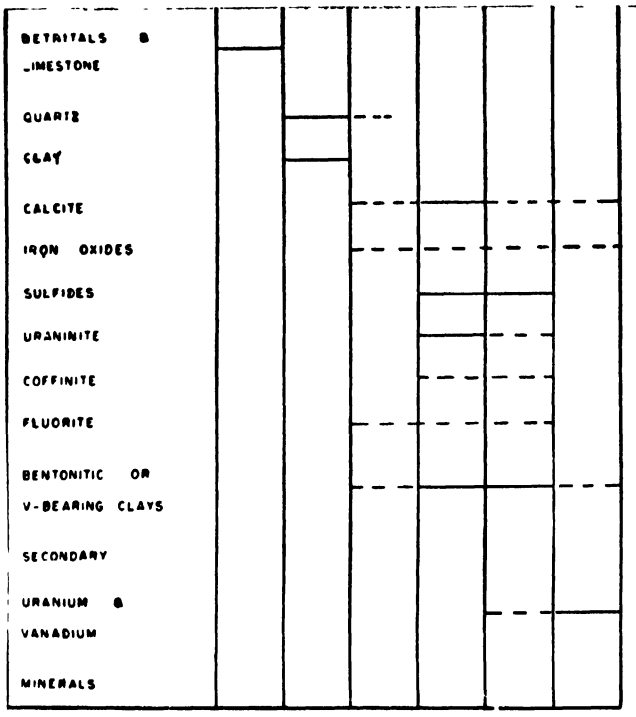


Figure 9. Composite paragenesis of uranium ores, previous charts

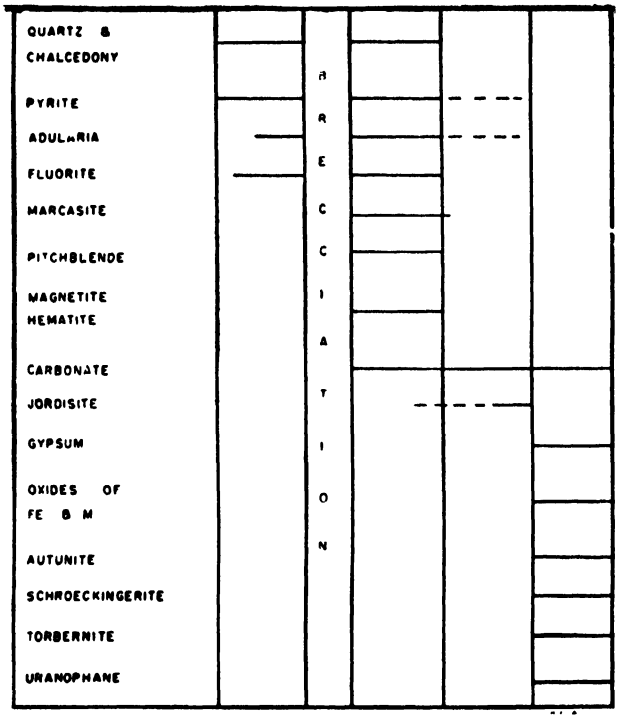


Figure 10. Uranium deposits, Marysvale, Utah

poses, Kerr's written paragenesis has been expressed in chart form (Fig. 10) for which we assume responsibility.

Similarities to the composite paragenetic sequence (Fig. 9) are: (*a*) pre-ore silicification and fluoritization, (*b*) contemporaneous fluorite, base metal sulfides, and black oxides of uranium and vanadium, (*c*) late oxidation products of metallic minerals.

SUMMARY OF SIMILARITIES AND DIFFERENCES

Host Rocks

The most striking similarity of rocks which are host to uranium ores on the Colorado Plateau is the content of organic material. The organic material may be in the form of petroleum, carbonized wood, or asphaltite or it may be submicroscopic.[2]

Most of the host rocks contain calcite or limestone. Most are poorly sorted although uranium deposits occur both in well-sorted sandstones and in conglomerates. Most host rocks contain seams or lenses of mudstone, siltstone or clay.

Precipitants

Organic remains and calcite are the two main precipitants for the black uranium ore minerals. Although lenses of clay and mudstone are used as a guide to ore in several regions, it is not clear whether these lenses act as an active precipitant or whether they serve merely to define the aquifers along which the ore solutions moved. In some cases, notably in Elk Ridge, base metal sulfides act as a precipitant for the black uranium minerals.

Cements

Another striking similarity of ore deposits on the Colorado Plateau (Fig. 9) is the fact that uranium minerals never occur as detrital grains, although commonly as cements. Further, the uranium mineralization does not begin until the intermediate stage of the cement sequence at which time the uranium minerals are joined by base metal sulfides and by vanadium oxides of low valence. The oxidized minerals of uranium, vanadium, and copper always occur in the latest part of the cementation sequence.

The iron oxides and calcite usually occur throughout the cement sequence.

Geologic Environment

The major uranium producing formations on the Colorado Plateau are fluvial clastics laid down during Mesozoic time in an oxidizing environment. After burial, reducing conditions prevailed owing to the decomposition of interred woody material, and it was into such an environment that uranium-bearing solutions were introduced; time of mineralization was late Cretaceous or early Tertiary according to Stieff and Stern.[3] It may be noteworthy that a number of laccoliths invaded the Plateau in early to middle Tertiary time and these have geographic proximity to numerous major Plateau deposits.

REFERENCES

1. Kerr, Paul F. et al, *A Geologic Guide to the Marysvale Area,* US Atomic Energy Commission, RMO 924 (1952).
2. Gruner, John W., *The Problem of the Primary Ores of the Colorado Plateau,* US Atomic Energy Commission, RME 3094, Part I (1954).
3. Stieff, L. R. and Stern, T. W., P/298, *The Interpretation of the Pb^{206}/U^{238}, Pb^{207}/U^{235}, Pb^{207}/Pb^{206} Age Sequence of Uranium Ores,* Vol. 6, Session 6B, these Proceedings.

The Interpretation of the $Pb^{206}/U^{238} < Pb^{207}/U^{235} \ll Pb^{207}/Pb^{206}$ Age Sequence of Uranium Ores

By L. R. Stieff and T. W. Stern,* USA

During the past few years several workers have used lead-uranium and lead-lead age determinations as a geologic tool in the study of uranium-ore deposits and in the study of deposits of other metals that contain sufficient uranium for age determinations.[1-7] Many of the age determinations on uranium ores reported by these workers and by Nier[8,9] showed significant differences between the lead-uranium ages and the lead-lead age; the Pb^{206}/U^{238} age being the youngest, the Pb^{207}/U^{235} age being slightly older than the Pb^{206}/U^{238} age, and the Pb^{207}/Pb^{206} age being much older than either lead-uranium ages. The ages reported by the authors mentioned above can be used to show that the discrepancies between the lead-uranium and lead-lead ages are not necessarily related to the following: (1) age of the sample; (2) the correction for original common lead as indicated by the per cent of Pb^{204} in the isotopic analysis of the lead extracted from the radioactive ore; (3) the analyst; (4) the locality of the uranium ore; and (5) the grade of the uranium ore.

Where the lead-uranium and lead-lead ages of uranium ores are in marked disagreement, the investigators mentioned above and others[10,11,12] have selected one age in preference to the two remaining ages and have assigned the age discrepancies to one or more of the following causes: (1) variations in the U^{235}/U^{238} activity ratio; (2) selective loss of radon or other daughter products; (3) loss of lead, uranium, or both by alteration; (4) deposition of original radiogenic lead, i.e., radiogenic lead formed prior to the deposition of the uranium ore and deposited with the uranium; or (5) analytical errors, both chemical and instrumental.

In this paper, explanations that have been advanced for the $Pb^{206}/U^{238} < Pb^{207}/U^{235} \ll Pb^{207}/Pb^{206}$ age sequence of uranium ores will be briefly discussed and our evaluation of the age selections based on these explanations will be made. The geologic consequence of this age selection may be far reaching both in terms of the origin of the uranium deposit and in terms of the controls that could have operated to localize the ore. It is, therefore, of more than academic interest to establish whether the age anomalies observed in uranium ores are due to variations in the physical constants used in calculations, to analytical errors, to geologic processes of alteration and diffusion, or to the presence of at least two generations of radiogenic lead.

LOSS OF DAUGHTER PRODUCTS

Nier, in his fundamental paper,[8] discussed briefly the possibility of "a partial loss of the intermediate products of the uranium series" as an explanation for the difference that he reported between the lead-uranium and lead-lead ages. It was not, however, until Wickman[11] in 1942 considered in detail Nier's age discrepancies for the Swedish kolm and several other samples that a quantitative theoretical explanation based on radon loss was postulated for the high Pb^{207}/Pb^{206} age as compared to the lead-uranium ages. Wickman suggested that the observed sequence of ages from a radioactive ore could be explained by the relatively greater diffusion of radon (Rn^{222}) compared to the diffusion of actinon (Rn^{219}), both gaseous daughter products in the U^{238} and the U^{235} series, respectively. His suggestion was based on the fact that radon has a half life of 3.82 days whereas actinon has a half life of only 3.9 seconds, that is, a factor of 84,000 in the time available for the diffusion of radon compared to actinon. The selective diffusion of radon would ultimately result in the loss of Pb^{206}, a Pb^{206}/U^{238} age lower than the real age of the sample, a Pb^{207}/U^{235} age closely approximating the true age of the sample, and an abnormally high Pb^{207}/Pb^{206} age.

A graphical treatment of the "radon diffusion age" for a billion (10^9)-year-old sample is shown in Fig. 1A. A 25% loss of radon for this sample results in a Pb^{206}/U^{238} age of approximately 800 million years. The increase in the Pb^{207}/Pb^{206} age to 1,570 million years is a result of the extreme sensitivity of this method of calculation to relatively small changes in the amounts of either Pb^{207} or Pb^{206} present. As can easily be seen in Fig. 1A the Pb^{207}/U^{235} age is the most reliable from the point of selective diffusion of radon. The errors due to the presence of original lead and loss of uranium, lead, or both, are assumed to be negligible. (See Figs. 1B, 1C, 1D.)

Recently Kuroda[12] has examined the Ra^{223}/Ra^{226} ratio of a number of uranium ores. He has shown that the measured Ra^{223}/Ra^{226} activity ratio is variable and usually larger than the presently accepted value of 0.046 determined by Nier.[8] Using his re-

* US Geological Survey.

cently measured activity ratio, Kuroda was able in many cases to greatly reduce or eliminate the discrepancy between the lead-uranium and lead-lead ages.

The high activity ratios were interpreted as enrichment of U^{235} caused by the neutron-capture reaction of U^{238}, resulting in the formation of Pu^{239}, which decays to U^{235} by alpha disintegration. Kuroda concluded that the enrichment in U^{235} of the Colorado Plateau took place before the mineral was formed. However, mass spectrographic analysis by the Mass Assay Laboratory, Oak Ridge, Tennessee, of uranium extracted from Colorado Plateau ores and other ores analyzed by Kuroda have failed to show any significant variation greater than 1% in the U^{238}/U^{235} ratio. Kuroda's results must, for the present at least, remain unexplained. Enrichment in the daughter products of U^{235}, however, would introduce smaller errors in the Pb^{207}/U^{235} age than in the Pb^{207}/Pb^{206} age.

THE Pb^{207}/U^{235} AGE

In their recent paper, Kulp, Bate, and Broecker[13] have stated a marked preference for the Pb^{207}/U^{235} age because it does not involve radon loss. They stated that the $Pb^{206}/U^{238} < Pb^{207}/U^{235} \ll Pb^{207}/Pb^{206}$ age sequence could be explained by (1) radon leakage, (2) an uncertainty in the half life of U^{235}, and (3) excessive neutron capture by Pb^{206}. They concluded that radon leakage is the primary cause of the difference in ages obtained from the different ratios. This conclusion was based in part on their own studies of the measured leakage of radon at room temperature and the observations that the rate of leakage increased as the temperature increased.

The effects of systematic mass-spectrometric errors and errors resulting from the failure to make the proper corrections for the isotopic composition of the original common lead in the sample were assigned relatively minor roles in the interpretation of the lead-uranium and lead-lead age differences. Correction for the presence of original radiogenic lead was not considered. Kulp and his coworkers did not mention that these three additional corrections introduce larger errors in the Pb^{207}/U^{235} age than in the Pb^{206}/U^{238} age.

The effects of leaching and alteration are, in the opinion of Kulp and coauthors, mostly limited to the loss of uranium rather than lead. They support this opinion by citing the recent work by Phair and Levine,[14] which has shown that leaching in and around pyritic mines affects uranium so much more than lead that it is impossible to lower the Pb^{206}/U^{238} ratio by H_2SO_4 leaching.

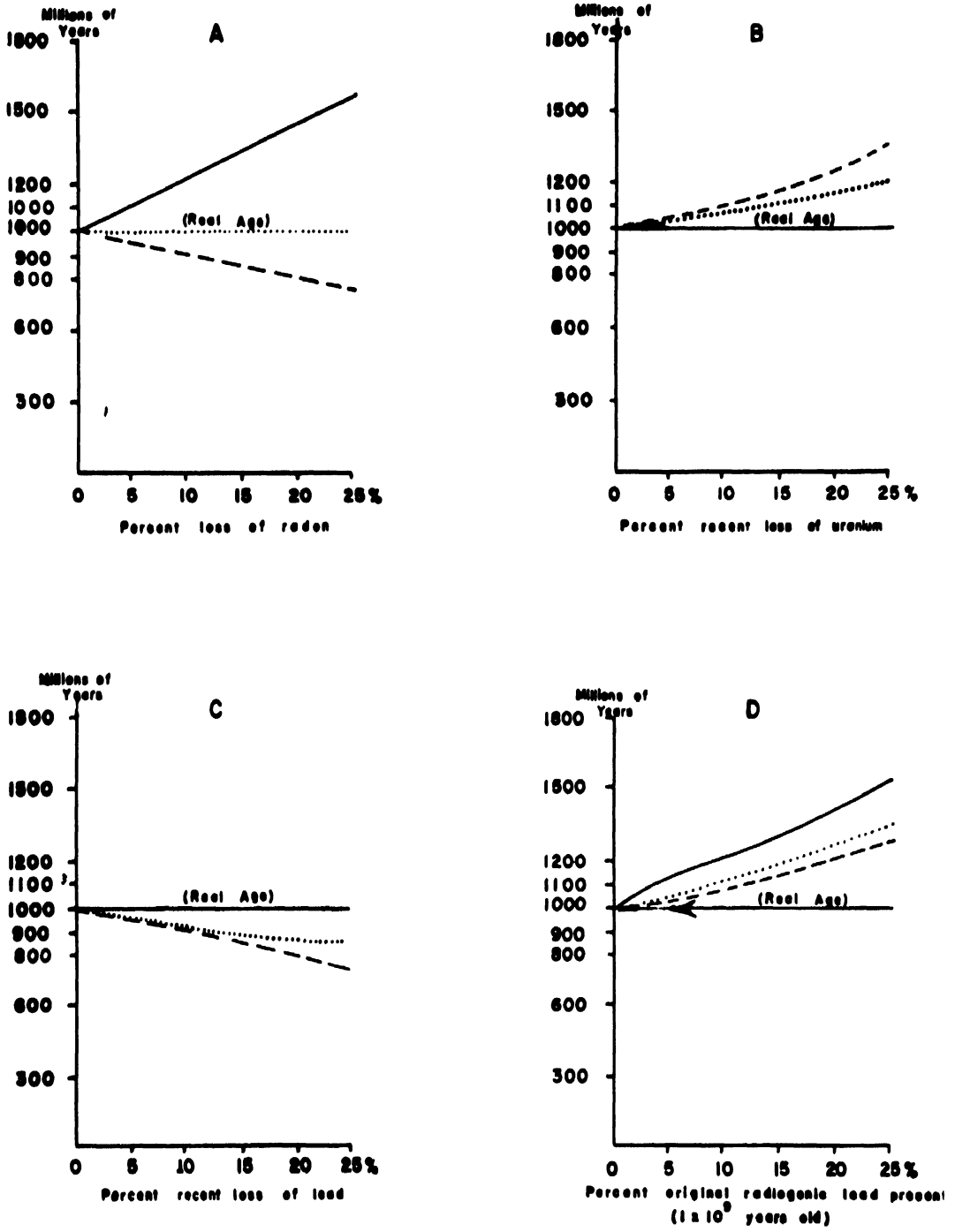
The preference of Kulp and others[13] for the Pb^{207}/U^{235} age was apparently based on the opinion that ". . . since uranium minerals seldom show evidence of even 5% leaching, this does not seem to be an important factor." This conclusion is a surprising one in view of the published analyses[8,9,15,16] whose sequence of ages can best be explained by the loss of uranium considerably in excess of 5%. Unless great care is taken in the selection of essentially fresh, unaltered uranium ores, it is our opinion that loss of uranium may be assumed to be a possible source of significant errors.

It should be emphasized that the "radon diffusion age" simply assumes that the Pb^{207}/U^{235} age is the most reliable and that instrumental errors, corrections for original common and radiogenic lead, and corrections for the possible loss of lead or uranium due to alterations are negligible. The mathematical manipulations required to produce agreement of the two lead-uranium ages and the lead-lead age by restoring the amount of Pb^{206} equivalent to the assumed radon loss in no way improves the reliability of the Pb^{207}/U^{235} age, and the agreement in ages does not establish the fact that radon loss has occurred. At the present time there is no independent evidence, such as the abnormal concentrations of only Pb^{206}, that the large-scale diffusion of radon from uranium ores during most of their history has been a significant geologic process. As Collins and his coworkers[5] have observed, "Other arguments must be considered in order to establish the most probable age for the minerals from the considerations of the experimental data without any adjustment of that data."

LOSS OF URANIUM

Collins, Farquhar, and Russell[5] have recently published a large number of Pb^{207}/Pb^{206} ages. Their preference for the lead-lead age follows the original suggestion of Nier that the isotopic composition of the lead in a uranium ore would be essentially unaffected by recent loss of lead, uranium, or both, due to alteration and weathering. The effects of a recent loss of as much as 25% of the uranium on the lead-uranium and lead-lead ages are shown graphically in Fig. 1B. As can be seen, the Pb^{207}/Pb^{206} age is unaffected. Even loss of uranium during most of the life of the specimen results in smaller errors for the Pb^{207}/Pb^{206} age than for the lead-uranium ages.[10] The lead-uranium ages, in contrast, show a marked response to the loss of uranium, the sequence of ages being $Pb^{206}/U^{238} > Pb^{207}/U^{235} \gg Pb^{207}/Pb^{206}$.

In general, it is extremely difficult, if not impossible, to evaluate the lead-uranium $\gg$ lead-lead age sequences published in the literature because of the inadequacy or the complete omission of the descriptions of the samples on which the age determinations have been made. One exception, the yellow ore from Katanga analyzed by Nier,[8] has been stated to be an alteration product of the approximately 600-million-year-old unaltered pitchblende ores from this mine. The Pb^{206}/U^{238}, Pb^{207}/U^{235}, and Pb^{207}/Pb^{206} ages for the yellow Katanga ore are 973, 858, and 635 million years, respectively. This sequence of ages is precisely the sequence that is predicted on purely theoretical grounds. It would seem reasonable, therefore, to assume that the remaining samples whose state of oxidation and freedom from alteration is not



Explanation

Apparent age calculated from:

Pb^{206}/U^{238} _ _ _ _ _

Pb^{207}/U^{235} .....

Pb^{207}/Pb^{206} _____

Figure 1. Some factors affecting age calculations

known but which show similar sequence of their lead-uranium ages are the result of the loss of uranium.

It would unquestionably be desirable to make age determinations only on completely fresh, unaltered uranium ores. Unfortunately the geologist seldom finds such excellent material for age studies, and he is forced to use the best material that is available. The problem of interpreting and evaluating the results, however, would be greatly simplified if there were included along with calculated ages an adequate description of the uranium ore sample, including its geologic setting, associated minerals, an estimate of the degree of alteration, its specific gravity, and —for pitchblende or uraninite—the size of the unit cell as determined from X-ray diffraction studies.

LOSS OF LEAD

The effects on the lead-uranium and lead-lead ages of a recent loss of as much as 25% of the radiogenic lead produced are shown graphically in Fig. 1C. As can be seen, the Pb^{207}/Pb^{206} age is unaffected. Even the loss of lead during most of the life of the specimen results in smaller errors for the Pb^{207}/Pb^{206} age than for the lead-uranium ages.[10]

Loss of lead results in a sequence of ages similar to that produced by the loss of radon. It is possible to bring the lead-uranium ages into agreement with the lead-lead ages by restoring the lead assumed to have been lost. In the loss of lead, however, the Pb^{207}/Pb^{206} age is considered to be the most nearly correct, rather than the Pb^{207}/U^{235} age, which is preferred if radon loss is considered to be the significant process. In the evaluation of age determinations, it is important to recognize that analytical errors in the determinations of uranium and lead can produce age patterns indistinguishable from those produced by the loss of lead or uranium.

Pb^{207}/Pb^{206} AGES

The Pb^{207}/Pb^{206} method of age calculations is essentially free from the effects of recent loss of either uranium or lead due to alteration. In addition, this method does not require quantitative analysis for either lead or uranium. The lead-lead method of age determination is not, however, without its serious limitations. Figure 1A and Fig. 1D show graphically the marked changes in the Pb^{207}/Pb^{206} age that accompany even small changes in the relative amounts of radiogenic Pb^{206} or Pb^{207} used in the calculation. This method of age calculation becomes increasingly sensitive to quantitative errors as the age of the sample decreases. Unless great care is taken, the Pb^{207}/Pb^{206} age of uranium ores younger than 200 million years may be essentially meaningless.

The sources of error in the Pb^{207}/Pb^{206} method of age calculation are: (1) mass spectrometric analysis; (2) assumptions concerning the isotopic composition of the original lead, both common and radiogenic; (3) diffusion of radon or other daughter products; and (4) uncertainties in the physical constants.

Although the mass spectrometric errors can be significant, it seems very unlikely that these errors could account for most of the discrepancy between the lead-lead and lead-uranium ages. It should be noted, however, that most if not all of the mass spectrometric errors result in a greater increase in the lead-lead ages than in the lead-uranium ages. In addition any errors in the physical constants used in the age calculations will also result in greater errors in the lead-lead age than in the lead-uranium ages.

To avoid some of the difficulties resulting from the original common lead corrections, Collins and his coworkers[5] have published lead-lead ages only on samples that contain extremely small amounts of Pb^{204}, the nonradiogenic index of common lead and that were assumed to contain no original radiogenic lead. The low Pb^{204} content, however, cannot be used as a guide to the amount of original radiogenic lead deposited with the sample. This procedure limits the Pb^{207}/Pb^{206} method to uranium ores that are essentially uncontaminated by any type of original lead and are believed to be uncontaminated by original radiogenic lead. The procedure eliminates the large number of remaining uranium ores that contain significant amounts of both original common lead and radiogenic lead and that otherwise would be perfectly satisfactory for age studies. Thus, with the exception of loss of lead or uranium, all the possible sources of error tend to introduce greater uncertainties in the lead-lead ages than in the lead-uranium ages.

Collins and coworkers[5] have attempted to establish the greater reliability of the Pb^{207}/Pb^{206} age, not only on the basis of the improbability of radon loss but also by analysis of the age sequence for a uraninite and a monazite, both collected from Huron claim, Manitoba. The sequence of ages as originally reported by Nier has been modified by Collins to bring the lead-uranium ages and lead-lead ages into agreement, assuming a loss of 42.1% of the radiogenic lead present in the uraninite and a loss of 22.1% of the uranium present in the monazite.

The interpretation of the $Pb^{206}/U^{238} > Pb^{207}/U^{235} \gg Pb^{207}/Pb^{206}$ age sequence for the monazite as a result of loss of uranium would seem to be reasonable. As has been mentioned,[13,14] the interpretation of the $Pb^{206}/U^{238} < Pb^{207}/U^{235} \ll Pb^{207}/Pb^{206}$ age sequence for the uraninite as a result of loss of 42.1% lead would seem to be less satisfactory. The $Pb^{206}/U^{238} < Pb^{207}/U^{235} \ll Pb^{207}/Pb^{206}$ pattern of ages has been found for relatively young, extremely fresh, unaltered Colorado Plateau uranium ores. It is exceedingly unlikely that such fresh specimens of uranium ore could have lost significant proportions of their radiogenic lead without any evidence of alteration.

Collins, however, noted the approximate agreement in the Pb^{207}/Pb^{206} ages of the two uraninite

and monazite samples (2468 million years and 2590 million years, respectively). He observed that in view of the discrepancies in the lead-uranium and lead-lead ages, the Pb^{207}/Pb^{206} ages were the most reliable. He concluded:

"The original findings of Nier (1939) and of Nier, Thompson, and Murphey (1941) that ages from the Pb^{207}/Pb^{206} ratio are usually close to the true age of the mineral, even when that mineral had been subjected to alteration and loss of lead or uranium, is still the most important experimental evidence we have."

ORIGINAL RADIOGENIC LEAD

In 1931 Kovarik wrote:[16] ". . . if we assume that besides common lead, we have also radium G (Pb^{206}), thorium D (Pb^{208}), and actinium D (Pb^{207}) in separate quantities to that at time, $t = 0$, the atomic weight of the lead isotopes is different from 207.20 (common lead) or different from zero (no common lead: a possibility) then we shall have more unknown quantities than equations connecting them and the problem becomes unsolvable unless we have many minerals of varied content but of the same geologic age."

Following Kovarik's suggestion, original common lead is defined as the Pb^{204}, Pb^{206}, Pb^{207}, and Pb^{208} present and precipitated with the uranium and thorium at the time of formation of the radioactive ore, $t = 0$. The per cent abundances of these four isotopes may vary considerably, but proportions of these isotopes should not exceed the abundances reported for lead in lead-ore deposits or in igneous rocks with average concentrations of lead, uranium and thorium.

Original radiogenic lead is defined as the Pb^{206}, Pb^{207}, and Pb^{208} of radio-radiogenic origin that was present and was precipitated with the uranium and thorium at the time of formation of the radioactive mineral, $t = 0$. The amount of Pb^{206}, Pb^{207}, and Pb^{208}, and the Pb^{207}/Pb^{206} ratio of the original radiogenic lead will depend, in part, on the age of the source material, the relative concentration of lead, uranium and thorium in the source material, and the chemical environment at the time of transportation and deposition.

Although the suggestions of Kovarik, that the presence of original radiogenic lead could considerably complicate that problem of age determination, preceded the work of Wickman, Kulp and Collins by many years, modern investigators apparently have not considered this correction in analyzing the discrepancy between the lead-uranium and lead-lead ages. The presence of old radiogenic lead in a uranium ore would also result in the $Pb^{206}/U^{238} < Pb^{207}/U^{235} \ll Pb^{207}/Pb^{208}$ age sequence. As can be seen from Fig. 1D, the Pb^{206}/U^{238} age, rather than the Pb^{207}/U^{235} or Pb^{207}/Pb^{206} ages, would most nearly represent the "real age" of the sample. This conclusion, it should be noted, does not agree with the choice of either Kulp or Collins.

The currently accepted explanation for the relatively large variations in the isotopic composition of common lead is that the primeval lead present at the time of the formation of the earth's crust has been mixed at various times with radiogenic lead produced by the decay of uranium and thorium in the crustal rocks. It is remarkable, in view of the long-recognized fact that uranium ores may contain significant amounts of original common lead, that the effects of original radiogenic lead were ignored. It might, therefore, be expected that in the vicinity of uranium deposits the isotopic composition of the lead minerals present would show abnormal concentrations of radiogenic lead.

Isotopic analyses of uranium-free galena specimens from several uranium-rich provinces[5,7,17] show that the lead minerals in the vicinity of some uranium deposits do contain extremely large amounts of Pb^{206}. Unfortunately, relatively little attention has been paid to the lead minerals associated with radioactive ores. If the primary-lead minerals from the radioactive area show relatively large concentrations of radiogenic lead, it would not seem unreasonable that the radioactive ores from the same area might contain original lead with concentration of an earlier generation or radiogenic lead at least equal to that of the primary-lead minerals. Possibly the radioactive ores might contain much more radiogenic lead than the primary-lead minerals. It should be quite clear that the presence of small amounts of Pb^{204}, the common-lead index, would in no way indicate the amount of original radiogenic-lead contamination that the radioactive ore contained.

As Kovarik implied, the problem of correcting for the presence of original radiogenic lead is not an easy one, and, as he suggested, it can only be resolved if there are isotopic analyses of many minerals of varied uranium or thorium content from the same locality and same period of deposition. We have made graphical analyses[17] of many Colorado Plateau uranium ores and lead minerals from the same mine. The analyses show that it is possible to obtain agreement between the lead-uranium and the lead-lead ages without resorting to either loss of radon or lead. Of equal importance, the required isotopic composition of the original common plus radiogenic lead used to bring the Pb^{207}/Pb^{206} ages of mill-pulp samples into agreement with the lead-uranium ages of unaltered uraninite specimens from the same mine actually falls within the limits of the experimentally determined composition of the galena from the mine. A detailed discussion of the corrections for original radiogenic lead is in preparation and will be published elsewhere.

THE Pb^{206}/U^{238} AGE

To Nier's experimental evidence that the Pb^{207}/Pb^{206} ratios are least affected by loss of lead and uranium may now be added the experimental evidence that certain uranium-rich provinces contain a type of radiogenic lead that does not appear to have

been formed by the uranium after its deposition in its present sites, i.e., the ores contain original radiogenic lead. Failure to correct for original radiogenic lead results in Pb^{207}/U^{235} ages slightly greater than the Pb^{206}/U^{238} ages, and in Pb^{207}/Pb^{206} ages considerably greater than the Pb^{207}/U^{235} ages. Although a little high, the Pb^{206}/U^{238} age most nearly approximates the actual age of the sample (Fig. 1D).

The most serious limitation of the Pb^{206}/U^{238} age, its susceptibility to loss of uranium and possible loss of lead as a result of geologic processes, can be minimized in several ways. In each instance, the primary responsibility for reducing the uncertainty in the calculated ages falls on the geologists who collect and prepare the material used for the age determinations. Unless there is no alternative, a suite of radioactive ores and related common lead-bearing materials, rather than a single ore specimen, should be collected for any age study on a given locality. Unfortunately, the practice of reporting single age determinations is quite often followed. The suite of samples should include the freshest, least-altered uranium ores obtainable as well as examples of the more oxidized, altered ores. If possible, the unaltered ores should differ appreciably in grade. Composite samples have only a limited use in age studies. An exhaustive search should be made for specimens of non-radioactive lead minerals or, failing this, other non-radioactive ore minerals containing at least trace amounts of common lead.

Of equal importance in an age study are the field relations of the samples within the suite, to each other and to the deposit from which they have been collected. A satisfactory appraisal of the geologic processes, as expressed in the age discrepancies, can best be made in terms of these field relations and in terms of the geologic history and environment of the area. In geologic literature, age data accompanied by an adequate geologic description of the locality from which the sample was collected are unusual.

The careful examination and preparation of samples for age work may also contribute substantially to the reduction of observed lead-uranium and lead-lead age anomalies. From polished-section studies, it is frequently possible to determine the order in which the uranium and lead minerals were deposited, later periods of deposition of lead and uranium, and the type and extent of alteration. Careful separation and isotopic analysis of the primary and secondary radioactive phases and of the associated lead minerals, if present, will provide additional data on part of the alteration history of the sample. Complete mineralogic descriptions of the samples used for age work are as rare in the literature as are full descriptions of the samples' geologic setting.

CONCLUSION

The interpretation of the $Pb^{206}/U^{238} < Pb^{207}/U^{235} \ll Pb^{207}/Pb^{206}$ age sequence of uranium ores presents several problems, the unequivocal solution of which remains for future detailed studies. The available data, however, suggest: (1) the natural variation in the U^{238}/U^{235} ratio is less than 1%, (2) selective loss of large amounts of radon (Rn^{222}) does not occur in massive unaltered uranium ores, (3) recent alteration of pyritic uranium ores results in loss of uranium rather than loss of lead, (4) the Pb^{207}/Pb^{206} age is least affected by loss of lead or uranium, and (5) lead minerals associated with many uranium ores contain large amounts of radiogenic lead appreciably older than the surrounding uranium ores.

The selection of the Pb^{207}/U^{235} "radon diffusion age" from the age sequence for massive unaltered uraninites would seem to be difficult to support. Similarly, there seem to be serious objections to the selection of the much higher Pb^{207}/Pb^{206} age from the age sequence on the assumption of lead loss, particularly from the fresh, unaltered uranium ores. The selection of the Pb^{206}/U^{238} age as the most nearly correct on the basis of the presence of original radiogenic lead can be confirmed experimentally. The Pb^{206}/U^{238} age, however, is the most sensitive of the three to losses of lead or uranium. In contrast, the Pb^{207}/Pb^{206} age is essentially unaffected by loss of lead or uranium, although this age is the most sensitive of the three to all of the remaining corrections and sources of error.

The most serious limitation of the Pb^{206}/U^{238} ages—its susceptibility to loss of uranium and lead—can be minimized by the selection of fresh unaltered specimens for age study. Additional information on the suitability of the samples for age determinations should be obtained from polished section, semiquantitative spectrographic, specific gravity, and X-ray studies. The analysis of several pairs of uranium ores, differing in uranium content, and of the associated lead minerals from the same ore body may, in favorable cases, establish the corrections for original radiogenic lead.

An independent method of evaluating the reasonableness of the three ages of a sample (Pb^{206}/U^{238}; Pb^{207}/U^{235}; Pb^{207}/Pb^{206}) is the comparison of these ages with the relative ages of the geologic events which preceded, which were contemporary with, and which followed ore deposition. A Pb^{207}/Pb^{206} age several times greater than the approximate age of the enclosing rocks is questionable. The analysis of extremely old samples for comparative age studies is particularly unfortunate because of the relative paucity of information on the sequence of geologic events in Proterozoic time. A choice of samples of Cambrian age or younger for such studies permits the great bulk of independent, corroborative, geologic data to be used. Studies on suites of geologically young samples are now being undertaken in an effort to provide a firmer basis for the interpretation of lead-uranium and lead-lead age sequences. Also the careful investigation of relatively young uranium ores offers a particularly fruitful approach to some of the geologic processes of alteration and weather-

ing. Before a valid choice of one age in preference to the remaining two ages can be made, the geologic field and laboratory evidence for the process, or processes, producing the age anomalies must be established. The conclusion that one age from the $Pb^{206}/U^{238} < Pb^{207}/U^{235} \ll Pb^{207}/Pb^{206}$ sequence is preferable to the two remaining ages and that one geologic process is operative in all cases, without regard for the particular sample's geologic history and environment, can only result in discrediting all age methods in general and in hopelessly confusing the young science of geochronology.

REFERENCES

1. Bain, G. W., *The Age of the "Lower Cretaceous" from Bisbee, Arizona, Uraninite,* Economic Geology 47: 305–315 (1952).
2. Kerr, P. F. and Kulp, J. L., *Pre-Cambrian Uraninite, Sunshine Mine, Idaho,* Science 115: 86–88 (1952).
3. Davidson, C. F., *The Gold-Uranium Ores of the Witwatersrand,* The Mining Magazine 88: 73–85 (1953).
4. Stieff, L. R., Stern, T. W. and Milkey, R. G., *A Preliminary Determination of the Age of Some Uranium Ores of the Colorado Plateau by the Lead-Uranium Method,* US Geological Survey Circular 271: 1–19 (1953).
5. Collins, C. B., Farquhar, R. M. and Russell, R. D., *Isotopic Constitution of Radiogenic Leads and the Measurement of Geologic Time,* Bulletin of the Geological Society of America 65: 1–21 (1954).
6. Louw, J. D., *Geological Age of Witwatersrand Uraninites,* Nature 179: 349–350 (1955).
7. Louw, J. D. and Strelow, F. W. E., *Geological Age Determinations on Witwatersrand Uraninites Using the Lead Isotope Method,* Transactions of the Geological Society of South Africa (in press).
8. Nier, A. O., *The Isotopic Constitution of Radiogenic Leads and the Measurement of Geological Time. II,* Physical Review 55: 153–163 (1939).
9. Nier, A. O., Thompson, R. W. and Murphey, B. F., *The Isotopic Constitution of Lead and the Measurement of Geological Time. III,* Physical Review 60: 112–116 (1941).
10. Holmes, A., *The Construction of a Geological Time-Scale,* Transactions of the Geological Society of Glasgow 21: 117–152 (1945).
11. Wickman, F. E., *On the Emanating Power and the Measurement of Geological Time,* Geologiska Foreningens I Stockholm Forhandlingar 64: 465–476 (1942).
12. Kuroda, P. K., *On the Isotopic Constitution of Radium (Ra^{228}/Ra^{226}) in Uranium Minerals, and Recent Problems of Geochronology,* Annals of the New York Academy of Sciences (in press).
13. Kulp, J. L., Bate, G. L. and Broecker, W. S., *Present Status of the Lead Method of Age Determination,* American Journal of Science, 5th Series, 252: 345–365 (1954).
14. Phair, G. and Levine, H., *Notes on the Differential Leaching of Uranium, Radium, and Lead from Pitchblende in H_2SO_4 Solutions,* Economic Geology 48: 358–369 (1953).
15. Ellsworth, H. V., *Rare-Element Minerals of Canada,* Canada Geological Survey, Economic Geologic Series, No. 11: 1–272 (1932).
16. Kovarik, A. F., in Knopf, Adolph, (Chairman), *Physics of the Earth. IV. The Age of the Earth. Part III. Calculating the Age of Minerals from Radioactivity Data and Principles,* National Research Council Bulletin 80, 73–123 (1931).
17. Stieff, L. R. and Stern, T. W., *Original Radiogenic Lead, An Additional Correction for Lead-Uranium and Lead-Lead Age Calculations* (abstract), Bulletin of the Geological Society of America 65: 1308 (1954).

The Isotope Geology of Some Uranium Minerals

By Henry R. Hoekstra and Joseph J. Katz,* USA

Variations in the isotopic ratio of O^{16}/O^{18} in atmospheric oxygen and in oxygen-containing compounds have been the subject of many investigations. The normal abundance of O^{18} has been found to be approximately 0.2%; variations above and below the normal isotopic ratio obtained by various investigators are summarized in Table I. The O^{18} values reported have been recalculated for the most part, using the average of twenty samples of ocean-water[1] as a standard. In some instances, no direct comparison between the standards used by individual investigators and the ocean-water standard was available, but the estimated values given in Table I are probably accurate to ±.2%. The results on uraninites and pitchblendes† reported in this paper are included at the end of the table.

Determination of oxygen isotope ratios for uranium ores may provide an answer to the questions: (1) Is there a variation in the isotopic ratio which can be of assistance in explaining the origin of uranium deposits, and (2) can any observed variation in isotopic ratio be correlated with the temperature of formation of the ore? Work done in search of answers to these questions was aided by the cooperation of H. C. Urey and by spectrometer analyses by Edwards and Craig.

The origin of some uranium deposits has been the subject of considerable controversy and interpretation of their history would be aided by use of an isotopic thermometer scale. It was realized at the outset that an isotopic temperature scale for uranium ores would, at best, be an approximation. As has been shown,[12] isotopic fractionation effects decrease as temperature increases. Since most uranium deposits are formed at elevated temperatures, little fractionation should be expected. However, it should be possible to distinguish between deposits formed at several hundred degrees and those formed at ambient temperatures.

GENERAL CONSIDERATIONS

In measuring variations in oxygen isotope ratios of uraninites and pitchblendes, several factors must be considered relative to the significance of the measurements:

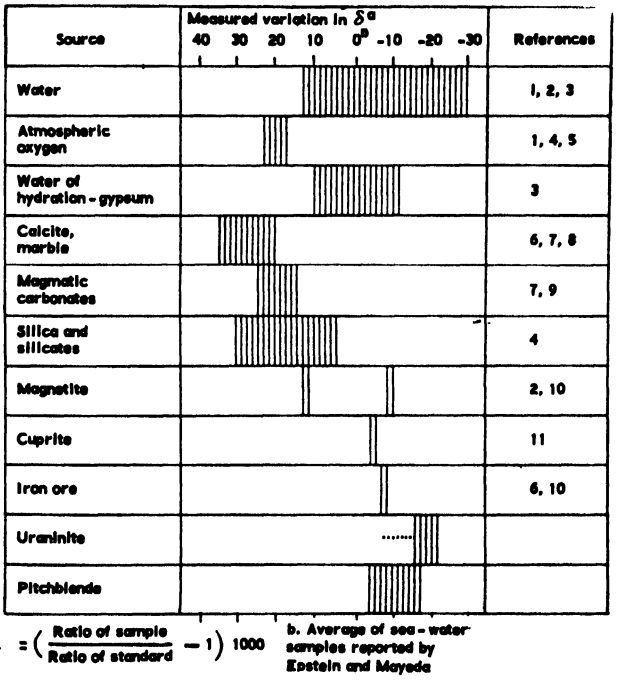
Exchange of Uranium Oxides with Water

The rate of exchange as a function of temperature for the reaction

$$UO^{16}{}_2 + xH_2O^{18} \rightleftharpoons UO^{18}{}_2 + xH_2O^{16}$$

should be known. The minimum temperature at which measurable exchange occurs will set an upper limit on a hydrothermal pitchblende temperature scale.

Table I. Variations in O^{16}/O^{18} Ratio



Exchange studies by Katz and Johnson on synthetic uranium oxides indicated that UO_2 and U_3O_8 did not exchange at a measurable rate below 200°C, while UO_3 (probably as a result of hydrate formation) exchanges slowly at 25°C and rapidly at 100°C. There was some indication that rate of exchange depends on variation in particle size. Some of the results are given in Table II.

Type of Deposit

If uranium oxides (uraninite and pitchblende) show fractionation of oxygen isotopes during precipitation, the effect should be found to increase in the order of decreasing temperature of formation:

* US Atomic Energy Commission.

† In this paper, the term uraninite referes to uranium oxides of pegmatitic origin, and pitchblende to oxides precipitated from aqueous solution.

uraninite, hydrothermal pitchblende, secondary pitchblende. Isotopic composition of the medium from which precipitation occurs must also be considered, since this composition serves as a base-line from which fractionation digresses. Uraninites are generally associated with a high percentage of quartz and silicates. These have been shown[5] to concentate O^{18}, thus one might expect uraninites to be depleted in the heavier oxygen isotope.

Hydrothermal pitchblende precipitation should involve principally the uranium dioxide-water equilibrium. As shown in Table I, water shows the largest variation in O^{16}/O^{18} ratio of any of the compounds measured. Table III lists water analyses from various sources and should aid in selection of a base-line for determination of the presence or absence of fractionation effects in the precipitation of uranium oxides.

Table II. Exchange Experiments with Uranium Oxides

Oxide	*Temp.*	*Time, hr*	*Fraction exchanged*
UO_2	290°	16	23.6
	350	3	36.7
	400	3	73.2
U_3O_8	360	2	38.1
	360	2	57.3
UO_3	25	24	23.6
	100	4	100

Table III. Oxygen Isotope Ratios in Water[1, 2, 3]

Source	δ
Dead Sea water	+11.0
Condensate from fumarole (Paracutin)	+ 6.8
Sea water (average of twenty samples)	0.0 (standard)
Mississippi River (Baton Rouge, La.)	− 4.9
Lake Michigan (Chicago, Ill.)	− 6.1
Rain	− 3.4 to −10.7
Snow	−15.2 to −17.0
Columbia River (Trail, B. C.)	−17.5
Glacier water (Lake Louise, Alta.)	−32.0

If it is assumed that magmatic, or juvenile, water is the medium from which hydrothermal pitchblendes are precipitated, its isotopic composition is probably most closely approximated by fumarole condensates. Corroboratory evidence is supplied by Silverman's silicate analyses which indicate a δ of 6.4 to 7.0 for primary igneous rocks. However, dilution of juvenile water by ground water would cause a change in isotopic composition of the solution, and in the pitchblende precipitated from it. Secondary pitchblende should reflect the composition of the associated ground water.

Sample Purity

Uraninites and pitchblendes are never found in a pure state. It is imperative to obtain samples of maximum purity to minimize the fractionation effects of other constituents. Thorium is not considered to be an impurity, since its reactions should, for these purposes, parallel those of uranium, Nor is lead, resulting from radioactive decay, considered as an impurity, since the oxygen associated with the lead was originally part of the uranium oxide crystal lattice.

Weathering

Another factor to be considered is the effect of weathering on the uranium ores. As shown by Table I, atmospheric oxygen is enriched in O^{18} relative to water oxygen, thus dissolved oxygen in water taking part in weathering of uranium ores will increase the fraction of O^{18} present in the resulting oxidized ore. The fact that pitchblendes almost invariably have smaller lattice parameters than uraninites as shown by X-ray crystallography, suggests that oxidation beyond UO_2 has taken place. This may have occurred before precipitation as a result of contact with ground water containing dissolved oxygen. Oxidation may also have occurred subsequent to precipitation, since uranium oxides crystallized at low temperatures are more readily oxidized than those formed at high temperatures.

EXPERIMENTAL CONSIDERATIONS

Molecular oxygen was obtained from the uranium oxides by the use of bromine trifluoride. The equation for the reaction is

$$UO_2 + 2\,BrF_3 \rightarrow UF_6 + Br_2 + O_2$$

Oxygen is easily separated from the other products by condensing them with liquid nitrogen. The equipment and procedure have been described elsewhere.[14] Complete oxygen evolution was obtained in two hours at 75°C except for a few of the least pure ore samples. Twelve runs on two different batches of U_3O_8 ignited at 750°C in air were made to test the accuracy and precision of the procedure. Oxygen to uranium ratios of 2.66 ± 0.01 were obtained.

Isotopic analyses of the oxygen samples as well as all other samples included in this report were made using a high precision mass spectrometer. By comparing oxygen from an unknown with a standard working sample, the probable error in isotope ratio is about 0.2%. The twelve reproducibility runs on oxygen from U_3O_8 showed an average deviation in the O^{16}/O^{18} ratio of less than ± 1%. The average of these twelve results was taken as the composition of atmospheric oxygen (+ 22% relative to ocean water).

An attempt has been made to calculate a theoretical fractionation curve for the UO_2–H_2O system from infrared data. The infrared spectrum of a potassium bromide disk containing 1% UO_2 showed a single broad absorption at 425–475 cm^{-1} near the long wave length limit of the potassium bromide prism. Measurements on the Raman spectrum have not been run as yet.

Attempts were also made to obtain an experimental UO_2–H_2O fractionation curve by precipitation of synthetic pitchblende at 25° and 100°C. Unfortunately uranium dioxide precipitated at these

low temperatures is extremely reactive towards oxygen. This fact demands that precipitation, washing, and drying of the sample be carried out in a completely oxygen-free atmosphere, and further, that no opportunity for isotopic fractionation of the water occur during drying of the sample, since the freshly precipitated oxide will exchange with water at room temperature. Before the dioxide can be safely exposed to air without danger of oxidation, it must first be deactivated by heating to 500–600°C in vacuum or in an inert atmosphere. Our synthetic pitchblendes, precipitated as nearly as possible under equilibrium conditions, analyzed $UO_{2.07}$ to $UO_{2.12}$, but did not show reproducible isotopic ratios.

DISCUSSION

A number of observations can be made from the results tabulated in Table IV:

1. In general, uraninites show a smaller O^{18} content than pitchblendes. Since uraninites form at higher temperatures, this might be considered evidence for isotopic fractionation in the uranium oxide-water system, but the effect can probably be traced to the large amounts of silicates associated with the uraninite. As indicated earlier, concentration of O^{18} in the quartz and silicates will serve to deplete the supply available for the uraninite.

2. Ore from the Belgian Congo treated with high pressure steam at the Geophysical Laboratories of the Carnegie Institution of Washington and synthetic pitchblendes prepared by Gruner (Table IV) show O^{18} contents close to that expected from tap waters from these locations. In general, the least oxidized pitchblendes show O^{18} contents quite close to that expected for the ground waters in their immediate vicinity. These observations suggest that exchange rates even at low temperatures are appreciable on a geologic time scale involving millions of years.

3. Impurities may play an important part in the results obtained as indicated by the variation in δ of runs 3 and 4, Table IV, and the Beaverlodge district samples (runs 9–12, Table IV).

4. Oxidation, as expected, causes an increase in O^{18} content. This is best illustrated by the Spruce Pine samples (Nos. 16, 17, Table IV). The Congo samples (Nos. 5, 7, Table IV) also show this effect, but differences in purity may play some part.

In order to check isotopic exchange of pitchblendes and uraninites, a series of runs were made

Table IV. Isotope Ratios in Pitchblende and Uraninite

Source	*% U+Th+Pb as dioxides*	*Treatment before analysis*	*O/U Ratio*[a]	δ[b]
A. Pitchblendes from Colorado Plateau				
1. Happy Jack mine, San Juan Co., Utah	84.1	as rec'd.	2.46	−14.3
			2.46	−14.9
2. Happy Jack mine, San Juan Co., Utah		air dried 100°	2.39	−14.6
			2.40	−14.0
3. Shinarump No. 1 claim	64.9	air dried 100°	2.52	− 8.5
4. Shinarump No. 1 claim, Superpanned	83.9	as rec'd.	2.72	−11.8
B. Vein deposits				
5. 4521A_2 Belgian Congo, reconc.	(95)[c]	as rec'd.	2.84	− 9.2
6. 4521A_2 Belgian Congo, reconc.		vac dried 100°	2.76	− 9.3
7. Congo Pitchblende	85.8	air dried 100°	2.97	− 3.4
8. Congo Pitchblende (steam treated)	90.8	as rec'd.	2.26	−10.9
9. R508, Beaverlodge Uranium Mine, Sask., Canada	72.1	vac dried 70°	3.04	− 8.5
10. R535, Martin Lake Mine, Sask., Canada	(60)	as rec'd.	2.33	−16.7
11. R547 Rix Mine, Sask., Canada	(70)	as rec'd.	2.80	−19.0
12. R633, Ace Mine, Sask., Canada	(60)	as rec'd.	3.42	− 5.7
C. Synthetic pitchblende—J. W. Gruner				
13. 217°	(99)	vac dried 70°	2.33	−11.1
14. 210°	(99)	vac dried 70°	2.24	−11.9
D. Pegmatitic deposits				
15 Karelia, Russia (hand-picked sample)	(90)	as rec'd.	2.39	−20.3
16. Spruce Pine, N. C. (hand-picked, no secondary or coaly material)	(90)	vac dried 100°	2.93	− 7.4
17. Spruce Pine, N. C. (hand-picked, coaly material)		vac dried 100°	3.11	− 3.5
18. Cardiff TWP, Ontario (hand-picked separate)	(93)	vac dried 70°	2.41	−16.0
19. Cardiff TWP, Ontario (methylene iodide separate)		vac dried 70°	2.56	−15.9
20. Cardiff TWP, Ontario (selected fragments)		vac dried 70°	2.59	−15.3
21. Lot 6, concession XV, Cardiff TWP −80+100 mesh	(93)	as rec'd.	2.66	−16.7
22. Lot 6, concession XV −100+150 mesh		as rec'd.	2.66	−16.6
23. Lot 6, concession XV −150+200 mesh		as rec'd.	2.69	−16.7
24. Boqueirao pegmatite, Rio Grande de Norte, Brazil	(90)	vac dried 70°	2.58	−17.1
25. Viking Lake, Beaverlodge Dist., Sask., Canada	85.4	as rec'd.	2.48	−22.0

[a] The O/U ratio is calculated on the assumption that the sample is pure uranium oxide. The ratio is given only as an indication of the true oxidation state of uranium, since oxygen from most oxide impurities is also included.

[b] The δ's are given relative to standard sea-water (Table I).

[c] Values in parentheses are estimates obtained by subtracting impurities reported in spectrographic analyses.

on some of the ore samples listed in Table IV. These were heated at 100°C with water which had been slightly enriched in O^{18} ($\delta = +100$). The Colorado Plateau samples, from deposits generally conceded to have been formed at relatively low temperatures, showed the greatest exchange rate (30% and 20% in 24 days). The Spruce Pine sample also showed ~20% exchange in 24 days, which can be attributed to its relatively high oxidation state. The other pegmatitic samples showed relatively little exchange (2 to 10%), the majority of which occurred during the first day and is probably due to the presence of readily exchangeable impurities. In general, the exchange experiments served to indicate that pitchblendes are in isotopic equilibrium with their present environment, while uraninites, if relatively unweathered, may not be. It should be noted that nearly all of the pegmatitic samples are from regions of relatively cold climate. Since snow has been shown to be low in O^{18}, the observed isotopic ratio in these uraninites may also be due to equilibration with ground water rather than retention of the original low O^{18} content. Analysis of a number of uraninites from regions where the isotopic ratio of O^{18} is known to be high should answer this problem.

From the observations cited above, it becomes evident that the measured differences in O^{16}/O^{18} ratio of uraninites and pitchblendes are traceable to a number of variables (composition of the precipitating medium, possible exchange subsequent to precipitation, impurities, and weathering) which effectively mask any contribution due to the fractionation factor inherent in the uranium dioxide-water system.

REFERENCES

1. Epstein, S. and Mayeda, T., Geo. chim. Cosmochim Acta *4*, 213–24 (1953).
2. Thode, H. G., Research *2*, 154–61 (1949).
3. Baertschi, P., Helv. Chim Acta *36*, 1352 (1953).
4. Silverman, S. R., Geochim. Cosmochim Acta *2*, 26–42 (1951).
5. Dole, M., J. Chem. Phys. *4*, 268–75 (1936).
6. Dole, M. and Slobod, R. L., J. Am. Chem. Soc. *62*, 471–79 (1940).
7. Teis, R. V., Akad. Nauk SSSR, Doklady *72*, 73–6 (1950).
8. Epstein, S., Buchskaum, R., Lowenstam, H. A. and Urey, H. C., Geol. Soc. Am. Bull. *62*, 417–25 (1951).
9. Vinogradov, A. P. and Dontsova, E. I., Akad. Nauk SSSR, Doklady *56*, 391–2 (1947).
10. Dontsova, E. T., Akad. Nauk SSSR, Doklady *71*, 905–6 (1950).
11. Hall, W. H. and Hochandel, C., J. Am. Chem. Soc. *62*, 3259–60 (1940).
12. Urey, H. C., J. Chem. Soc. 562–81 (1947).
13. Hoekstra, H. R. and Katz, J. J., Anal. Chem. *25*, 1608 (1953).

Summary of Hypothesis of Genesis of Uranium Deposits

By V. E. McKelvey,* D. L. Everhart† and R. M. Garrels,* USA

Concentrations of uranium more than 10 times the average of the earth's crust, i.e., more than 0.002% U, are formed by a variety of igneous and sedimentary rock-forming processes as well as by ore-forming processes as they are ordinarily conceived. The nearly ubiquitous geologic distribution of uranium stems, of course, from its chemical and physical properties, particularly its polyvalence, its large atomic radius, its high chemical reactivity, the relative solubility of many of its hexavalent compounds in aqueous solutions, and its relative abundance compared to some other ore metals. These attributes permit it to form compounds with many other elements, to enter the structure of a wide variety of minerals, to take part in many chemical reactions, and hence to be deposited in many rocks and minerals of diverse origins and compositions. The same properties that lead to the wide geologic distribution of uranium also lead to its dispersion so that concentrations of uranium are not as great as those of other, less active metals of comparable abundance such as lead and molybdenum. The partition of uranium from other elements, and hence its concentration in valuable deposits, seems to be favored by its large radius and high valence, which prevent its concentration in ordinary rock-forming minerals, and also by the relative insolubility in aqueous solutions of its common tetravalent compounds, which leads to the precipitation of uranium in a wide variety of environments where reducing conditions prevail.

In the summary the follows attention is focused on the origin of deposits that are currently and potentially most important economically—specifically the uraniferous igneous rocks, the hydrothermal veins, the uranium deposits in sandstones, uraniferous coals and associated carbonaceous shales, uraniferous marine black shales, and uraniferous marine phosphorites. Moreover, we give most consideration to those hypotheses which seem most tenable to us.

URANIFEROUS IGNEOUS ROCKS, PEGMATITES, AND MIGMATITES

The uranium content of igneous rocks is about 0.03 parts per million in ultramafic rocks, 1 ppm in gabbroic rocks, 2 ppm in intermediate rocks, 3 to 4 ppm in granitic rocks, and reaches a maximum of 10 to 200 ppm in a few alkalic granites.[1] The unmistakable enrichment of uranium in intrusives rich in silica and alkalies is observable also in volcanics.[2] Some silica-poor rocks, such as lamprophyres, are also relatively rich in uranium, however; Larsen and Phair,[1] believe that "the safest generalization that can be made at this time is that the maximum concentration of uranium and thorium is found in the youngest member of a series, regardless of the particular liquid line of descent that the magma may have followed."

The uranium and thorium fractionation in igneous rocks is explained by Larsen and Phair[1] as a function of the size, valence, and abundance of the uranium ion and of oxidation-reduction equilibria. Because uranium is low in concentration in basic magmas and because the large size and tetravalence of the uranium ion impose hard to meet coordination requirements, uranium neither precipitates as a separate mineral nor isomorphously substitutes in plagioclase and other rock-forming minerals. Hence it concentrates in late-stage magmas from which it may be deposited as a miner constituent of accessory minerals (such as zircon, xenotime, apatite, and sphene) in which it can substitute isomorphously. As differentiation proceeds toward the highly hydrous pegmatite stage more uranium is deposited as discrete minerals and less enters the accessory minerals, probably because increase in the water content of the magma reduces the solubility of tetravalent uranium. During very late magmatic stages, uranium may be oxidized to the hexavalent state, possibly as a consequence of pressure changes. This shift to oxidizing conditions is shown by the replacement of early formed ferrous magnesium silicates by magnetite. In the hexavalent state uranium forms relatively soluble compounds in aqueous solutions. Some may be deposited as acid-soluble, interstitial material[3,4,5] from residual solutions but much of the uranium is carried off in hydrothermal solutions. Deposition of uranium in veins takes place when conditions once again become reducing, a conclusion in accord with the facts that the common vein mineral is pitchblende and that sulfides are a constant component of pitchblende veins. Because thorium occurs only in the tetravalent state it is not affected by a change to oxidizing conditions and is probably not transported with uranium in hydrothermal solutions. This hypothesis explains the absence of thorium in pitchblende veins—a previously puzzling phenomenon in view of the rather constant 3 : 1 ratio of thorium and uranium in igneous rocks.[1]

* US Geological Survey.
† US Atomic Energy Commission.

Pegmatites contain a wide variety of uranium minerals, including uraninite as well as many multiple oxides containing rare earths, niobium, tantalum and titanium. According to Page[6] uranium minerals appear to be commonest in those bodies that contain an abundance of potash feldspar; in zoned pegmatites they are most common in intermediate zones and cores also rich in potash. The covariation of uranium with potash has also been noted in igneous rocks,[1] and is explained by Adams,[2] as a reflection of the exclusion of these two elements (because of their radii and coordination numbers) from common minerals formed during earlier stages of crystallization. Zonation of pegmatites is now believed to result from fractional crystallization of the pegmatite liquid from the walls inward,[6] so the zonal distribution of uranium in pegmatites also demonstrates its tendency to concentrate in late stage liquids. Some pegmatites or zones within pegmatite, particularly those that contain uraninite, minor sulfides, and no thorium, are veinlike in character and may have formed as a result of replacement by or direct deposition from high-temperature hydrothermal solutions.

Certain migmatites in Canada composed of thin, parallel bands of granite pegmatite, and biotite-bearing schist or gneiss, contain uraninite or uranothorite.[7] The origin of migmatites in general is controversial—they may have been formed as a result of partial fusion of sedimentary rocks, by injection of granitic material, or by replacement from high-temperature hydrothermal solutions. The origin of the uranium-bearing migmatites has been little studied, but as Adams implies[2] analysis of their uranium-thorium ratios might show whether they have been derived from primary igneous sources or from partial fusion of sedimentary rocks. In any event, the uranium in migmatites was deposited at high temperatures.

URANIUM IN HYDROTHERMAL VEIN AND REPLACEMENT DEPOSITS

Three important types of uraniferous veins may be recognized:[8] (1) nickel-cobalt-native silver veins; (2) silica-iron-lead veins; and (3) iron-titanium veins. The nickel-cobalt-native silver veins are characterized by pitchblende, a complex assemblage of sulfides, carbonates, and minor amounts of silica; they occur typically in metasediments and metavolcanics and are represented by large deposits such as those at Shinkolobwe and Great Bear Lake. The silica-iron-lead veins are also characterized by pitchblende, but the assemblage of associated minerals is generally a simple one—mainly pyrite, galena, and quartz or jasper. They occur mainly in felsic intrusives; examples are deposits at Urgerica, Portugal, and Marysvale, Utah. The iron-titanium veins are characterized by uranium titanites—such as davidite—ilmenite, rutile, and quartz. They occur mainly in igneous intrusives and are typified by the deposits at Radium Hill, South Australia. Disseminated iron oxides are widespread in all these deposits.

As discussed in the foregoing section, uranium in hydrothermal veins is derived mainly from residual solutions arising from late-stage differentiates, generally those rich in silica and the alkalies. The problems of chief concern, then, are the composition and temperature of transporting solutions, depth and pressure relationships at the site of deposition, the chemistry of precipitation, and structural control in the localization of the ore.

Little is known directly about the composition of uranium-bearing hydrothermal solutions, but from the fact that the most uraniferous natural waters are those high in sulfate and or carbonate, as well as from experimental data[9,10,11] that indicate the solubility of uranyl sulfates and carbonates in aqueous solutions it may be assumed that uranium is transported as the uranyl ion[12] in sulfate or carbonate solutions and that they may be either acid or alkaline. Because the physical chemical properties of CO_2 and the system CO_2–H_2O indicate that under some shallow earth conditions CO_2 can exist as a separate phase with a density approximately that of water, liquid CO_2 has also been suggested as the ore-transporting solution.[13]

From the mineral assemblages as well as some experimental evidence,[9,10,14] the Si-Fe-Pb veins that contain sooty pitchblende are classed as epithermal; the remainder of the silica-iron-lead veins and the Co-Ni-Ag veins are believed to be mesothermal; and some uraninite,[15] brannerite,[16] and davidite veins[17] which somewhat resemble pegmatite deposits, are regarded as hypothermal. The temperature of the transporting fluids and the depth and pressure at the site of deposition of the uranium veins are thus believed to have ranged widely. According to Lindgren,[18] epithermal deposits are believed to have probably formed at temperatures of less than 200°C, depths of less than 4000 feet, and pressures of less than 140 atmospheres; mesothermal deposits probably formed at temperatures of 175° to 300°C, depths of 4000 to 1200 feet, and pressures of 140 to 400 atmospheres; and hypothermal deposits likely formed at greater temperatures (possibly several hundred degrees C), depths and pressures. Field evidence strongly indicates that most of the pitchblende veins were formed at depths shallow enough and at pressures low enough to provide open spaces along regular fissures.

Precipitation of primary uranium minerals in veins may be caused solely by a reduction in the amounts of sulfate or carbonate in solution by whatever cause, by a decrease in temperature, pressure, or both, or by chemical interaction with the host rock. Either pressure or chemical interaction with the host rock may result in reduction, which seems to be the factor of major importance in the precipitation of uranium minerals in hydrothermal and many other types of deposits. Experiments by Miller and Kerr[10] confirming earlier work by Gruner,[9] indicate that pitchblende may be precipitated from uranyl sulfate solutions by the use of hydrogen sul-

fide gas, according to the equation:

$$H_2S + (UO_2)^{2+} + 4H^+ = S \pm UO_2^{4+} + 2H_2O$$

Ferrous iron also may be a reducing agent for uranyl iron. The reaction:

$$3H_2O + 2Fe^{2+} + (UO_2)^{2+} \rightarrow Fe_2O_3 + UO_2^{4+} + 6H^+$$

goes to completion ($(UO_2)^{2+} < 10^{-6}$) at 25°C at pH 4 and above over a wide range of Fe^{2+} concentration. This may explain the widespread association of iron oxide with pitchblende in vein deposits.

Most of the pitchblende vein deposits show a marked structural control, a tendency to be deposited along straight portions of fractures rather than along crooked portions. In a few deposits pitchblende is found impregnated in wall rock, but most deposits away from through-going structures are concentrated along related tensional fractures. Replacement deposits are rare except in carbonatic or carbonaceous host rocks and in some high-temperature deposits.

URANIUM DEPOSITS IN SANDSTONE

The two best known uraniferous sandstone districts are those of the Colorado Plateau and the Witwatersrand. Unweathered deposits in both districts consist of pore-space fillings of uraninite, pyrite and other sulfides, generally associated with carbon in the form of woody or asphaltic material. In addition, coffinite (a hydroxy-substituted uranium orthosilicate) and low-valent vanadium minerals are prominent in some of the Plateau deposits, and gold, of course, is an important constituent of the Rand deposits. Individual ore bodies are roughly parallel to bedding, are tabular and generally elongate in shape, and range in size from a few pounds to millions of tons. They are best developed in or along the margins of thicker and more permeable zones within the sandstones, such as fossil stream channels. Deposits are widespread within individual, relatively thin zones but in both the Plateau and Rand districts deposits are found in many beds over a wide stratigraphic range. The host rocks are nonmarine, generally fluviatile sandstones or conglomerates, though related deposits are occasionally found in rocks of other lithology. Whereas the distribution of the deposits is conspicuously related to sedimentary features, it is less commonly or only inconspicuously related to fractures and igneous rocks. Alteration of host rocks is not pronounced, although red mudstones are bleached to a gray or greenish color in the vicinity of ore deposits on the Plateau, kaolinite is associated with some deposits on the Plateau, and chlorite is prominent in both the Plateau and Rand deposits.

The origin of the sandstone ores is rather controversial. It is not possible to review the details of the hypotheses genesis of these deposits, much less the evidence on which they are based, but the salient information on problems of the age of the ores compared to the host rocks and the source, transportation and deposition of the ore metals is summarized briefly. A more complete review of the origin of this and other types of uranium deposits is given in the literature.[19]

Nearly all who have studied the sandstone deposits interpret the paragenetic relationships of ore and host—rock minerals to mean that the ores in their present form were deposited after the enclosing rocks. Many believe,[19,27] however, that the chief ore metals were introduced during or shortly after deposition of the host rocks, although most of those who favor a placer hypothesis agree that the sulfides were introduced later. New and convincing evidence on this problem with respect to the Plateau ores has been presented recently by Stieff, Stern, and Milkey[28] who show that the mean Pb^{206}/U age, after correction for the common Pb present, of many samples of Plateau ores is 71 million years, or about half the age of the enclosing rocks. The mean age of samples from ores in the Jurassic Morrison and Entrada formations and the Triassic Shinarump conglomerate are 72, 50, and 73 million years, respectively. These ages are much younger and more uniform than would be expected if the ores were formed at the time of deposition of the host rocks, but they compare favorably to the 60.5 million years determined as the mean age of four pitchblende samples from hydrothermal veins in the Colorado Front Range. Stieff, Stern, and Milkey interpret their results to mean either that syngenetic uranium deposits were redistributed in Late Cretaceous or early Tertiary time or that the uranium was introduced from depth at that time. They regard the first alternative as less probable because in such a redistribution the common lead found in the ores would be transported and redeposited with the uranium and the previously formed radiogenic lead carried away or deposited elsewhere.

Recent age determinations reported on Rand ores by Davidson[29] and Louw[30] give ages of 1682 and 1850–1950 million years, respectively. Davidson,[31] however, has since revised his figure to 465–816 million years. These ages are older than the Witwatersrand system was previously thought to be, but until the Louw's determination is better established the significance of the isotopic data will remain uncertain. Stieff believes correction for old radiogenic lead in the ore may significantly lower the ages computed by Louw. However, the occurrence of low-density thucholite (a uranium bearing hydrocarbon) with the gold in the Rand ores—an anomaly hardly explainable if both were placer minerals[33]—supports the conclusion that the uranium in the Rand ores is also epigenetic.

It is possible that the maximum age of the Witwatersrand system might be obtained by determination of the age of the zircons and other accessory minerals by the Larsen method.[32]

Several sources have been posulated for the uranium in the sandstone ores. (1) detrital uranium minerals [20,25,26,27,34] or chemical or biochemical pre-

cipitates of uranium deposited at the same time as the enclosing rocks;[22,35] (2) dispersed concentrations in tuffs or ordinary rocks in the sedimentary column;[23,36,37,38] (3) migrating petroleum or solutions derived from petroleum source beds;[39] and (4) hypogene solutions.[33,40,29,41,42,43] In our opinion, syngenetic sources may be omitted from further consideration because of the evidence already cited as well as the facts that uranium on both the Plateau and the Rand occurs in many horizons over a wide stratigraphic range, uraninite is nearly unknown as a placer mineral,[29] and uranium, when it is concentrated by sedimentary chemical or biochemical processes, is associated with fine-grained carbonaceous shale or phosphorite, never with coarse clastics.[29]

Dispersed sources within the sedimentary column as a whole seem ample to supply the volume of metals in even more extensive ore deposits than those already known.[36,44] Moreover, circulating ground water probably would not be far out of equilibrium with the sediments and hence would not produce the marked alteration effects expected of hydrothermal solutions but not observed in the field. That the process is a workable one is suggested by Denson and others[45] who present strong evidence to show that the uranium in lignites in North and South Dakota has been derived from volcanic ash in overlying beds. The hypothesis of a dispersed source has not been considered with respect to the Rand ores, and no evidence is available on which to appraise its merits. The isotopic data, however, cast some light on the source of the Plateau ores. According to Stieff and Stern,[28] the uranium ores, the galena associated with the deposits, the lead in Tertiary vein deposits in the San Juan Mountains, the Colorado Front Range, and the Tucson Mountains of Arizona, all contain lead that has the same peculiar isotopic composition or that varies systematically from this composition in a manner expectable by the addition of differing amounts of lead-206 and lead-207 produced by the decay of uranium. The additional uranogenic lead was formed before its deposition in Tertiary rock. Because this lead has a high 207/206 ratio it must contain an increment of lead derived from old radiogenic sources poor in thorium or from sources that have not released much thorium lead. The uniform composition of the lead in these several types of deposits suggests that they have a common source. From the presence of this lead in the Tertiary veins it seems most reasonable to assume that this source lay at depth, possibly in Precambrian thorium-poor, uranium-rich bodies in the basement complex. Syngenetic or penecontemporaneous derivation of the ore from the volcanic ash in the Triassic and Jurassic sediments is improbable because ores in these rocks do not show isotopic differences which would be expected if radiogenic lead was added that had formed in the ash before the uranium was removed from the tuffs. The isotopic data alone do not rule out the possibility that the ores might have been derived from a single source in the rocks above the deposits, but the presence of lead in the Tertiary veins and the fact that many of the deposits lie several thousand feet below the Tertiary make such a source improbable. Because the possibility of lateral secretion on such a grand scale as that required to form the Plateau and Rand deposits has been little explored, the hypothesis of a dispersed source probably deserves further consideration. The isotopic data, however, seem to make it an improbable explanation for the ores of the Colorado Plateau.

The occurrence of uraniferous "asphaltite" in oil-stained pore spaces, and the similarity of the assemblage of other metals in some asphaltites to that found in smaller concentrations in oil in nearby pools led Gott and Erickson[39,46] to the conclusions that "asphaltite" is residual petroleum and that petroleum fluids may transport uranium to sites of ore deposition, particularly in sandstone-type deposits. Goldschmidt[47] postulates a similar source and history for vanadium and other metals in petroleums and asphalts. Crude oils may contain a fraction of a part per billion to a few thousand parts per billion[46,48] most of which seems to be in asphaltenes, but a few analyses of the Plateau oils indicate that the higher concentrations are only in oil that has penetrated a uraniferous sandstone.[48] Oil is not common on the Plateau and is unknown in the Witwatersrand system. "Asphaltite" on the Plateau is common in only a few areas (much "asphaltite" is proving to be woody material), and the thucholite in the Rand ores bears a replacement relationship to early uraninite.[49] For these reasons it seems unlikely that migrating petroleum is the source of much if any of the uranium on the Plateau or the Rand. It is possible, however, that some uranium in both areas may have been transported short distances by fluid hydrocarbons.

Several lines of evidence have been cited to support a hydrothermal source for both Plateau and Rand ores (1) both contain ore minerals—uraninite, sulfides, etc.—typical of other hydrothermal deposits;[33,29,49] (2) the gangue minerals—quartz (mainly as overgrowths but also in veins in the Rand), chlorite and clay minerals—are typical of or not incompatible with a hydrothermal association;[33] (3) evidence of movement of mineralizing solutions in the form of altered dikes, vein quartz, and sulfides is found along cross-cutting fractures and dikes in the Rand;[33] and some Plateau ores, particularly those high in copper, are associated with faults or fractures;[50] (4) the uranium content of the sandstone ores is similar to that of other hydrothermal ores and dissimilar to that in deposits of other origins;[49] (5) the ores in some parts of the Plateau are zonally arranged around laccolithic intrusives;[51] and (6) isotopic data show the Plateau ores, which include vein copper deposits and limestone replacement ores as well as the more abundant and typical "bedded" deposits in sandstone, to be

genetically related to vein deposits of uranium in the same general region.

Some of these features may be explainable in other ways but one or another of them has been compelling enough to cause syngeneticists in both areas to admit that some of the deposits or some minerals in them[34] are hydrothermal.[22] The arguments have not been accepted for other deposits or minerals mainly because (1) most of the ores show no relation to structural or igneous features; (2) the host rocks are not as conspicuously altered as are most hydrothermal deposits, and (3) vanadium, an important component of some of the Plateau ores, is not an important mineral in other hydrothermal deposits. Those favoring a hypogene source admit the close relation to sedimentary features but believe that in the absence of fractures, solution movement would be controlled by the directional permeability of the rock. They believe the lack of alteration is more apparent than real[33] and because vanadium is a constituent of some vein deposits[7,47,52] they do not consider its presence in some of the Plateau ores a valid objection to the hydrothermal hypothesis. They thus imagine the deposits to be bedded or "interstitial" quartz-sulfide veins, differing from hydrothermal veins only in that they occupy pore spaces in sandstones instead of fractures.

The specific source of the hydrothermal solutions is problematical. The Plateau deposits show some spatial relationship to laccolithic intrusives but intrusives are not widespread on the Rand, though alkalic granites intrude the Witwatersrand system at Vredfort, southwest of the Rand.[26] Nevertheless, Davidson[29] points out that the Rand deposits, as well as those of the Plateau, the copper-cobalt-uranium ores of the Belgian Congo, and the uranium-copper deposits of Rum Jungle in Australia, are in a group of sediments that overlie a complex of Archean granites, which "have undergone domal uplift since the covering blanket of sediments was deposited, due presumably to 'younger' granites which are not always exposed. . . May it not be that the ore deposits in each of these regions represents a 'front' of mineralization which has emanated, through the older granites from the younger magma below?"

The sum total of the available evidence indicates to us that the deposits were derived from a deep-seated source and transported along fractures to permeable horizons, which they then followed to the site of deposition. The mineral assemblage and fine-grained texture of the ores suggest deposition at relatively low temperature and pressure, possibly in the range normal for water-saturated rocks buried by several thousand feet of sediments. Thus if a normal geothermal gradient prevailed at the time of deposition of the Plateau ores, the temperature in the host rocks probably was in the range of 70° to 120°C and the pressure in the range of 200 to 800 atmospheres (the range between the hydrostatic and lithostatic load). As to the chemical factors that led to the precipitation of the ore minerals, the low-valence state of the primary minerals suggests that precipitation probably was brought about by reduction, possibly by decaying carbonaceous matter. Sedimentary structures also played an important role in the localization of the ore. The lenticularity of permeable facies served to prevent solutions from dispersing so widely that no appreciable concentration of metals could result on precipitation.[33] In addition, as shown by the common occurrence of ore at bends in fossil stream channels and along the margins of the more permeable zones, certain structures acted as traps for ore. The mechanics of these traps is not understood; it is possible that their lower permeability lowered the velocity of percolating ore solutions sufficiently to allow time for precipitates to form and become fixed, possibly as replacements of organic matter, clay, and other matrix material.

URANIFEROUS COAL AND ASSOCIATED CARBONACEOUS SHALE

Coal and associated carbonaceous shale beds are generally non-uraniferous but some rather extensive beds in western United States[53] and elsewhere[54] contain 0.005 to about 0.1% uranium and a few in South Dakota contain 0.2% uranium or more.[48] Most of the uraniferous coals are rather high in ash content and low in rank. Secondary uranium minerals, such as autunite, meta-autunite, meta-tyuyamunite[48] and uranocircite[55] are found in some of the higher grade deposits but the uranium in lower grade deposits is in dispersed form, at least in part in organo-uranium complexes or ionic organic compounds.[56] In individual specimens of low-grade coals, the uranium is fairly uniformly distributed,[57] but in larger bodies the uranium content is irregular. In their studies of lignites in South Dakota, Denson, Bachman, and Zeller[45,58] found that in most places only the first lignite immediately below the tuffacaous White River formation of Oligocene age, which unconformably overlies the coal-bearing strata there, is appreciably uraniferous. Moreover, the uranium content of a given layer is highest at the top. Concentrations of uranium may be found in lower beds adjacent to faults or through-going joints, or where they are in contact with a pervious sandstone layer. These relationships have been found to characterize several other uraniferous coals in western United States.

The problems of the origin of uranium in coal and carbonaceous shales are analogous to those of the sandstone ores but are perhaps not as complex. Because certain land plants concentrate enough uranium to be of value in prospecting for ore deposits,[59] it might be supposed that uranium in coal is concentrated by living plants. It appears, however, that significant concentrations of uranium—1 ppm or more in the ash—are found only in plants growing on mineralized ground.[59] Even there it is exceptional to find a uranium content of 100 ppm in the ash, an amount common in the ash of uraniferous lignites and carbonaceous shales. It thus seems unlikely that

the uranium in coaly beds was first concentrated by living plants.[54] Moreover, the irregular distribution of uranium in the individual beds, its regional relationship to unconformities, its vertical distribution within individual beds, and its local concentration along fractures and permeable beds indicate that it was introduced after deposition of the enclosing rocks, though its even distribution in individual specimens suggests that it was introduced prior to coalification.[57]

The source of the uranium is more debatable and may be different from place to place. Because of the relationships already described, Denson and his colleagues concluded that the uranium in the Dakota lignites was derived from uranium tuffaceous materials in the White River formation. The presence of uraniferous bones in the White River as well as the relatively high amounts of uranium in ground water draining from the White River formation tend to support this view. Similar sources have been suggested for uranium in several other uraniferous coals in western United States. Other sources besides tuff, such as decaying granitic or archosic rocks or hydrothermal solutions, might be the source of uranium in other deposits. Thus Turner[55] postulated that the uranium in peat deposits in Madagascar came from the decomposition of nearby titanoniobates (because these minerals are ordinarily resistant to weathering, it seems more probable that the uranium in these deposits was derived from rhyolitic pumice, which is reported to occur in the alluvium of which the peats are a part) and Page suggested that the uranium in a coal bed cut by a shear zone in the Old Leyden mine at the foot of the Colorado Front Range probably was derived from hydrothermal solutions.

The uraniferous waters now draining certain tuffaceous terranes are conceivably similar to solutions from which the uranium in coals was derived. They contain as much as 0.5 ppm uranium (ordinary waters contain less than 0.001 ppm), several hundred parts per million of sulfate or bicarbonate or both, are very high in total dissolved solids, and are moderately alkaline. Because source solutions are thus dilute, the formation of a large uraniferous coal deposit probably takes a long period of time, for the coal must be exposed to a considerable volume of a solution so dilute. Moreover, many coals are not pervious enough to permit passage of large volumes of solution. Thus Breger and Deul were unable to pass water through a column of −50 mesh subbituminous coal, even under a pressure of 15 psi of nitrogen, without mixing diatomaceous earth with the coal to increase its permeability. As Gott and others assumed for other reasons, this may mean that introduction of uranium must take place before coalification. Permeability relationships possibly account for the concentration of uranium at the top or base of many beds and for its relative enrichment in high-ash beds.

The deposition of the uranium in coal doubtless took place by chemical reaction or adsorption. Szalay[60] has shown that brown coal will absorb uranium from a solution of potassium uranyl carbonate. Moore[61] found that subbituminous coal, lignite, and peat irreversibly removed more than 98% of the uranium from a solution containing 196 ppm U (in the form of UO_2SO_4) to which they were exposed for 12 days. Under the same conditions, wood adsorbed 40% of the uranium, a bituminous coal 17%, an anthracite 34%, graphite 28%, charcoal 31%, canneloid coal 80%, and silica flour none. On the basis of these results, Moore concluded that the uranium is precipitated as a metallo-organic compound. Breger and others,[56] after noting that the pH of several lignites from the western states is less than 6.5, observed that ". . . certain alkaline uranyl carbonates and alkaline-earth carbonates are extremely soluble in water. Typical compounds are $Na_4(UO_2)(CO_3)_3$, $Na_6(UO_2)_2(CO_3)_5$, and $Mg(UO_2)(CO_3)_3$. These compounds are sensitive to acids and break up with the release of carbon dioxide. If such a uranium-bearing solution came into contact with a lignite, a zone of low pH, the following type of reaction would be expected:

$$Na_4(UO_2)(CO_3)_3 + 6HA \rightarrow 4NaA + UO_2A_2 + 3CO_2 + 3H_2O$$

The acids from the lignite, represented by HA, are unknown in structure and, for the sake of balancing the above equation, are assumed to be monobasic. It is conceivable that a compound such as UO_2A_2 might be insoluble above pH 2.18. This is a suggested process to account for the introduction and retention of the uranium in a coal."

URANIFEROUS BLACK SHALE

Many marine black shales contain 0.005 to 0.02% uranium.[57,62,63,64] The uranium is in acid-soluble form, but it probably does not occur in a distinct uranium mineral. In the Devonian and Mississippian Chattanooga shale of Tennessee, autoradiograph studies show that the uranium is in organic matter-pyrite complexes.[65] The largest amounts of uranium (as much as 0.5%) in the Cambrian alum shale of Sweden are in lenses of dark bitumen called "kolm";[66] the megascopic lenses do not contain an appreciable proportion of the total uranium in the shale, but microscopic particles of similar material may be the principal carrier of uranium in the shale matrix. In the Miocene nodular shale in California and the Pennsylvanian Cherokee shale equivalents in Oklahoma, the uranium may occur both in carbonaceous matter and phosphate.[67] Because the uranium content increases directly with increasing percentages of carbon in many shales,[62,68] Fredrickson suggests that the $(UO_2)^{2-}$ ion "is adsorbed between the graphite layers of carbonaceous material, forming a strong structure due to the stable UO_2^{++} ion holding the two layers together."

As a group the uraniferous marine black shales are highly carbonaceous and bituminous, high in sulfides, noncalcareous, somewhat phosphatic (or contain phosphatic nodules in the section), and thin

for the period of time they represent. In vertical sequences, the uraniferous black shales are associated with phosphatic rocks, chert, carbonate rock, and sandstone. The black shales are not appreciably uraniferous, however, where thick, high-grade phosphorite beds are present. The richest parts of the Swedish shale are in the middle or upper part of the shale sequence, in or closely adjacent to that part of the sequence which contains maximum amounts of distillable oil, total organic matter, pyrite, and kolm; really, the richest parts are in tongues, interpreted as embayments in the Upper Cambrian sea. The uranium in the most uraniferous shale known in this country, the Hartville in Wyoming, seems also to have been concentrated near the margin of deposition of that shale.

The problem of the origin of the uranium in the marine black shales is more one of the environment, manner, and causes of precipitation than one of the time of deposition of the uranium compared to that of the host rock or the source of the uranium. Although it is generally assumed that the uranium in these beds is syngenetic, in view of the capacity of carbonaceous materials to adsorb uranium, it is possible that some of the uranium may have been adsorbed after deposition, either from sea water or from water released from other sediments during compaction. Uranium in waters draining overlying beds might be adsorbed also,[69] but because this would not take place until after compaction and perhaps lithification, uranium derived in this way might be concentrated along joints, a phenomenon rarely observed in the marine black shales.

Although most of the uranium in the shales is derived directly or indirectly from sea water, which contains 1.0–1.8 $\times$ 10^{-6} grams of uranium per liter,[70] the question arises whether the uranium has been derived locally or brought to the site of deposition through oceanic circulation. Glebov[69] and Strøm[71] postulate that uranium is derived from adjacent terranes, presumably during periods when chemical weathering is the dominant process of erosion. This is a reasonable assumption if the basins of deposition are restricted embayments, and it may account for the uranium content of the alum shale, the most uraniferous parts of which apparently were deposited in embayments not far from a granitic terrane. It seems unlikely, however, that local sources contributed much of the uranium found in the more widespread black shales, such as the Chattanooga. Moreover, because the uranium content of ocean waters and large river waters is about the same—ocean water range from about 1.1 $\times$ 10^{-6} gm/l in surface waters to 1.3–1.4 $\times$ 10^{-6} gm/l in deeper waters; river waters range from about 0.3 to 20 $\times$ 10^{-6} gm/l[72] but none of any size contain more than 1–2 $\times$ 10^{-6} gm/l—the identification of source of the uranium in black shales does not seem of critical significance.

Of more importance may be the environment of deposition. The rocks of the phosphorite family of sediments, to which the black shales belong, are generally deposited on a shelving bottom where cold waters rich in phosphate, nitrate, and possibly other elements whose solubility is influenced by pH, upwell from oceanic depths.[73,74] As these waters are warmed, some of the dissolved substances become insoluble and are chemically precipitated or removed from the sea by organisms. The nutrients in these upwelling waters fertilize the upper waters of the sea, producing tremendous blooms of plankton[75] that lead to the development of an anaerobic sapropel on the sea bottom, even in the open ocean.[76] Nutrient-rich fresh waters draining into a restricted embayment may produce the same effect. The close relationship between the maximum amounts of uranium, oil, total organic matter, and sulfides, as well as the concentration of uranium in some shales in embayments or near their margins of deposition, suggests that the formation of a highly reducing environment may be a prerequisite to the concentration of uranium in the shales. According to Goldschmidt,[47] precipitation of uranium in black shales "might result from a reduction of hexavalent uranium to the quadrivalent stage by the action of hydrogen sulfide in stagnant bottom waters. . . . We may therefore expect accumulation of the solute uranium from sea water by reprecipitation in areas where strongly reducing conditions prevail." It seems probable that appreciable deposition or preservation of uranium takes place only when the pH and Eh lie within narrow limits—limits that may be approached closely enough in the deposition of ordinary black shales to permit the formation of some sulfides and the preservation of some organic matter, but that are reached only rarely.

Deposition of uranium in the shales might have taken place in one or both of two ways: (1) direct precipitation or (2) chemical adsorption by organic matter (living or dead) or by apatite. The absence of any uranium mineral in the shales argues against direct precipitation. Some marine algae, however, concentrate minor metals[77,78] and dead plankton is reported to be an effective adsorbent for uranium and other metals.[79,80] Most of the uranium in apatite is thought to be removed from the seam by adsorption, and possibly some of the uranium in the shales may also have been adsorbed by phosphatic materials. Even though biochemical precipitation or adsorption may be the chief mechanisms of deposition of uranium in the shales, these processes are not likely to be effective in the permanent removal of uranium from the sea unless chemical conditions favor or approach those necessary for direct precipitation of uranium. It is possible, however, that organisms may remove uranium from the upper waters of the sea, where reducing conditions do not prevail, and, after death, carry it to the bottom where the reducing conditions necessary for the retention of uranium do exist.

The uranium in the hydrocarbons in the black shales probably enters these compounds after deposi-

tion. Smith,[81] in reporting his discovery of oil in recent sediments, adopts Whitmore's earlier hypothesis that "the generation of petroleum is very largely a process of selection and concentration of hydrocarbons originally synthesized by the metabolism of marine (or even terrestrial) plants." Collection and concentration of the hydrocarbons probably begins shortly after burial, and minor metals probably are dissolved at this stage.[46,47]

URANIFEROUS MARINE PHOSPHORITES

Marine phosphorites contain 0.005 to 0.03% uranium.[63,82] Traces of secondary uranium minerals are occasionally found in weathered deposits but most of the uranium is in dispersed form. It is acid-soluble, tetravalent, and seems to be in the mineral carbonate-fluorapatite, where it probably substitutes for calcium.[83] Although there are numerous exceptions, the uranium content of the phosphorites increases roughly as the phosphate content increases, but, in the Permian Phosphoria formation at least, the uranium content falls off rapidly as the CO_2 content rises above 3 or 4%, regardless of the phosphate content. Phosphatic limestones are thus only weakly uraniferous, but phosphatic nodules in certain black shales are uraniferous,[84] generally more so than the enclosing shale. Black shales associated with the phosphorite formations are only weakly uraniferous. Fossil bones and teeth contain as much as 0.5% U without showing a separate mineral phase[82] and the uranium content seems to be greater in older than in younger species.[85] In the Phosphoria formation, however, beds composed of organic fragments are less uraniferous than other kinds of phosphatic materials.

As with the black shales, much of the uranium in the phosphorites and phosphatic nodules probably was derived from sea water at or shortly after the time the rocks were deposited. Because the phosphorites are more permeable than the shales, more of the uranium in the phosphorites may have been derived from later solutions, or redissolved and redeposited by them.

The environment of deposition of the marine phosphorites is much the same as that of the black shales with which they are associated, except that the phosphorites probably accumulate in shallower, more aerated water. The negligible uranium content of modern bones[85] and the absence of a separate uranium mineral indicate that precipitation of uranium in the phosphorites must have taken place not by biologic activity or direct precipitation but by one or another of the processes known as chemical adsorption—perhaps coprecipitation, or isomorphous substitution of uranium for calcium at some time after the deposition of carbonate-fluorapatite. The efficacy of this process has been shown by Moore,[61] who found that phosphate rock removed 63% of the uranium present in a solution of UO_2SO_4 containing 196 ppm U; and by Neuman and others,[86,87,88] who demonstrated that bone (which consists of hydroxyapatite) can adsorb as much as 4.8% U from a dilute, bicarbonate buffered solution of uranyl acetate, replacing calcium at the surface of the apatite crystal. Other experiments[88] show that the precipitation of uranium in bone ash decreases with increase in calcium and increase in bicarbonate ions in solution and with increasing pH, from 6.5 to 8.0. These results indicate "that a direct competition exists between calcium and uranium for the combining sites on the bone phase . . . between carbonate ion (which forms a relatively undissociated complex with uranyl ion) and the surface phosphate groups for uranium. The reduced uranium adsorption observed at elevated pH is somewhat more complicated but, in part, may be viewed as a competition between surface phosphate groups and hydroxyl ions." Inasmuch as the uranium in the phosphorites is tetravalent, a reduction reaction must be involved in its precipitation.

Variation in the uranium content of phosphorites of similar P_2O_5 content may arise in part from differences in the uranium content of the sea water at the time of deposition, but the most significant variations probably result from differences in the pH, calcium, and carbonate ion concentration of the source water, the length of time phosphate particles are exposed to the sea before burial, and their postdepositional history.

These factors are well demonstrated by the distribution of uranium in the Florida phosphate field. The principal phosphate deposits there are in the Pliocene Bone Valley formation, which formed as a result of the marine reworking of a phosphatic residuum formed on the underlying phosphatic Miocene Hawthorn limestone during an intervening period of weathering. Since its deposition, the Bone Valley itself has been deeply weathered. It now consists of carbonate-fluorapatite pellets, montmorillonite, and quartz sand in the lower part and of a vesicular, leached rock composed mainly of quartz sand, wavellite, and crandallite in the upper part.[89] The phosphate pellets of the Hawthorn contain only small amounts of uranium, probably because of the abundance of calcium and carbonate ions in the sea at the time of their deposition. The phosphate pellets of the Bone Valley are much more uraniferous, presumably because they adsorbed more uranium during their second exposure to sea water. As a result of the subtropical weathering to which they have since been exposed, some uranium has been leached out of the Bone Valley pellets, with the result that small pellets are less uraniferous and more phosphatic than the large ones. In the most weathered rock, where carbonate-fluorapatite has been largely destroyed, most of the uranium has been removed. Some has been readsorbed in a zone of secondary enrichment below the zone of most advanced weathering, but some has followed calcium in recombining with aluminum and phosphate to form crandallite.[89]

The reason for the concentration of uranium in the phosphorites rather than the shales where both are present is not clear, but it may be that uranium bears

a greater affinity for phosphate than it does for organic matter, expressed either at the time of deposition or during later migration of solutions.

CONCLUSIONS

Origin of the diverse types of uranium deposits reflects the fundamental properties of uranium, chiefly its large ionic radius, its polyvalence, the solubility of many of its uranyl compounds, and the great stability of its uranous compounds under reducing conditions. Thus, its concentration in late-stage igneous magmas reflects the effect of radius and valence in preventing it from entering the structure of common rock-forming minerals. Its migration away from the magma, and its separation from thorium at that stage, arises from its susceptibility to oxidation and the solubility of uranyl compounds. The same effect, including the separation from thorium,[72] is illustrated in the behavior of uranium during weathering. Precipitation of uranium may take place in several ways, but its widespread association with carbonaceous matter and sulfides shows that its deposition in a wide variety of deposits is influenced or stabilized by reduction. Precipitation of uranium by chemical adsorption or isomorphous substitution, whether in igneous or sedimentary rocks, is favored where uranium forms a relatively stable compound with the anions involved, where it can displace an ion of similar radius and valence, and where the solution carries few ions that can compete successfully with uranium for structural positions.

The chief geologic control in the formation of uranium deposits has to do with the avenues followed by uranium-bearing solutions. These are the usual ones—joints and fractures in crystalline igneous, metamorphic, and sedimentary rocks, and pore spaces in pervious sedimentary rocks—but the occurrence of large uranium deposits in sandstones and lignites emphasizes the importance of lenticular aquifers in channeling ore solutions through sedimentary rocks and in localizing their precipitates.

REFERENCES

1. Larsen, E. S., Jr. and Phair, George, *The Distribution of Uranium and Thorium in Igneous Rocks,* in Faul, H., Nuclear Geology, John Wiley & Sons, Inc., New York, 75–89 (1954).
2. Adams, J. A. S., *Uranium and Thorium Contents of Volcanic Rocks,* in Faul, H., Nuclear Geology, John Wiley & Sons, Inc., New York, 89–98 (1954).
3. Hurley, P. M., *Distribution of Radioactivity in Granites and Possible Relation to Helium Age Measurement,* Geological Society of America Bulletin 61: 1–8 (1950).
4. Picciotto, E. E., *Distribution de la Radioactivité dans les Roches Eruptives,* Bulletin de la Societie Belge de Géologie de Paléontologie et d'Hydrologie 59: 170–199 (1950).
5. Brown, H., *et al., Leaching Studies of Interstitial Materials in Igneous Rocks,* Geological Society of America Bulletin 64: 1400 (1953).
6. Page, L. R., *Uranium in Pegmatites,* Economic Geology 45: 12–34 (1950).
7. Lang, A. H., *Canadian Deposits of Uranium and Thorium* (Interim Account), Geological Survey of Canada, Economic Geology Series 16 (1952).
8. Everhart, D. L. and Wright, R. J., *The Geologic Character of Typical Pitchblende Veins,* Economic Geology 48: 77–96 (1953).
9. Gruner, J. W., *New Data of Syntheses of Uranium Minerals,* US Atomic Energy Commission RMO–983, Technical Information Service, Oak Ridge, Tennessee (1952).
10. Miller, L. J. and Kerr, P. F., *Progress Report on the Chemical Environment of Pitchblende,* US Atomic Energy Commission RME–3096 (part 2): 72–99, Technical Information Service, Oak Ridge, Tennessee (1954).
11. Katz, J. J. and Rabinowitch, E., *The Chemistry of Uranium,* McGraw-Hill Book Co., Inc. (1951).
12. Phair, George, *Radioactive Tertiary Porphyries in the Central City District, Colorado, and Their Bearing upon Pitchblende Deposition,* US Geological Survey TEIR–247, US Atomic Energy Commission Technical Information Service, Oak Ridge, Tennessee; Nuclear Science Abstract 6: 776 (1952).
13. Garrels, R. M. and Richter, D. H., *Is Carbon Dioxide an Ore-forming Fluid under Shallow Earth Conditions?* Economic Geology (in press) (1955).
14. Lang, S. M., *Solid State Reactions of the Uranium Oxides,* National Bureau of Standards Circular 535 (1953).
15. Stevenson, J. S., *Uranium Mineralization in British Columbia,* Economic Geology 46: 353–366 (1951).
16. Pabst, A., *Brannerite from California,* American Mineralogist 39: 109–117 (1954).
17. Nininger, R. D., *Minerals for Atomic Energy,* D. Van Nostrand Co., Inc., New York (1954).
18. Lindgren, W., *Mineral Deposits,* 4th edition, McGraw-Hill Book Co., Inc. (1933).
19. McKelvey, V. E., Everhart, D. L. and Garrels, R. M., *The Origin of Uranium Deposits,* Society of Economic Geologists 50th Anniversary volume (in press) (1955).
20. Bain, G. W., *Uranium in the Dirty Devil Shinarump Channel Deposit,* US Atomic Energy Commission RMO–66, Technical Information Service, Oak Ridge, Tennessee (1952).
21. Coffin, R. C., *Radium, Uranium, and Vanadium Deposits of Southwestern Colorado,* Colorado Geological Survey Bulletin 16 (1921).
22. Fischer, R. P., *Sedimentary Deposits of Copper, Vanadium-uranium, and Silver in Southwestern United States,* Economic Geology 32: 906–951 (1937).
23. Gruner, J. W., *The Origin of the Uranium Deposits on the Colorado Plateau and Adjacent Regions,* Mines Magazine 44: 53–56, No. 3 (1954).
24. Hess, F. L., *Hypothesis for the Origin of the Carnotites of Colorado and Utah,* Economic Geology 9: 681 (1914).
25. Mellor, E. T., *The Conglomerates of the Witwatersrand,* Transactions of the Institute of Mining and Metallurgy 25: 226–348 (1916).
26. Reinecke, L., *The Location of Payable Ore-bodies in the Gold-bearing Reefs of the Witwatersrand,* Transactions of the Geological Society of South Africa 30: 89–119 (1927).
27. Young, R. B., *The Banket,* Gurney & Jackson, London (1917).
28. Stieff, L. R., Stern, T. W. and Milkey, R. G., *A Preliminary Determination of the Age of Some Uranium Ores of the Colorado Plateaus by the Lead-uranium Method,* US Geological Survey Circular 271 (1953).
29. Davidson, C. F., *The Gold-uranium Ores of the Witwatersrand,* Mining Magazine 88: 73–85 (1953).

30. Louw, J. D., *Geological Age Determinations on Witwatersrand Uraninites Using the Lead Isotope Method,* Geological Society of South Africa, p. 1–19 (advance proof) (1954).

31. Davidson, C. F., *Discussion,* Institute of Mining and Metallurgy Bulletin, p. 247 (February 1954).

32. Larsen, E. S., Jr., Keevil, N. B. and Harrison, H. C., *Method for Determining the Age of Igneous Rocks, Using the Accessory Minerals,* Geological Society of America Bulletin 63: 1045–1052 (1952).

33. Graton, L. C., *Hydrothermal Origin of the Rand Gold Deposits,* Economic Geology 25: supplement to no. 3 (1930).

34. Liebenberg, W. R., *Rare Minerals in the Banket of the Witwatersrand System,* Dissertation, Pretoria University, Pretoria, Transvaal, US Atomic Energy Commission NP-3992, Technical Information Service, Oak Ridge, Tennessee (1948).

35. MacGregor, A. M., Discussion of *The Gold-uranium Ores of the Witwatersrand* by C. F. Davidson, Mining Magazine 88: 281–282 (1953).

36. Hillebrand, W. F. and Ransome, F. L., *On Carnotite and Associated Vanadiferous Minerals in Western Colorado,* US Geological Survey Bulletin 262: 9–31 (1905).

37. Koeberlin, F. R., *Discussion of Sedimentary Copper, Vanadium-uranium, and Silver in Southwestern United States by R. P. Fischer,* Economic Geology 33: 458–461 (1938).

38. Proctor, P. D., *Geology of the Silver Reef (Harrisburg) Mining District, Washington County, Utah,* Utah Geological and Mineralogical Survey Bulletin 44 (1953).

39. Gott, G. B. and Erickson, R. L., *Reconnaissance of Uranium and Copper Deposits in Parts of New Mexico, Colorado, Utah, Idaho, and Wyoming,* US Geological Survey Circular 219 (1952).

40. Dodd. P. H., *Happy Jack Mine, White Canyon, Utah,* US Atomic Energy Commission RMO-660, Technical Information Service, Oak Ridge, Tennessee (1950).

41. Cater, F. W., Jr., *Geology of the Bull Canyon Quadrangle, Colorado,* US Geological Survey Geologic Quadrangle Map GQ 33 (1954).

42. Rasor, C. A., *Uraninite from the Grey Dawn Mine, San Juan County, Utah,* Science 116: 89–90 (1952).

43. Waters, A. C. and Granger, H. C., *Volcanic Debris in Uraniferous Sandstones, and its Possible Bearing on the Origin and Precipitation of Uranium,* US Geological Survey Circular 224 (1953).

44. Gruner, J. W., *Origin of the Uranium Deposits in the Shinarump Formation, a Preliminary Study,* US Atomic Energy Commission RMO-837, Technical Information Service, Oak Ridge, Tennessee (1951).

45. Vine, J. D. and Moore, G. W., *Uranium-bearing Coal and Carbonaceous Rocks in the Fall Creek Area, Bonneville County, Idaho,* US Geological Survey Circular 212 (1952).

46. Erickson, R. L., Myers, A. T. and Horr, C. A., *Association of Uranium and Other Metals with Crude Oil, Asphalt, and Petroliferous Rock,* American Association of Petroleum Geologists 38: 2200–2218 (1954).

47. Goldschmidt, V. M. (edited by Alex Muir), *Geochemistry,* Clarendon Press Oxford (1954).

48. US Geological Survey, *Geological Investigations of Radioactive Deposits, Semiannual Progress Report June 1 to November 30, 1954,* US Atomic Energy Commission TEI-490, Technical Information Service, Oak Ridge, Tennessee (1954).

49. Davidson, C. F. and Bowie, S. H. U., *On Thucholite and Related Hydrocarbon-uraninite Complexes, with a Note on the Origin of the Witwatersrand Gold Ores,* Geological Survey of Great Britain Bulletin 3: 1–19 (1951).

50. Bucher, W. H., *Fracture Studies in the Zuni and Lucero Uplifts, New Mexico,* US Atomic Energy Commission RME-3042, Technical Information Service, Oak Ridge, Tennessee (1953).

51. Reinhardt, E. V., *The Distribution of Uranium-vanadium Deposits in the Colorado Plateau Relative to Tertiary Intrusive Masses,* US Atomic Energy Commission RMO-816, Technical Information Service, Oak Ridge, Tennessee (1952).

52. Eckel, E. B., Williams, J. S, Galbraith, F. W. *et al., Geology and Ore Deposits of the La Plata District, Colorado,* US Geological Survey Professional Paper 219 (1950).

53. McKelvey, V. E., *Search for Uranium in the United States,* US Geological Survey Bulletin 1030A (1955).

54. Davidson, C. F. and Ponsford, D. R. A., *On the Occurrence of Uranium in Coals,* Mining Magazine 91: 265–273 (1954).

55. Turner, H. W., *Review of the Radioactive Minerals of Madagascar,* Economic Geology 23: 62–84 (1928).

56. Breger, I. A., Deul, M. and Rubinstein, S., *Geochemistry and Mineralogy of a Uraniferous Lignite,* Economic Geology 50: 206–226 (1955).

57. Gott, G. B., Wyant, D. G. and Beroni, E. P., *Uranium in Black Shales, Lignites, and Limestones in the United States,* US Geological Survey Circular 220 (1952).

58. Miller, R. L. and Gill, J. R., *Uranium from Coal,* Scientific American 191: no. 4, 36–39 (1954).

59. Cannon, H. L., *The Effect of Uranium-vanadium Deposits on the Vegetation of the Colorado Plateau,* American Journal of Science 250: 735–770 (1952).

60. Szalay, S., *The Enrichment of Uranium in Some Brown Coals in Hungary,* Acta Geologica Hungarica 2: 299–310 (1954).

61. Moore, G. W., *Extraction of Uranium from Cold Water Solutions by Coal and Other Materials,* Economic Geology 49: 652–658 (1954).

62. Beers, R. F., *Radioactivity and Organic Content of Some Paleozoic Shales,* American Association of Petroleum Geologists Bulletin 29: 1–22 (1945).

63. McKelvey, V. E. and Nelson, J. M., *The Characteristics of Marine Uranium-bearing Sedimentary Rocks,* Economic Geology 45: 35–53 (1950).

64. Russell, W. L., *Relation of Radioactivity, Organic Content and Sedimentation,* American Association of Petroleum Geologists Bulletin 29: 1480 (1945).

65. Bates, T. F., Strahl, E. O., Short, N. M., Silverman, E. N. and Camilli, E., *Mineralogy and Petrography of the Chattanooga Shale,* Geological Society of America Bulletin 65: 1230 (1954).

66. Munthe, H., Westergard, A. H. and Lundquist, G., *Beskrivining till Karbladet Skovde* (description relating to the Skovde map sheet), Sveriges Geologiska Undersökning, Series As Kartblad i skalan 1:50,000 med Beskrivningar, no. 121, Stockholm (1928).

67. Whitehead, W. L., *Studies of the Effect of Radioactivity in the Transformation of Marine Organic Materials into Petroleum Hydrocarbons,* (1952) in American Petroleum Institute, Fundamental Research on Occurrence and Recovery of Petroleum, 192–201 (1950–51).

68. Burton, V. L. and Sullivan, G. R., *Carbon Content and Radioactivity of Marine Rocks,* Transactions of the American Geophysical Union 32: 881–884 (1951).

69. Glebov, S. M., *Radioaktivnost Diktionemovykh Slantzer,* Leningradski Gornyi Institut Zapiski 14: 1–12 (1941).

70. Koczy, Gerta, *Weitere Uranbestimmunger an Meerwasserproben,* Akademie Wissenschaft Wien, Mathematical-naturwissenschaftlich Klasse, Sitzungher, Abteilung IIa, 158 Band, 1–5, Heft, 113–122 (1950).

71. Strøm, K. M., *A Concentration of Uranium in Black Muds,* Nature 162: 922 (1948).

72. Koczy, F. F., *Geochemical Balance in the Hydrosphere,* in Faul, H., Nuclear Geology, John Wiley & Sons, Inc., New York, 120–127 (1954).

73. Kazakov, A. V., *The phosphorite Facies and the Genesis of Phosphorites, in Geological Investigations of Agricultural Ores,* Scientific Institute Fertilizers and Insecto-Fungicides Transactions no. 142 (published for the 17th International Geological Congress), Leningrad, 8–21 (1937).

74. McKelvey, V. E., Swanson, R. W. and Sheldon, R. P., *The Permian Phosphorite Deposits of Western United States,* 19th International Geological Congress Compte Rendu 11: 45–64, Algiers (1953).

75. Brongersma-Sanders, M., *The Importance of Upwelling Water to Vertebrate Paleontology and Oil Geology,* Verhandelinger der Koninklijke Nederlandsche Akademie van Wetenschappen, Afdeling Natuurkunde, Tweede Sectie, Deel 45, no. 4 (1948).

76. Brongersma-Sanders, M., *On Conditions Favouring the Preservation of Chlorophyll in Marine Sediments,* World Petroleum Congress Proceedings 1: 401–413, The Hague (1951).

77. Lexow, S. G., Manenghi, E. P. P. and Sa, A. M., *Preliminary Note on the Presence of Uranium in Living Things in Argentina,* Anales Asociación Química Argentina 26: 203–207 (in Spanish) (1948); see also Nuclear Science abstract 3: 76 (1949).

78. Black, W. A. P. and Mitchell, R. L., *Trace Elements in the Common Brown Algae and in Sea Water,* Marine Biological Association of the United Kingdom Journal 30: 575–584 (1952).

79. Harvey, H. W., *Recent Advances in the Chemistry and Biology of Sea Water,* Cambridge University Press (1945).

80. Krauskopf, K. B., *Control of Trace-element Concentrations in Sea Water,* Geological Society of America Bulletin 63: 1336 [abstract] (1952).

81. Smith, P. V., *Studies on Origin of Petroleum, Occurrence of Hydrocarbons in Recent Sediments,* American Association of Petroleum Geologists Bulletin 38: 377–404 (1954).

82. Davidson, C. F. and Atkin, D., *On the Occurrence of Uranium in Phosphate Rocks,* 19th International Geological Congress Compte Rendu 11: 13–31, Algiers (1953).

83. Altschuler, Z. S., Clarke, R. S., Jr. and Young, E. J., *Uranium in Apatite,* Geological Society of America Bulletin 65: 1225 [abstract] (1954).

84. Runnels, R. T., Schleicher, J. A. and Van Nortwick, H. S., *Composition of Some Uranium-bearing Phosphate Nodules from Kansas Shales,* Kansas Geological Survey Bulletin 102: 93–104 (1953).

85. Jaffe, E. B. and Sherwood, A. M., *Physical and Chemical Comparison of Modern and Fossil Tooth and Bone Material,* US Geological Survey TEM–149, US Atomic Energy Commission, Technical Information Service, Oak Ridge, Tennessee (1951).

86. Neuman, W. F., Neuman, M. W., Main, E. R. and Mulryan, B. J., *The Deposition of Uranium in Bone, IV,* Adsorption Studies in Vitro, Journal of Biological Chemistry 179: 325–333 (1949).

87. Neuman, W. F., Neuman, M. W., Main, E. R. and Mulryan, B. J., *The Deposition of Uranium in Bone, V,* Ion Exchange Studies, Journal of Biological Chemistry 179: 335–340 (1949).

88. Neuman, W. F., Neuman, M. W., Main, E. R. and Mulryan, B. J., *The Deposition of Uranium in Bone, VI,* Ion Competition Studies, Journal of Biological Chemistry 179: 341–348 (1949).

89. US Geological Survey, *Search for and Geology of Radioactive Deposits, Semiannual Progress Report December 1, 1952–May 31, 1953, TEI–330,* US Atomic Energy Commission, Technical Information Service, Oak Ridge, Tennessee (1953).

The Geology of Thorium Deposits in the United States

By W. S. Twenhofel and K. L. Buck,* USA

Thorium has long been used, in small quantities relative to most other metals, for a variety of industrial purposes. It was first used industrially during the period 1890 to 1911 as an essential ingredient of gas mantles; the development and widespread use of the tungsten lamp since that time has largely supplanted the gas mantle and the consequent market for thorium. The manufacture of gas mantles is, however, still the principal use of thorium, although the amount consumed for such use is decreasing. Thorium is used also in tungsten lamp filaments, high temperature refractories, polishing compounds, vacuum tubes, magnesium alloys, and as a catalyst.

Thorium has a potential use, which cannot yet be evaluated, as a source of fissionable material for the production of nuclear power. The future demands for thorium for the production of atomic energy will be determined by results of current experimentation.

Thorium, unlike uranium, does not have a natural fissionable isotope. However, natural thorium-232 when bombarded by slow neutrons produces thorium-233, which disintegrates through protactinium-233 to uranium-233, a fissionable isotope.

Much of the data contained in this report was assembled from unpublished reports by our colleagues of the US Geological Survey, whose assistance is gratefully acknowledged.

GEOCHEMISTRY OF THORIUM

Thorium is not known to occur in elemental form in nature; it occurs chiefly as a minor constituent combined with oxygen and other elements to form oxides, silicates, phosphates, carbonates, and fluorides. All thorium compounds are quadrivalent and most of them are highly refractory to weathering. Thorium is associated with the rare-earth metals, zirconium, hafnium, and uranium.

According to Rankama and Sahama[1] thorium "is conspicuously concentrated in the lithosphere, particularly in the uppermost parts of this geosphere," and, hence, is strongly lithophilic.

Thorium is concentrated in felsic igneous rocks during magmatic differentiation, and granitic rocks contain three to six times as much thorium as do basaltic rocks.[1,2] In this respect thorium is similar to hafnium, zirconium, the rare-earth metals, and uranium.

Data on the amount of thorium in various rocks are few because of the difficulties of analyzing minute amounts of thorium. Published figures are of questionable validity because they were obtained by calculation from measurements of the thoron content and from measurements of radioactivity, assuming radioactive equilibrium. The available data indicate that the thorium content of most igneous rocks is within the range of zero to 25 parts per million (25×10^{-6} gm/gm), but some igneous rocks contain as much as several hundred parts per million.

Thorium and uranium seem to be closely associated in igneous rocks; the two elements are associated in the same minerals and data indicate that the thorium-uranium ratio of various rocks throughout the world is approximately uniform. The average thorium-uranium ratio in igneous rocks is about 3 to 1, with the ratio ranging from 0 to 20.

The thorium-uranium ratio is much smaller in ocean waters than it is in igneous rocks. In fact, ocean waters contain more uranium than thorium, probably because thorium minerals are less soluble than are the uranium minerals.

The following data compiled by Rankama and Sahama[1] suggest the order of magnitude of thorium content in sedimentary rocks:

Rock	*Approximate Th content (gm/ton)*
Rocks of arenaceous origin (Joly, 1910)	5.4
Rocks of argillaceous origin (Joly, 1910)	12
Shales (Minami, 1935)	10.1
Limestones (Evans and Goodman, 1941)	1.1

Outside of igneous rocks thorium and uranium display marked dissimilarities. In ore deposits minable concentrations of both thorium and uranium almost never have been found together.

A possible explanation of the fact that thorium and uranium are associated in the magmatic cycle, but are not associated in the hydrothermal environment, is offered by Larsen and Phair.[3] In the magmatic cycle both thorium and uranium crystallize along similar paths because of their similarities in ionic radius and similarly low concentrations. However, in the very late magmatic cycle Larsen and Phair postulate a change to oxidizing conditions whereby four-valent uranium changes to six-valent uranium, the latter being highly soluble in aqueous solutions whereas the former is not. Thorium has only the one stable valence (four) and it is not rendered more soluble by the change to oxidizing

* US Geological Survey.

conditions. Thus, because of the change in solubility of uranium and lack of change in solubility of thorium, the two elements naturally become separated under hydrothermal and later magmatic conditions.

THORIUM MINERALS

The most important thorium minerals are: monazite, thorianite, thorite, and thorogummite. Other minerals that contain minor amounts of thorium are: allanite, bastnaesite, xenotime, fluorapatite, and zircon.

Monazite is the principal ore mineral of thorium in the United States and elsewhere. It is a complex phosphate of the rare-earth metals (principally cerium and lanthanum) and thorium. The thorium content normally ranges from a few percent to 10.6%, but probably can be as much as 26.4% thorium. Commercially recovered monazite contains from 55 to 65% of rare-earth oxides and thoria. Minable monazite deposits are found in the United States mostly in placers. Monazite also is an accessory mineral in many gneissic and granitic rocks and in calcareous metamorphic rocks and is a minor constituent of certain carbonate veins.

Thorianite (ThO_2) is isomorphous with uraninite (UO_2) and is a very minor constituent of some igneous rocks and placer deposits. It is not now an ore mineral as its known occurrences are small and low grade.

Thorite ($ThSiO_4$) may contain from 25.2 to 62.7% thorium and as much as 10.1% uranium.[1] It is typically a primary mineral of pegmatites and certain hydrothermal veins recently discovered in the United States; it is considered to be a potential thorium ore mineral.

Thorogummite (hydrothorite) is a hydrated silicate of thorium and uranium containing 2.5 to 31.4% uranium and 18.2 to 50.8% thorium.[4] It occurs in possibly significant amounts in veins or pegmatites in central Wisconsin. It has been found elsewhere in the United States in very minor amounts associated with pegmatites and granitic rocks. Thorogummite is important in veins and mineralized shear zones in parts of Colorado, Idaho, and California.

Allanite is a complex silicate containing as much as 3.2% thorium.[4] Its characteristic occurrence is as an accessory mineral of plutonic igneous rocks and pegmatites; it also is found as a contact-metamorphic mineral associated with magnetite deposits. Allanite is not known in sufficient concentrations to be a source of thorium.

Bastnaesite is a fluocarbonate of the rare-earth metals, principally cerium and lanthanum, with less than one percent uranium and thorium.[4] Though bastnaesite is not an ore mineral of thorium, it may become a source of byproduct thorium from the recovery of rare-earth metals. Most bastnaesite deposits are in contact metamorphic zones that are rich in rare earths, barium, carbon dioxide, and fluorine. Bastnaesite deposits are being mined at Mountain Pass, California,[5] and in the Gallinas district, New Mexico.[6]

Xenotime, an yttrium phosphate may contain as much as 2.2% thorium.[4] It characteristically occurs in pegmatites and as a minor accessory mineral in granitic and gneissoid rocks. Xenotime is not known in sufficient concentrations to be a source of thorium but would contribute to the total obtainable from placers.

Fluorapatite is a fluorine-bearing apatite which in some localities contains rare-earth metals and thorium. In the Mineville district of New York,[7] thorium-bearing fluorapatite is associated with magnetite ore, where it might be a byproduct source of thorium.

At the present time the only ore mineral of thorium is monazite, which is principally an ore mineral of rare earths, but from which thorium is recovered as a coproduct. Thorite and thorogummite are of potential importance as sources of thorium from several districts in the western United States.

THORIUM DEPOSITS

Thorium minerals in possible economic concentrations are found in granitic rocks, pegmatites, veins, and placers. The principal thorium deposits of the United States are shown on Fig. 1.

No known thorium deposits are comparable in grade and size to the well-known uranium deposits of pitchblende. Similarly, because thorium is relatively insoluble and occurs in highly refractory minerals, there are no known commercial thorium deposits of supergene origin.

In recent years, as interest in radioactive minerals has increased, vein deposits containing rare earths and thorium in significant amounts have been found in Colorado, Idaho, Montana, Wyoming, California, and New Mexico. Monazite, thorogummite, and thorite, particularly the latter, are the principal thorium-bearing minerals of these veins. These thorium-bearing vein deposits are characterized by the association of such gangue minerals as barite, carbonates, and iron oxides, with varying amounts of other minerals. Most thorium-bearing veins occur in igneous and metamorphic terranes that have been intruded by alkalic igneous rocks, believed to be genetically related to the veins.

At least 33 deposits of thorium are known in the Powderhorn district of Colorado in an area 6 miles wide and 20 miles long. The deposits and the general geology are described by Olson and Wallace.[8] The area is underlain principally by Precambrian metamorphic and igneous rocks which have been intruded by pre-Jurassic alkalic dikes and composite stocks of irregular shape. The thorium deposits occur as thorite-bearing carbonate-rich veins and mineralized shear zones in or near the alkalic igneous rocks.

Selected high-grade samples of vein material contain as much as 4% thoria; the average thoria content of the veins is less than 1%. The veins are a few inches to 18 feet wide and a few feet to more than 3500 feet long. The vein material is composed principally of carbonate, quartz, and feldspar, with minor amounts of barite, pyrite, sphalerite, galena,

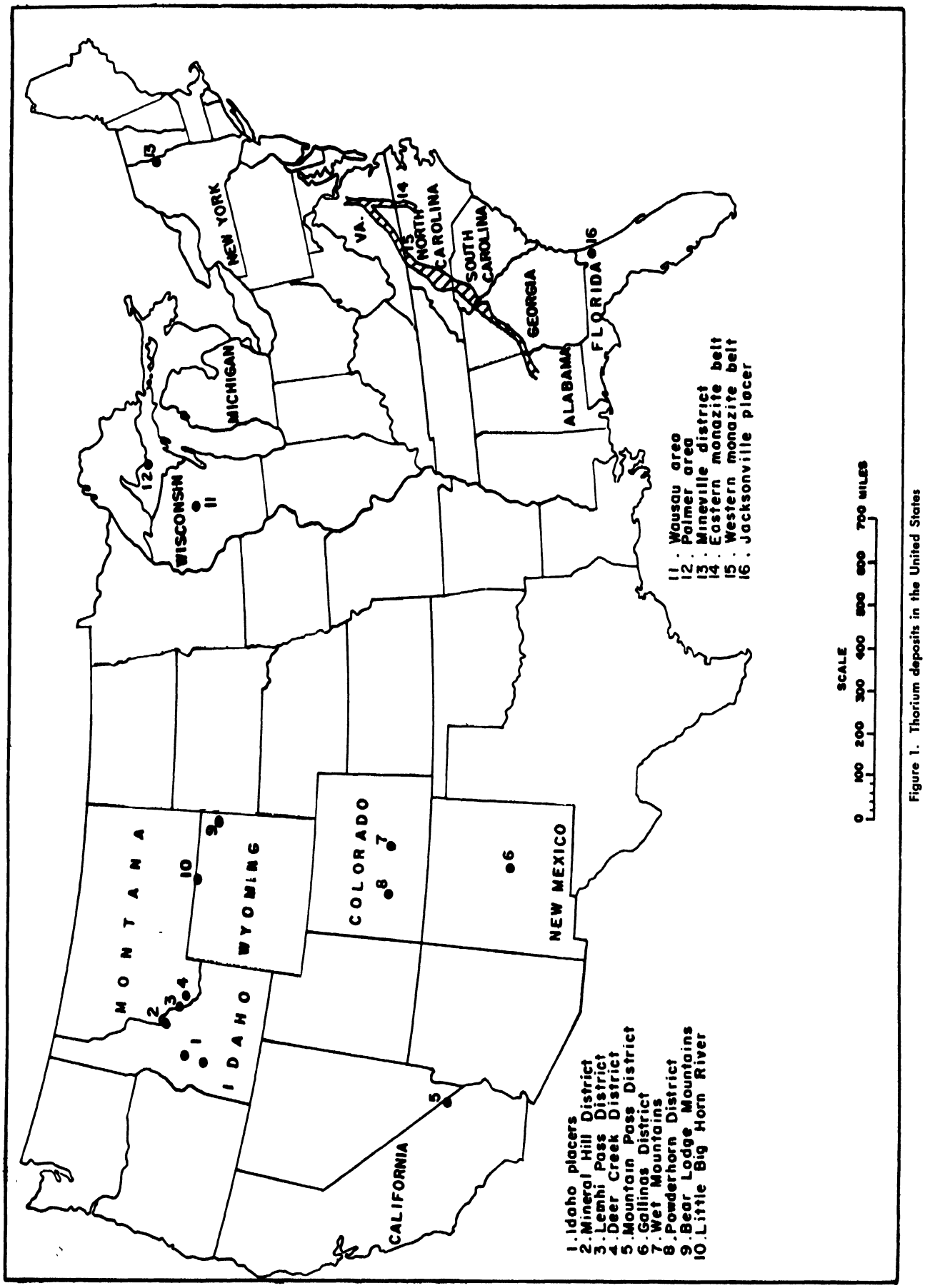


Figure 1. Thorium deposits in the United States

hematite, goethite, apatite, thorite, xenotime, and many other minerals.

The thorium-bearing veins are characterized by the presence of Ti, Ba, Sr, Nb, P, and the rare-earth metals, which also are present in greater than average amounts in the alkalic igneous rocks with which the veins are associated; these relationships suggest a genetic tie between the veins and the alkalic igneous rocks. The thorium minerals are accompanied by both oxidized and unoxidized iron-bearing minerals.

Thorium-bearing veins recently were discovered by the U. S. Geological Survey on the west flank of the Wet Mountains in Custer and Fremont Counties, Colorado.[9] Over 350 thorium-bearing veins are known in the Wet Mountains area. Most of them are less than 5 feet wide and 100 to 1000 feet long: a few are as much as 50 feet wide and 5000 feet long. The country rocks of the area consist of a Precambrian complex of interlayed para-gneisses, migmatite, and granitic gneisses that have been transected by an abnormally radioactive albite syenite stock and by numerous northwest-trending dikes, veins, and fractures. The veins are composed principally of quartz, barite, and iron-bearing carbonates with an unidentified hydrated thorite-like mineral. Minor amounts of pyrite, chalcopyrite tetrahedrite, galena, fluorite, and secondary copper minerals occur sparingly in the veins. The thorium mineral, or minerals, rarely are visible with the naked eye because they are masked by ubiquitous iron oxides and hydroxides.

The thorium content is not uniform within the veins. Concentrations in the form of shoots, pockets, pods, and lenses are distributed erratically and discontinuously along the veins. Some portions of veins contain as much as 1.0% thoria, but large portions of the veins contain only 0.1% thoria. The thorium in the veins is thought to be genetically related to the albite syenite stock.

In the Lemhi Pass district,[10] Idaho-Montana, there are four types of veins, two of which contain thorium minerals. They are: (*a*) quartz-copper veins, some of which have been mined for copper-gold ore; (*b*) quartz-hematite veins, some of which contain more than traces of thorium; (*c*) quartz-barite-hematite-thorite veins, containing zones rich in barite and thorite (these so constitute the largest percentage of thorium-bearing material in the district); and (*d*) quartz-copper-thorite veins, some of which contain significant quantities of thorite. The country rock consists of sandstone, argillite, and quartzite of the Precambrian Belt series.

The quartz-copper-thorite veins range from a few inches to 10 feet in width and are as much as 500 feet long; the quartz-barite-hematite-thorite veins range from less than 1 foot to 50 feet in width and from 10 to more than 700 feet in length.[11] Trites and Tooker[11] have estimated some of the samples of vein material to contain as much as 6.6% calculated thoria, but most contain 0.1 to 1.2% thoria.

In the Bear Lodge Mountains of Wyoming, thorium and rare-earth minerals occur in abnormal amounts of iron-manganese veins in Tertiary igneous rocks.[12]

The iron-manganese veins are composed principally of hematite, limonite, manganese oxides, orthoclase, and chalcedony; they are in intrusives (monzonite and syenite porphyry) of Tertiary age. No thorium or rare-earth minerals have been identified. The thoria content of the veins ranges from 0.04 to 0.25%. Rare earths are abundant within some veins, isolated specimens contain as much as 12.68% of rare earths.

Rare-earths-barium-thorium deposits occur in a belt six miles long in Precambrian carbonate rocks associated with potash-rich igneous rocks in the Mountain Pass district, San Bernardino County, California. The geology of the district is described in detail by Olson and others.[5] The deposits are of value principally as a source of rare-earth metals, which occur chiefly in the mineral bastnaesite, and as a source of byproduct barite. However, some deposits contain between 0.02 and 0.5% thoria, with local concentrations as rich as 6% thoria.

Thorium minerals occur as small amounts of monazite in a large body of carbonate rock, and as thorite and thorogummite in veins. The principal minerals of the thorium-bearing veins are calcite and quartz, with lesser amounts of hematite and hydrated iron oxides, bastnaesite, barite, thorite, and other minerals. The association of hematite with thorite is a conspicuous feature of these veins.

Late andesitic dikes cut the country rock and the thorium- and rare-earth-bearing veins. Some of the richer deposits are near andesitic dikes, suggesting that aqueous emanations accompanying the andesitic dikes may have redistributed thorium already in the veins and concentrated it as thorite near the dikes.[5]

The Mountain Pass deposits are now being mined for rare earths, and these deposits eventually may supplant placer monazite as the principal domestic sources of rare earths in the United States.

Bastnaesite occurs in the fluorspar deposits of the Gallinas Mountains, New Mexico,[13] where the two minerals are associated with abundant barite and goethite (pseudomorphic after pyrite). The deposits occur along fissures and faults, and in breccias and shatter zones in clastic rocks of Permian age. Post-Permian intrusive quartz monzonites, rhyolites, and syenites form stocks, irregular bodies, and numerous small dikes and sills. The fluorite-bastnaesite deposits are believed to have been formed by hydrothermal solutions related to the igneous activity. Bastnaesite is commercially recovered from these deposits.[6]

Near Wausau, Marathon County, Wisconsin, thorogummite and thorium-bearing zircon are found in residual soil in an area of Precambrian syenites. Samples from the more radioactive concentrations in the soil contain from 0.21 to 1.0% thorium, indicating possible thorium concentrations in the bedrock.[14]

The magnetite ore bodies of the Old Bed mine at Mineville, New York, contain fluorapatite unusually rich in thorium and rare earths.[7] Gangue minerals consist of hornblende, augite, quartz, and feldspar.

The fluorapatite is disseminated and in thin seams in the magnetite. Samples of the fluorapatite contain 4.28 to 32.4% rare-earth oxides, 0.01 to 0.38% thoria, and 0.009 to 0.11% uranium.

The Old Bed mine is currently being mined for magnetite. Other nearby magnetite deposits are not known to contain thorium-bearing fluorapatite.

Many igneous and metamorphic rocks, particularly biotite-rich granite and granite gneisses, contain monazite. Such rocks, together with monazite-bearing pegmatites which commonly occur in the same terrane, are the source of placer monazite. None of the igneous rocks in the United States contains sufficient concentrations of monazite and thorium to be considered ore, and it is unlikely that igneous and related metamorphic rocks in the United States will become an ore of thorium in the near future. Mertie[15] estimated the granites and gneisses of the monazite belts of the southeastern states to contain 0.00005 to 0.02% monazite.

Thorium- and monazite-bearing igneous and metamorphic rocks are also known in Idaho and Montana,[11] South Dakota,[16] and in San Bernardino County, California,[5,17] but none of the rocks appear to be appreciably richer in thorium than similar rocks of the southeastern states.

Many pegmatites contain thorium-bearing minerals, but none of the pegmatites known in the United States contain thorium minerals in economic concentrations. Two areas of thorium-bearing metamorphic rocks and pegmatites are known in Worcester County, Massachusetts.[18] At both of these localities the bed rock consists of alternating bands of feldspar gneiss and pegmatite, both of which contain thorium. The deposits are very large and probably average 0.03% thoria. Other pegmatites containing more-than-average quantities of thorium minerals are known in the Deer Creek district, Beaverhead County, Montana,[11] and in the St. Peters Dome area, El Paso County, Colorado.

Monazite is the principal thorium-bearing mineral in placer deposits of the United States. Important monazite placer deposits are in central Idaho and in an area extending from southern Virginia to Florida. Associated minerals in monazite-bearing placers are the usual heavy minerals such as gold, zircon, magnetite, rutile, ilmenite, and garnet.

Stream placers were mined for monazite in the Piedmont Province of North and South Carolina from 1887 to 1911 and from 1915 to 1917.[15] Since 1911, monazite exported from Brazil and India has effectively competed with domestic monazite. Within the last few years, imports of monazite from foreign sources have been seriously curtailed,[15,19] and monazite now is recovered from placers in central Idaho and Florida.

The monazite in the placers of the southeastern states is derived from the weathering and erosion of Precambrian igneous and metamorphic rocks of the Piedmont Province.[15] The monazite-bearing bed rocks are in two belts. Most of the rocks within these belts are not monazite-bearing; the belts delimit the areas within which monazite-bearing rocks are likely to be found. The western belt extends from east-central Virginia for 600 miles southwestward to Alabama; its width is 10 to 50 miles and averages 20 miles. The eastern belt extends from Fredericksburg, Virginia, southwestward for 200 miles into North Carolina; it averages about 5 miles wide.

Mertie[15] sampled 52 placer localities in the southern states. The mean content of these samples is 8.4 pounds of monazite to the cubic yard, but at some localities the tenor was as much as 41.9 pounds of monazite to the cubic yard. The mean tenor of the monazite as determined by Mertie[15] from 53 samples is 5.67% thoria and 0.38% U_3O_8, with tenor ranging from 2.48 to 7.84% for thoria and from 0.18 to 0.98 for U_3O_8.

A large volume of sediments that contain heavy minerals, including monazite, derived from the Piedmont rocks has been deposited since Paleozoic time on the Coastal Plain of the southeastern states. In some areas workable deposits of heavy minerals are found where ocean currents and streams have reworked these sediments. Placer deposits near Jacksonville and Starke, Florida, and at Hollow Creek, South Carolina, are being mined for heavy minerals. At the Jacksonville and Hollow Creek deposits by-product monazite is being recovered, but at Starke monazite is not being recovered.

Monazite placer deposits are scattered over a wide area in central Idaho and contain several other heavy minerals, notably zircon, magnetite, ilmenite, and gold.

Dredging and recovery of monazite from Idaho placers began in 1950[19] shortly after foreign shipments of monazite to the United States were curtailed. Three companies are now actively engaged in the production of monazite from the Idaho placer deposits.[15]

Monazite, and other heavy minerals found in the Idaho placers, are common in the Idaho batholith, which is in central Idaho and is 300 miles long and 50 to 100 miles wide. The batholith is the parent source for the monazite in the placer deposits. Weathering of the rocks of the Idaho batholith and transportation by streams of the monazite and other heavy minerals have resulted in gold and monazite placers being formed in many stream valleys and basins of central Idaho.

The Idaho batholith is not uniformly monazite-bearing; some portions contain only a trace; other portions may contain as much as half a pound of monazite per ton. So far as is known, there is no systematic pattern to the distribution of monazite in the Idaho batholith.

Monazite-bearing conglomerate is known in the basal part of the Deadwood formation of Cambrian

age in Sheridan and Big Horn Counties, Wyoming. The monazite occurs as detrital grains in the matrix of the basal conglomeratic facies of the formation. The monazite-bearing portions of the formation attain a thickness of as much as 8 feet and crop out over long distances along the valley of the Little Big Horn River.

Sufficient data are not available to estimate the thorium content of the monazite and the monazite content of the conglomerate. Estimates have been made ranging between 8 to 30 pounds of monazite per ton.

Monazite-bearing conglomerate beds in the Precambrian Goodrich quartzite occur in the vicinity of Palmer, Michigan.[14] Here the Goodrich quartzite is about 850 feet thick and is composed of a coarse basal conglomerate which grades upward into interbedded quartzites and pebble conglomerates. There are at least two monazite-bearing zones, one near the base of the formation and the other about 400 feet stratigraphically above the base. The continuity and thickness of these two zones are not yet known.

The monazite occurs as detrital grains in the matrix of layers and lenses of pebble conglomerates 1 inch to 2 feet thick.

The conglomeratic character of the monazite-bearing portions of the Goodrich quartzite and the detrital monazite crystals clearly indicate that parts of the Goodrich quartzite are ancient placers which subsequently have been metamorphosed and preserved essentially as originally formed.

Deposits of monazite in marble and calcareous schist recently have been discovered in the Mineral Hill district in northern Lemhi County, Idaho.[20] The monazite forms porphyroblasts in phosphatic calcareous rocks of the Precambrian Belt series. The economic potential of these deposits is poorly known as they have been explored only to a limited extent.

SUMMARY

Current data permit several generalizations on the characteristics of thorium deposits in the United States:

1. Placer concentrations of monazite are derived directly from monazite-bearing igneous and metamorphic rocks or by the reworking of sediments originally derived from such rocks.

2. Vein deposits of thorium generally are associated with and genetically related to alkalic igneous rocks.

3. The principal thorium vein minerals are thorite, thorogummite (hydrothorite), and monazite.

4. Barite, carbonates, quartz, and especially iron oxides are commonly associated with thorium minerals in veins.

5. The principal thorium-bearing veins have been found in the western United States and are believed to be either Precambrian or Cretaceous and Tertiary in age.

REFERENCES

1. Rankama, K. and Sahama, Th. G., *Geochemistry,* University of Chicago Press, Chicago (1950).
2. Fleischer, Michael and Rabbitt, J. C., *Geochemistry,* in *Annual Review of Nuclear Science,* Annual Reviews, Inc., Stanford, California, 465–478 (1952).
3. Larsen, E. S., Jr. and Phair, George, *The Distribution of Uranium and Thorium in Igneous Rocks,* in *Nuclear Geology,* H. Faul, editor, John Wiley and Sons, New York (1954).
4. Frondel, J. W. and Fleischer, Michael, *A Glossary of Uranium- and Thorium-Bearing Minerals,* US Geological Survey Bulletin 1009–F, 169–209 (1955).
5. Olson, J. C., Shawe, D. R., Pray, L. C. and Sharp, W. N., *Rare-Earth Mineral Deposits of the Mountain Pass District, San Bernardino County, California,* US Geological Survey Professional Paper 261 (1954).
6. Anonymous, *Companies Join with Heim to Develop Bastnaesite,* Engineering and Mining Journal 153: 108 (1952).
7. McKeown, F. A. and Klemic, Harry, *Rare-Earth Bearing Apatite at Mineville, Essex County, New York,* US Geological Survey Bulletin (in preparation).
8. Olson, J. C. and Wallace, S. R., *Thorium and Rare-Earth Minerals in the Powderhorn District, Gunnison County, Colorado,* US Geological Survey Bulletin 1027 (in preparation).
9. Christman, R. A., Heyman, A. M., Dellwig, L. F. and Gott, G. B., *Thorium Investigations, 1950–1952, Wet Mountains, Colorado,* US Geological Survey Circular 290 (1953).
10. Sharp, W. N. and Cavender, W. S., *Thorium Deposits of the Lemhi Pass District, Lemhi County, Idaho and Beaverhead County, Montana* (abstract), Geological Society of America Bulletin 64: 1555 (1953).
11. Trites, A. F. and Tooker, E. W., *Uranium and Thorium Deposits in East-Central Idaho and Southwestern Montana,* US Geological Survey Bulletin 988–H, 184–208 (1953).
12. Wilmarth, V. R. and Johnson, D. H., written communication.
13. Glass, J. J. and Smalley, R. G., *Bastnaesite,* American Mineralogist 30: 601–615 (1945).
14. Vickers, R. C., written communication.
15. Mertie, J. B., Jr., *Monazite Deposits of the Southeastern Atlantic States,* US Geological Survey Circular 237 (1953).
16. Vickers, R. C., *Occurrences of Radioactive Minerals in the Bald Mountain Gold-Mining Area, Northern Black Hills, South Dakota,* US Geological Survey Circular 351 (1954).
17. Moxham, R. M., *Airborne Radioactivity Surveys in the Mojave Desert Region, Kern, Riverside and San Bernardino Counties, California,* US Geological Survey TEM–360, US Atomic Energy Commission Technical Information Service, Oak Ridge (1952).
18. Johnson, D. H., *Reconnaissance of Radioactive Rocks of Massachusetts,* US Geological Survey TEI–69, US Atomic Energy Commission Technical Information Service, Oak Ridge (1951).
19. Argall, G. O., *New Dredging Techniques Recover Idaho Monazite,* Mining World 16: 26–30 (1954).
20. Abbott, A. T., *Monazite Deposits in Calcareous Rocks, Northern Lemhi County, Idaho,* Idaho Bureau of Mines and Geology, pamphlet 99 (1954).

The Mineralogy of Thorium

By C. Frondel,* USA

The average content of the element thorium in the outer crust of the earth is about 12 grams per ton. Thorium is a little less abundant than lead and about three times as abundant as uranium. Thorium in the lithosphere is contained chiefly in minerals in which it is a nonessential constituent. Of the six known thorium minerals, only the thorium silicates—thorite and thorogummite—and the thorium dioxide, thorianite, are of potential economic interest. Most of the earth's thorium is dispersed in small and variable amounts in solid solution in other minerals as an occasional, vicarious constituent. The distribution of thorium in this manner is a selective process. The principal ore mineral of thorium is the cerium phosphate, monazite, which contains variable amounts of thorium in solid solution.

The mineralogical expression and the geochemical distribution of thorium both as an essential and as a vicarious constituent show striking similarities, both genetically and economically, to certain other elements, namely, uranium, cerium, zirconium, and hafnium. The very similar elements hafnium and zirconium will be considered hereafter as a unit with the symbol Zr.

That close geochemical relations should exist among these elements is suggested by similarities in their general chemical behavior and, more fundamentally, by similarities in their electronic structures. In the lanthanide series of elements extending from atomic number 58 (Ce) to 71 (Lu), the back filling in the 4*f* shell that causes the very close chemical resemblances in this series is paralleled in the actinide series of elements 90 (Th) to 96 (Cm) through back filling in the 5*f* (or 6*d*) shell. Quadrivalent Ce thus is similar to Th. Ce(IV) also is analogous to both Hf (72) and Zr (40), through filling of the 5*d* and 4*d* shells. Quadrivalent uranium shows close analogies to thorium. The similarities between Th, U, Ce, and Zr are illustrated by the isostructural relation of their dioxides and orthosilicates and by the extensive mutual solid-solution series in these and other groups of compounds. The mineralogical and geochemical dissimilarities between these elements are due primarily to the small size of the Zr(IV) ion as compared to Th(IV), Ce(IV), and U(IV) as a group, and to the assumption by uranium of the sexivalent state and by cerium of the trivalent state—both stable states under geologic conditions—in addition to the quadrivalent states of these elements.

* US Geological Survey and Harvard University.

THE DESCRIPTIVE MINERALOGY OF THORIUM

The element thorium which was named after Thor, the Scandinavian God of War, was discovered in 1828 by the Swedish chemist Berzelius in a mineral from a pegmatite on the island of Lövö in the Langesund fiord, southern Norway. The name thorite was given to the mineral. Thorite and its hydroxyl-containing variant, thorogummite, are the most important and widely distributed of the six known thorium minerals (Table I).

Thorite ideally has the formula $ThSiO_4$, and material of this composition can be readily synthesized. The composition of the natural mineral, however, is always greatly modified both by the entrance of other elements into solid solution, notably U, Fe, Ca, rare earths and P, and by secondary alteration. The alteration is of two types, which operate concomitantly. Thorite is radioactive, and alpha particles together with beta and gamma radiation are emitted by it or its decay products in the passage to the stable end element lead–208. The internal emission and absorption of alpha particles disrupts the normal crystalline structure of the mineral and causes it to become partly or completely disordered (metamict). This type of alteration occurs in many other thorium and uranium minerals and in recent years has been the subject of much investigation.[1,2,3] This structural disintegration is accompanied by chemical alteration, involving hydration—commonly to the extent of 8 to 10 weight per cent H_2O—and oxidation of U(IV) to U(VI) and of Fe(II) to Fe(III). A partial leaching of Si also may take place at this stage. These features of thorite, together with difficulties in the chemical analysis of the mineral, have brought much confusion to the description of the species. No less than 14 different minerals described in the older literature as distinct species are now known or suspected to be identical with thorite or its variant thorogummite (Table I). The analytical difficulties attending thorite led to the description of three supposed new elements, carolinium, donarium, and berzelium. Zircon also has a bulky nomenclatural halo of ill defined or synonymous minerals because of similar analytical difficulties, which led to the naming of the supposed new elements ostranium, norium, and jargonium. The description and discrediting of supposed new minerals in these categories unfortunately is still an active matter.

Table I. Minerals Containing Thorium as an Essential Constituent, with their Varieties and Synonyms

Name	*Composition*	*Content of ThO_2 (%)*	*Reference**
Cheralite	$(Th,Ca,Ce)(PO_4,SiO_4)$	30, variable	*a,d*
Huttonite	$Th(SiO_4)$	81.5 (ideal)†	*a,c*
Pilbarite	$ThO_2 \cdot UO_3 \cdot PbO \cdot 2SiO_2 \cdot 4H_2O$	31, variable	*a,f*
Thorianite	ThO_2	Series to UO_2	*a,b*
Thorite	$Th(SiO_4)$	81.5 (ideal)†	*a,b*
Thorogummite	$Th(SiO_4)_{1-x}(OH)_{4x}$	24 to 58 or more	*a,g*
	Varieties and Synonyms		
Aldanite	Variety of thorianite high in Pb and U		*a,i*
Auerlite	Variety of thorite or thorogummite relatively high in (PO_4)		*a*
Calciothorite	Variety of thorite or thorogummite relatively high in Ca		*a,r*
Chlorothorite	Synonym of thorogummite		*g*
Enalite	Variety of thorite or thorogummite relatively high in U, rare earths, and PO_4?		*a*
Eucrasite	Variety of thorite or thorogummite relatively high in Ca and rare earths		*a,r*
Ferrothorite	Variety of thorite or thorogummite relatively high in Fe(III)		*a*
Freyalite	Variety of thorite or thorogummite very high in Ce		*a,r*
Hyblite	Synonym of thorogummite; apparently contains some SO_4		*a,g*
Hydrothorite	Synonym of thorogummite		*a,g*
Mackintoshite	Synonym of thorogummite; contains U(IV)		*a,g*
Maitlandite	Synonym of thorogummite; relatively high in U(IV) and Pb		*a,g*
Nicolayite	Synonym of thorogummite		*a,g*
Orangite	Varietal name for yellow to orange metamict thorite		*a,r*
Uranothorianite	Varietal name for thorianite high in uranium [uranoan thorianite, $(Th,U)O_2$]		*a*
Uranothorite	Varietal name for thorite high in uranium [uranoan thorite, $(TH,U)(SiO_4)$]		*a*
Wisaksonite	Synonym of thorite		*j*

* References cited at bottom of Table II.

† Usually less, due to substitution of other elements for thorium.

Thorogummite is a recently established[4] variant of thorite in which tetrahedral groupings of four OH ions substitute vicariously for the SiO_4 groups of the structure. The formula may be written $Th(SiO_4)_{1-x}(OH)_{4x}$ in which x is as much as 0.25 in natural material. In the uranium analogue, coffinite,[5] $U(SiO_4)_{1-x}(OH)_{4x}$, the value of x is about 0.5. Cyrtolite is an analogous hydroxyl-containing variety of zircon (Table IV). The mechanism of hydroxyl substitution in these minerals is similar to that operating in the so-called hydrogarnets, in which a partial series in natural material and a complete series in synthetic material extends from $Ca_3Al_2(SiO_4)_3$ via $Ca_3Al_2(SiO_4)_{3-x}(OH)_{4x}$ to $Ca_3Al_2(OH)_{12}$. Thorogummite always appears to be a low-temperature secondary mineral in nature, produced by the recrystallization of metamict thorite or by the weathering of other minerals, but the question of the entrance of OH into high-temperature pegmatitic or vein thorite and zircon remains open. Thorogummite and cyrtolite have been synthesized hydrothermally at temperatures as low as 150°C, and the occurrence of OH in both synthetic and natural material has been verified by thermal and infrared analysis.

Thorite and thorogummite are tetragonal in crystallization and belong in the zircon structure type. The structure is based on isolated SiO_4 tetrahedra (nesosilicates) with the thorium ions in 8-coordination with oxygen. Owing to its metamict character, thorite affords only faint and diffuse X-ray diffraction effects or gives no X-ray pattern at all. When metamict thorite is heated to 800–900°C or higher, it recrystallizes exothermally to an aggregate of minute crystals of either tetragonal or monoclinic $ThSiO_4$, or to a mixture of one or the other of these with ThO_2. The recrystallization products give sharp X-ray diffraction effects, and this is a convenient means of identification. Thorogummite gives X-ray patterns in unheated material. When thorogummite is heated, water including OH is lost, and a small amount of ThO_2 may appear, but the diffraction pattern remains that of tetragonal $ThSiO_4$. Metamict thorite is isotropic with a relatively low and variable index of refraction. Thorogummite is unisotropic, but the particle size is much too small for satisfactory optical study and optical techniques generally are unsatisfactory as a means of identifying these minerals.

Following the discovery of thorite in 1828, the next well defined mineral containing thorium as an essential constituent to be discovered was thorianite,

ThO_2, in 1904. This was followed by the description of pilbarite in 1910, huttonite in 1951, cheralite in 1953, and the redefinition of thorogummite in 1954. The crystal structure of thorianite is analogous to that of fluorite, CaF_2, with the thoruim ions in 8-coordination with oxygen. The crystallochemical and mineralogical relations of UO_2, CeO_2, and ZrO_2 to ThO_2 are discussed in the following section. Natural thorianite contains considerable amounts of other elements in solid solution, particularly U and Ce, and like all thorium and uranium minerals accumulates Pb due to radioactive decay. Helium also is present. The uranium is present as both U(IV) and U(VI). The content of U(VI) probably is secondary, owing to oxidation of U(IV) with a concomitant entrance of oxygen into the vacant 8-fold position of the structure, as in partly oxidized uraninite, but no study of the effect has been made. Thorianite and uraninite, almost alone among radioactive minerals, do not become metamict apparently because of the inherent stability of the fluorite-type structure.

Of the remaining thorium minerals, pilbarite is an ill defined substance found as a secondary mineral in the weathered outcrop of a pegmatite in Western Australia. It needs further study. Huttonite, the monoclinic polymorph of $ThSiO_4$, is known as detrital grains in the heavy-mineral fraction of beach sands in New Zealand. It may be more widely distributed as an accessory mineral in black sands than is known. Huttonite has not been found in place, but it probably occurs in pegmatites and quartz-segregation veins in metamorphic rocks. The factors that influence the formation of huttonite and thorite are not known. Both phases have been synthesized by sintering of ThO_2 and SiO_2, the formation of huttonite being favored at higher temperatures, and both phases have been obtained hydrothermally between 400° and 700°C by reaction of coprecipitated gels of ThO_2 and SiO_2 in the presence of ThF_4. Cheralite is monoclinic and isostructural with both monazite and huttonite. It represents an intermediate member of the system $ThSiO_4$-$CePO_4$-$CaTh(PO_4)_2$. In this system a considerable range of solid solution exists by the substitution of Ce(III) and Th(IV) with valence compensation effected by the coupled substitution of Ca(II) for Ce(III) or of Si(IV) for P(V). Material in this series near monazite in composition is quite common, but huttonite and cheralite are rare.

The first large-scale use for thorium came with the development by Welsbach in about 1884 of the incandescent gas mantle, composed of ThO_2 with about 1% of CeO_2. Thorium now also finds use as a catalyst in refractories and in thoriated tungsten filaments. It is of potential importance in the field of atomic energy, since the natural isotope of thorium, thorium–232, can be converted by neutron bombardment to thorium–233, which yields uranium–233, a fissionable isotope. The thorium for gas mantles was obtained from monazite. The radioactive element mesothorium is a byproduct. The occurrence of thorium in monazite was first established by Kersten in 1839. The amount of thorium present varies widely, although roughly constant in the material from a given locality or area, and thorium-free monazite is rare. The usual content is less than 8–10 wt % ThO_2, but in some specimens the content is as much as 30% ThO_2. Monazite is said to average about 1 part U_3O_8 per 50 parts ThO_2. The manner in which the thorium is contained in monazite is discussed extensively in the literature. It was long thought to be present as mechanically admixed thorite or other thorium compound, and a few such occurrences have been observed, but it is now believed that the element is present in solid solution in substitution for Ce.

Other minerals in addition to monazite contain thorium as a vicarious constituent. Table II lists approximately 60 minerals—some are ill defined—that have been found at times to contain over 0.1 wt % ThO_2. A great many minerals including several in which thorium could be expected to occur on crystallochemical grounds never have been examined for this element. The minerals that contain vicarious thorium are chiefly silicates, oxides, and niobate-tantalates. Almost all these minerals are primary, and occur chiefly in pegmatites associated with alkalic or granitic igneous rocks. Only five of them, monazite, xenotime, allanite, zircon, and—to a less extent—pyrochlore have a wide distribution as accessory minerals in igneous or metamorphic rocks. The cations that occur associated with Th in these minerals are typically Ce and other rare earths, Zr, Ca, and U. The main factors involved in this association are geochemical and crystallochemical. The former tend to associate these elements with thorium in the parent solutions or melts from which the minerals have formed, and the latter determine the entrance of thorium into the various mineral phases that are formed. The most effective host minerals for Th are compounds of U, Zr, or Ce that are isostructural with thorium compounds, such as zircon, uraninite, and monazite, or compounds in which mechanisms of coupled substitution are available for the housing of large, polyvalent ions, such as the niobate-tantalates and monazite.

COMPARISON OF THE MINERALOGY OF THORIUM, URANIUM, CERIUM, AND ZIRCONIUM

Th, U, Ce, and Zr are markedly oxyphile, and the known minerals of these elements all contain oxygen with the exception of a few rare fluorides of cerium. Sulfides, sulfosalts, tellurides, and the native metals are not known as minerals. Thorium and uranium form synthetic sulfides and carbides, and the oxysulfides ThOS and UOS, but the formation of these substances in nature is unlikely on thermochemical grounds.

The common minerals that contain Th, U, and Zr as essential constituents are oxides and silicates. Ce differs in that it does not occur directly as an oxide, although CeO_2 is a well known synthetic

Table II. Minerals Containing Thorium as a Vicarious Constituent, with Their Varieties and Synonyms

Name	*Composition*	*Content of ThO_2 (%)*	*Reference*
Abukamalite	$(Ca,Y,Th)_5(Si,P,AlO_4)_3(O,F)$	<1	*w*
Allanite	$(Ca,Ce,Th)_2(Al,Fe,Mg)_3Si_3O_{12}(OH)$	up to~3	
Alvite	Ill defined substance, near zircon	15 in one analysis	
Ampangabeite	$\sim(Y,Er,U,Ca,Th)_2(Nb,Ta,Fe,Ti)_7O_{18}$	1–2	*b*
Bastnaesite	$(Ce,La)(CO_3)F$	<1	*c*
Betafite	$\sim(U,Ca)(Nb,Ta,Ti)_3O_{9-n}H_2O$	up to~1	*a,b*
Blomstrandine	Synonym of priorite		
Brannerite	$\sim(U,Ca,Fe,Th,Y)_3Ti_5O_{16}$	up to 12	*a*
Bröggerite	Variety of uraninite relatively high in rare earths and thorium. Thorian uraninite	14	
Cappelenite	$\sim BaY_8B_6(SiO_4)_3O_{12}(OH)_2$	<1	*r*
Calciosamarskite	Variety(?) of samarskite relatively rich in Ca	2–3	*b*
Caryocerite	$\sim(Ce,La,Th,Ca)_5(Si,B)_3(O,OH,F)_{13}$	13.6 in one analysis	*r*
Chinglusite	$\sim(Na,K)_4(Mn,Ca)_5(Ti,Zr)_3Si_{14}O_{41}\cdot 9H_2O$	<1	*o*
Cordylite	$(Ce,La)_2Ba(CO_3)_3F$	<1	*c*
Clarkeite	$\sim(Na,Ca,Pb)_2U_2(O,H_2O)_7$	2.4 in one analysis	*a*
Cyrtolite	Altered zircon containing H_2O and often small amounts of U and Th		
Davidite	$(Fe,Ce,U)(Ti,Fe,V,Cr)_3(O,OH)_7$	<1	*a*
Euxenite	$(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_5$	up to~5	*b*
Eschynite	$(Ce,Ca,Fe,Th)(Ti,Nb)_2O_6$	up to 17	*b*
Fergusonite	$(Y,Er,Ce,U,Th)(Nb,Ta,Ti)O_4$	up to~5	*b*
Fersmite	$(CaCe,Na)(Nb,Ti,Fe,Al)_2(O,OH,F)_6$	<1	
Formanite	$(Y,Er,U,Th)(Ta,Nb)O_4$	~1	*b*
Fourmarierite	$\sim PbO\cdot 4UO_3\cdot 5H_2O$	Small	*a*
Hagatelite	Variety of Zircon containing rare earths, CB, Ta, and Th	~1.5	*q*
Hokutolite	Radioactive variety of barite containing Pb and probably also Ra, U, Th		*c*
Gummite	Generic term for orange-red to yellowish alteration products of uraninite; chiefly fourmarierite and vandendriesscheite		*a*
Irinite	Thorian variety of loparite (perovskite) with composition $(Na,Ce,Th)(Ti,Cb)(O,OH)_3$		*m*
Johnstrupite	Silicate of Ce,Ca,Ti,Zr,Na	<1	*a,b*
Khlopinite	$\sim(Y,U,Th)_3(Cb,Ta,Ti,Fe)_7O_{20}$	2.2 in only analysis	*b*
Lovchorrite	$\sim Ce_4Ca_{10}Ti_3Si_{10}O_{39}F_6$	<1	*p*
Lovozerite	$\sim(Na,K)_2(Mn,Ca)ZrSi_6O_{16}\cdot 3H_2O$	small amount	*n*
Lyndochite	Variety of euxenite-polycrase relatively high in Ca and Th	~5	*b*
Melanocerite	$\sim(Ce,Y,La,Ca)_5(Si,B,P)_3(O,OH,F)_{13}$	1.7 in one analysis	*r*
Microlite	$(Na,Ca)_2(Ta,Nb)_2O_6(O,OH,F)$	<1	*a,b*
Mosandrite	$\sim NaCa_6Ce_2(Ti,Zr)_2Si_7O_{25}(OH,F)_7$	<1	*r*
Muromontite	Apparently a variety of allanite high in Be	~1	
Monazite	$(Ce,Y,La,Th)(PO_4)$	up to~30, usually 10–12	*c*
Naegite	Variety of zircon containing rare earths, U, and Th (2.8)		*t*
Nuolite	Ill defined mixture with $2to4ThO_2$		*b*
Orthite	Synonym of allanite	up to~3	
Oyamalite	Variety of zircon containing rare earths, (PO_4), and Th (~1)		*q*
Perrierite	Perhaps identical with allanite	4.6	*u*
Pisekite	Niobate-tantalate with U, Th, rare earths; Th present, amount not known		*a*
Pyrochlore	$NaCa(Nb,Ta)_2O_6F$	up to~5	*a,b*
Polycrase	$(Y,Ca,Ce,U,TH)(Ti,Nb,Ta)_2O_5$	1–5	*b*
Polymignyte	$\sim(Ca,Fe,Y,Zr)(Nb,Ti,Ta)O_4$	3.9 in one analysis	*b*
Priorite	$(Y,Er,Ca,Fe,Th)(Ti,Nb)_2O_6$	up to~8	*b*
Rinkite	$\sim(Na,Ca)_{12}(Ce,Ti)_5Si_5(O,F)_{36}$	<1	*p*
Rinkolite	$\sim(Ca,Na)_{22}Ce_2(Si,Ti)_{10}O_{28}(F,OH)_8$	small	*p*

Table II. Minerals Containing Thorium as a Vicarious Constituent, with Varieties and Synonyms (Continued)

Name	Composition	Content of ThO_2 (%)	Reference
Samarskite	$(Y,Er,Ce,U,Fe,Th)(Nb,Ta_2)_2O_6$	up to~4	*b*
Steenstrupine	$\sim(Na,Ca,Ce,La,Th)_3(Mn,Fe,Ta)(Si,Be,P)_3(O,OH,F)_{12}$	2-7	*v*
Tanteuxenite	Variety of euxenite relatively rich in Ta	2.8 in one analysis	*b*
Thalenite	$Y_4Si_4O_{13}(OH)_2$	<1	
Thucholite	Hydrocarbon mixture containing much U, Th, and rare earths in the ash		*k,l*
Tritomite	Silicate with B,F,Ce,La,Ca,Th	~9	*r*
Tscheffkinite	Silicate of Ce,La,Th,Fe,Ti,Ca	up to 20, usually~1	*s*
Tengerite	$\sim CaY_3(CO_3)_4(OH)_3{\cdot}3H_2O$	~1	*c*
Uraninite	UO_2 (ideally); usually partly oxidized, with Ce,Y,Pb, Th, etc	up to 14 at least	*a,b*
Uranophane	$Ca(UO_2)_2(SiO_3)_2(OH)_2{\cdot}5H_2O$	~2 in one analysis	*a*
Vandendriesscheite	$\sim PbO{\cdot}7UO_3{\cdot}12H_2O$	small	
Wiikite	Ill defined mixture with up to 3.7 ThO_2		*b*
Xenotime	$Y(PO_4)$	up to 2.5	*c*
Yttrialite	$\sim(Y,Th)_2Si_2O_7$	~12	*h*
Yttrocrasite	$\sim(Y,Th,U,Ca)_2(Ti,Fe,W)_4O_{11}$	8.75 in only analysis	*b*
Yttrotantalite	$(Fe,Y,U,Ca)(Nb,Ta)O_4$	<1	*b*
Vudyavrite	Altered variety of lovchorrite	~1	*p*
Zircon	$Zr(SiO_4)$	Usually <1 or none; some varieties higher	
Zirkelite	$\sim(Ca,Fe,Th,U)_2(Ti,Zr)_1O_5$	7.3 in only analysis	*b*

a Frondel, et al.: Mineralogy of Uranium. US Geol. Survey Bull. (in preparation).
b Palache, Berman, and Frondel: Dana's System of Mineralogy, 7th ed., v. 1, 1944.
c Palache, Berman, and Frondel: Dana's System of Mineralogy, 7th ed., v. 2, 1951.
d Bosie and Horne: Min. Mag. *30*, 93, 1953.
e Pabst: Amer. Min. *36*, 60, 1951; and Hutton: Amer. Min. *36*, 66, 1951.
f Simpson: Chem. News *102*, 283, 1910.
g Frondel: Amer. Min. *38*, 1007, 1953.
h Hata: Sci. Pap. Inst. Phys. Chem. Res. Tokyo, *34*, 455, 1938.
i Bespalov: Problems Soviet Geol., no. 6, 105, 1941.
j Hutton: Amer. Min. *39*, 825, 1954.
k Davidson and Bowie: Geol. Survey Great Britain, Bull. 3, 1, 1951.
l Barthauer, Rulfs, and Pearce: Amer. Min. *38*, 802, 1953.
m Borodin and Kazakova: Doklady, Ak. Nauk USSR *97*, 725, 1954.
n Gerasimovsky: C. R. (Doklady) Ac. Sci. URSS *25*, 753, 1939.
o Gerasimovsky: Bull. Ac. Sci. URSS, Serv. Geol. 1953, 1938.
p Borneman-Starynkevich: Mat. Geochem. Khibina Tundra, Ac. Sci. USSR, 43, 1953.
q Kimura: Japan. J. Chem. *2*, 82, 84, 1925.
r Brögger: Zeits. Krist. *16*, 1890.
s Kauffman and Jaffe: Amer. Min. *31*, 582, 1946.
t Shibata and Kimura: J. Chem. Soc. Japan *42*, 1, 1921.
u Bonatti and Gottardi: Rend. Soc. Min. Ital. *9*, 242, 1953.
v Bøggild: Mineralogy of Greenland (Medd. om Grnland *149*, no. 3, 1953).
w Hata: Sci. Pap. Inst. Phys. Chem. Res. Tokyo *34*, 1018, 1938.

compound, and Ce(IV) is commonly present—sometimes in large amounts—in solid solution in natural UO_2 and ThO_2. Cerium is carried in minerals chiefly as phosphates and silicates. In their roles as vicarious constituents, Th, U, Ce, and Zr again are found principally in oxides and silicates. Th also is an important vicarious constituent in the cerium phosphate, monazite. Further, these four elements are characteristic constituents of the niobate-tantalates.

The principal differences in the mineralogy and geochemistry of Th, U, Ce, and Zr stem from the valence states taken by these elements in nature. Th and Zr always are quadrivalent. On the other hand, U occurs both as quadrivalent and sexivalent ions, and Ce both as quadrivalent and trivalent ions. The diversity of the mineralogy of uranium—about 70 distinct species containing uranium as an essential constituent are known as compared to 6 for thorium and 15 for zirconium—is due primarily to the stability of the sexivalent U(VI) ion. More properly, U(VI) should be described as the uranyl ion. In crystal structures, U(VI) ordinarily is in distorted 6-fold or 8-fold coordination, with the two apical oxygens of the coordination group more closely associated with the U(VI) to give a linear complex cation, $(UO_2)^{=}$. In $(UO_2)(CO_3)$ the U(VI) is in 8-fold coordination with 6 oxygens in a plane and 2 apical oxygens.[6] The U(VI) in partly oxidized UO_2 presumably is in distorted 8-fold coordination. The bivalent uranyl ion is of sufficient stability to preserve its identity in solution. All the primary uranium minerals, including uraninite and coffinite, which contain U as an essential constituent, and the numerous minerals that contain U as a vicarious constituent, house the element only in the quadrivalent state, so far as is known. The 68 or so remaining minerals that contain U as an essential constituent are built of the uranyl ion. All are of secondary origin. None of these minerals have analogues containing Th, Ce, or Zr in place of U. This is due to the large size and unusual shape of the uranyl ion, which has no counterpart in the com-

Table III. Ionic Radii of Certain Elements (Goldschmidt's Values, in kX - units)

	Usual coordination number with oxygen							
Valence	*4*		*6*		*8*	*8 or higher*		
4	Si	V	Ti	W	Zr	Ce(IV)	U	Th
	0.39	0.61	0.64	0.68	0.87	1.02	1.05	1.10
3	Al	Al	Fe(III)			Y	La	Ce(III)
	0.57	0.57	0.67			1.06	1.22	1.18
2	Be	Mg	Fe(II)			Ca		
	0.34	0.78	0.83			1.06		
1						Na	K	
						0.98	1.33	

pounds of Th, Ce, or Zr. It is only quadrivalent uranium that forms compounds isostructural with compounds of Th, Ce, and Zr. In these minerals the ions involved all are of the same charge and are of spherical shape with comparable radii (Table III), so that they play the same crystallochemical role. It also may be noted that the uranyl ion, so far as is known, does not occur as an important vicarious constituent in other minerals. This strongly contrasts with the behavior of Th, Zr, quadrivalent U, and both quadrivalent and trivalent Ce. This behavior again is due to the size and shape of the uranyl ion, which does not allow it to proxy readily for the ordinary ions of crystal structures. The entrance of sexivalent uranium into solid solution in the structure of the silicates of igneous rocks and pegmatites also would be influenced by other factors, including the thermal instability of the uranyl ion at high temperatures and the oxygen content of the magma.

Uranium differs from Th and Zr in that it occurs in large amounts in hydrothermal deposits formed at relatively low temperatures. In hydrothermal veins, uraninite is typically associated with sulfides, arsenides, and sulfosalts of Cu, Fe, Ni, Co, Zn, Bi, Ag, and other elements. These deposits are generally very low in their content of Th, Ce, and Zr. On exposure to weathering, uraninite readily oxidizes to the uranyl ion, and the other minerals oxidize to relatively soluble sulfates and other oxysalts. This results in the formation in the oxidized zone of such deposits of a large variety of hydrated uranyl oxides, sulfates, arsenates or phosphates, for the most part also containing Cu, Ca, Mg, Ba or other cations in addition to the uranyl ion. The uranyl oxysalts in general are relatively soluble and occur typically in gossans, as efflorescences on outcrops and the walls of mine workings, and in caliche-type deposits. Large amounts of uranium can be lost during oxidation by solution in meteoric circulation, particularly in acid waters. This again contrasts with the behavior of Th and Zr. The primary compounds of these elements are chemically stable and quite insoluble, and during the weathering cycle tend to accumulate in the detrital residues. Soluble salts of these elements hydrolyze readily to insoluble hydrous oxides. Zr does not form minerals in the zone of weathering, and Th and Ce only very rarely.

Cerium, like uranium, differs from Th and Zr in that it possesses two valences that are stable under geologic conditions, Ce(IV) and Ce(III). Both ions are mineralogically important. The Ce(IV) ion bears a close crystallochemical resemblance to Th(IV) and U(IV) in particular. It has not yet been found in minerals as an essential constituent although the occurrence of CeO_2 and $CeSiO_4$ analogous to ThO_2 and $ThSiO_4$ could be expected. Ce(IV) does occur, however, dispersed in solid solution as a vicarious constituent in U, Th, and other minerals. It may be noted in this connection that cerium apparently often has been reported in mineral analyses in the trivalent state, as Ce_2O_3, without knowledge of its actual valence state in the mineral. The Ce(III) ion is considerably larger than the Ce(IV) ion (Table III) and has no mineralogically stable counterpart in Th, U, or Zr. The mineralogy of the trivalent cerium ion therefore stands alone among these elements. Ce(III) occurs in minerals both as an essential and as a vicarious constituent (Table II). Ce(III) occurs in significant amounts as a vicarious constituent much more widely than does Zr, although Zr is roughly five times more abundant than Ce in the lithosphere. This is due partly to the fact that the Ce(III) ion is relatively close in size to certain other elements and enters readily into solid solution in their compounds. These elements include the trivalent rare earths and particularly the common element Ca. Calcium is bivalent, and the substitution of Ca(II) by Ce(III) requires a concomitant substitution to compensate for the change in valence. In cerian fluorite, the substitution of Ce(III) for Ca is compensated by the entrance of additional F into structural vacancies; in apatite and the apatite-type mineral britholite and its numerous analogues the substitution of Ce(III) for Ca(II) is compensated by a concomitant substitution of Si(IV) for P(V); in sphene the entrance of Ce(III) is compensated by the substitution of Al(III) for Ti(IV). The initial content of Ce, and especially of Y, in alkalic igneous rocks retained in the magmatic stage of crystallization is much larger than that of Th. Y is taken into solid solution in accessory sphene, apatite, fluorite, and garnet more readily than in monazite.[7]

Although Zr is a relatively abundant element, its mineralogy both as an essential and as a vicarious constituent is very restricted. This is due primarily

to the high charge and intermediate size of the Zr(IV) ion (Table III). Among the geologically important quadrivalent elements, Zr does not substitute appreciably for Si into the framework of silicates or for Ti because of the large difference in size. Zr ordinarily is 8-coordinated with oxygen, whereas Si and Ti are 4- and 6-coordinated, respectively. Among other geologically important elements, where bivalent Fe, Ca, and Mg and the univalent alkalies come into consideration, there is a somewhat closer approximation in ionic size to Zr(IV), but there is a larger difference in ionic charge, involving 2 or 3 units instead of but 1 as in the pair Ce(III)-Ca(II). This latter circumstance severely limits the extent of a possible coupled substitution through both the demands of local electrostatic (Pauling rule) balance in the crystal structure and the lack of small, low-charged cations that can substitute concomitantly either for the central ion (Si, Al, P, As, S) of the anionic framework or for other cations in order to effect valence compensation. Actually the great bulk of Zr in nature is contained in but a single mineral, zircon, $ZrSiO_4$. Almost all the known minerals containing Zr as an essential or vicarious element are silicates. None of these minerals aside from zircon are known to carry appreciable amounts of Th in solid solution, although minerals containing Ce(III) commonly contain small amounts of Th(IV). Th(IV) is much closer in size to Ce(III) than to Zr(IV).

The dioxides of Th, U, and Ce are isostructural, in the CaF_2 structure type, and form a complete solid-solution series between all end compositions, $(Th,U,Ce)O_2$ at elevated temperatures in synthetic material.[8,9,10] In natural material, CeO_2 or solid solutions with Ce > (Th,U) is not known, but Ce(IV) is present in solid solution in considerable amounts in both natural UO_2 and ThO_2. ZrO_2 has several polymorphs. The form stable at natural conditions is the monoclinic phase, baddeleyite, with a distorted CaF_2-type structure, but one of the high-temperature polymorphs, not known in nature, is isometric with the CaF_2 structure. In the synthetic system UO_2-ZrO_2 a series[11] extends from UO_2 up to about 40 wt % ZrO_2, with a diphase region up to about 50 wt % ZrO_2 and a tetragonal series from that point to ZrO_2. There also is evidence of solid solubility of Th in synthetic monoclinic ZrO_2. Very much smaller amounts of Zr occur in solid solution in natural ThO_2 and UO_2. CeO_2 forms only a partial series with ZrO_2 in synthetic material.[12] The solubility relations of the dioxides of Th, U, and Ce on one hand and of Zr on the other clearly show the effect of the relatively small Zr ion. Trivalent rare earths such as La and Y go into limited solid solution in ThO_2 in both natural and synthetic material.[13] The C-type polymorphs of La_2O_3, Y_2O_3, etc. have a structure related to that of ThO_2 but with certain cation positions vacant, and the series from ThO_2 involves coupled entrance of vacancies to provide valence compensation.

In natural material the series between ThO_2 and UO_2 apparently has a large central gap. In general, the uraninite of pegmatites contains relatively large amounts of Th and Ce in solid solution, whereas the uraninite of hydrothermal veins and black-ore sandstone deposits of the Colorado Plateau is notably deficient in these elements. This is a problem of geochemical association rather than of the temperature dependency of the solid solubility.

In addition to the dioxides, some of the elements under consideration form other oxides. Ce forms Ce_2O_3, not known as a mineral, U forms U_3O_8, several polymorphs of UO_3 and other anhydrous oxides. None of these are known as minerals, although U_3O_8 might be expected to occur in nature. Uranium also forms a number of hydrated uranyl oxides, in part also containing Ba or Pb, that are widespread in small amounts. None of these uranium compounds have counterparts with Th, Ce, or Zr.

The economic importance of the oxides of Th, U, Ce, and Zr varies widely. Uraninite (here referred to as UO_2 but actually departing considerably from this composition owing to partial oxidation and solid solution) is the principal ore mineral of uranium. CeO_2 does not occur in nature, and cerium is obtained almost wholly from the cerium phosphate, monazite. ThO_2 is not an important actual or prospective ore mineral of thorium, although it is probably widely distributed as a very minor accessory mineral in beach and river sands. Small amounts of thorianite, however, have been obtained in Ceylon. Baddeleyite ZrO_2, although an extremely rare mineral as compared to zircon, is an important ore mineral at one locality, in the Poços de Caldas, Brazil,[14] where it occurs in large amounts with zircon as fibrous crusts in hydrothermal veins derived from and situated in syenitic igneous rocks. The parent rocks contain much Zr as eudialyte and as a vicarious constituent in alkalic pyroxenes and other silicates. The complex Zr silicate eudialyte occurs in large deposits in alkalic rocks in southern Greenland[15] and the Kola Peninsula and is a potential source of Zr; it contains some Ce but lacks significant amounts of Th. Thorianite, ThO_2, does not occur in hydrothermal deposits analogous to baddeleyite. Soda metasomatism in alkalic rocks may result in the liberation and hydrothermal concentration of Zr and certain other polyvalent ions.[16]

The principal silicates of the elements here considered are those of the thorite and thorogummite groups (Table IV). The available evidence indicates a very limited solid solubility between the isostructural phases $ThSiO_4$ and $ZrSiO_4$, extending perhaps to a few mol per cent under natural conditions. In the ternary system $USiO_4$-$ThSiO_4$-$ZrSiO_4$ there is extensive solid solubility of U into $ThSiO_4$ and a very limited solid solubility, apparently of the order of a few atomic per cent, of U into $ZrSiO_4$. Anhydrous $USiO_4$ does not occur in nature and has not been synthesized in spite of repeated attempts, but the solid solution $(Th,U)SiO_4$ extends from $ThSiO_4$

toward $USiO_4$ up to at least Th:U = 1:1. $CeSiO_4$ also does not occur in nature and has not yet been synthesized. The ill defined mineral freyalite may represent a Th-containing variety of $CeSiO_4$ or its hydroxyl-containing analogue. Cerium is commonly present in considerable amounts in thorite and thorogummite but is lacking or present only in small amounts in zircon. The mutual solubility in the system $ThSiO_4$-$USiO_4$-$ZrSiO_4$ and the entrance of Ce(IV) into the phases of this system clearly illustrate the role played by ionic size. The extent of solid solubility of U in both natural and synthetic material appears to be greater in thorogummite and cyrtolite than in anhydrous thorite and zircon. Th is lacking in the uranium member of the thorogummite group, coffinite, in the Colorado Plateau area but this is due to the lack of Th in this geochemical province.

Huttonite, a monoclinic polymorph of $ThSiO_4$ isostructural with monazite, has no known analogues in U, Ce or Zr silicates. Among the eight monoclinic and tetragonal polymorphs possible between $ZrSiO_4$, $ThSiO_4$, YPO_4 and $CePO_4$, it may be noted that the tetragonal structure is taken by the small ions Zr and Y and the monoclinic structure by the large ion Ce. Only Th, intermediate in size, develops both polymorphs. In synthetic material the solid solubility of U in monoclinic $ThSiO_4$ appears to be less than that in tetragonal $ThSiO_4$.

Thorium forms no natural silicates other than thorite, thorogummite, huttonite, and the ill defined mineral pilbarite. Uranium forms no silicates that contain solely U(IV), other than coffinite, but does form a number of uranyl silicates. All of these are secondary in origin, and none have analogues with Th, Ce, or Zr in place of U. Cerium forms silicates containing essential Ce(III), and Ce(III) enters as a vicarious element into still others (Table II). Some cerium silicates contain Th and U in solid solution, but others, such as cerite, have not yet been observed to carry significant amounts of these elements. Allanite, a common silicate of the epidote group, carries Ce, Th, and U in solid solution. The elements Ca, La and Y also are close associates of Ce in silicates. In addition to zircon, zirconium forms a considerable number of silicates. Most of these are complex in constitution, and all are rare. Further, none of them have analogues with Th, Ce, or U. The complex zirconium silicates generally contain alkalies in their composition; this feature is less marked with the cerium silicates and is lacking with uranium silicates.

U(IV) and Zr have not been found as phosphates. Th forms a silicate phosphate, cheralite, that has already been discussed. Small amounts of (PO_4) are commonly found in thorite and thorogummite substituting for (SiO_4). This series, with accompanying valence compensation by substitution of Ce(III) for Th, leads to a hypothetical tetragonal polymorph of $CePO_4$ isostructural with xenotime, YPO_4, and zircon. Compared to monazite, xenotime carries negligible amounts of Th. Cerium has a marked affinity for P as compared to U(IV), Th, and Zr. Monazite is a very common mineral, and other cerium minerals contain P as an essential or vicarious constituent (Table II). Some of these magmatic or pegmatitic minerals including britholite, abukamalite, belovite, melanocerite, and others are structural derivatives of apatite. The vicarious Th content of these apatitelike minerals is of interest in connection with the occurrence of U(IV) in small amounts in the apatite of phosphate rock. The substitution of Th is much larger than that of U, probably owing to factors favoring the entrance of compensating Si into magmatic rather than sedimentary apatite. Both the Th and the U substitute into the Ca positions of the apatite structure.

Table IV. Tetragonal Nesosilicates of Th, U, Ce, and Zr

Thorite Group	*Thorogummite Group*
$Th(SiO_4)$, thorite	$Th(SiO_4)_{1-x}(OH)_{4x}$, thorogummite
$U(SiO_4)$ (not known)	$U(SiO_4)_{1-x}(OH)_{4x}$, coffinite
$Ce(SiO_4)$ (not known)	$(Ce,Th)(SiO_4)_{1-x}(OH)_{4x}$, freyalite?
$Zr(SiO_4)$ zircon	$Zr(SiO_4)_{1-x}(OH)_{4x}$, cyrtolite

The only natural halogen-containing compounds of Th, U, Ce, and Zr are those of Ce. Thorite is found with fluorite in pegmatites and in some vein deposits, and the fluocarbonates of cerium are typical associates, but fluorine does not occur as an essential constituent in any thorium mineral.

The numerous uranyl carbonates include rutherfordine and a considerable number of complex carbonates containing uranyl ion together with other cations, chiefly Cu, Ca, Mg, and Na. These minerals together with the carbonate-fluoride-sulfate schroeckingerite and lanthanite are relatively soluble secondary minerals that occur chiefly as efflorescences. The numerous fluocarbonates of cerium, on the other hand, are relatively insoluble and form at much higher temperatures. These minerals appear to contain relatively little thorium in solid solution as compared to the silicates and phosphates of cerium.

The niobate-tantalates are characterized as a group by the presence—often in large amounts—of Th, U, Zr, Ti, Fe(III), and rare earths. The relative amounts of these elements vary widely through mutual substitution, and commonly a distinction between essential and vicarious constituents is not significant. The yttrium group of rare earths usually predominates over the cerium group. The diverse and large content of ions of high valence in the niobate-tantalates offers opportunities for mutual substitution that are not available to the same ions as they occur individually in silicates and other compounds dominated by the presence of bivalent and univalent cations. The niobate-tantalates are not of economic importance as sources of Th or U, because of their rarity and refractory chemical nature.

GEOCHEMISTRY AND OCCURRENCE OF THORIUM

The geochemistry of Th, U, Ce, and Zr as these elements appear in igneous rocks is very similar and is governed largely by the low concentration and high valence of their ions. The activation energy of migration of their ions (E-value)[17] is relatively high, which would tend to freeze the ions in the main stage of crystallization of the magma, but their concentration is in general too low to permit the appearance of phases in which these elements are essential constituents. In broad terms, they either concentrate in residual solutions or are included in solid solution in the minerals that form the bulk of the rock. In the case of gallium, an element of roughly the same abundance as thorium, the identity in valence and near identity in ionic radius with aluminum causes virtually all of this element to become dispersed in solid solution in alumino-silicates of the magmatic stage. In thorium and uranium, on the other hand, the high charge and large size of their quadrivalent ions do not permit entrance into the normal rock minerals, and as crystallization proceeds the residual solutions become enriched in these elements. Zirconium, much commoner than uranium and thorium, in part crystallizes in the magmatic stage as accessory zircon and may then house a certain amount of Th and U, a circumstance on which the age-determination method of Larsen is based. Both monazite and xenotime, however, appear to house Th and U more readily than zircon.[18] Zr and the rare earths, notably Ce(IV), together with other polyvalent elements such as Nb and Ta also tend to concentrate in the residual solutions. Th, Ce, and U have a marked affinity for alkalic rather than granitic or intermediate igneous rocks in the broad course of magmatic differentiation.

The main types of deposits that carry concentrations of thorium minerals are pegmatites, hydrothermal veins, and detrital deposits. Pegmatites associated with alkalic igneous rocks, particularly nepheline syenites and their variants, are notably rich in thorium. Well known and important occurrences of this type are in southern Norway,[19] the Kola Peninsula of Russia[20,21] and southern Greenland.[14] These pegmatites also are relatively high in the rare earths, with the cerium earths predominating over the yttrium earths, together with Zr, Nb, Ca, F, and F. Ta and U are minor constituents. These pegmatites are feldspathic but generally lack quartz and may contain nepheline (often altered to zeolites) together with pyroxenes and a variety of complex silicates containing Zr. Apatite is a characteristic accessory mineral in the pegmatites, and it sometimes occurs separately, as in the Kola Peninsula,[22] as very large deposits associated with alkalic igneous rocks. This apatite typically contains Ce and Si together with very small amounts of thorium. Pegmatites derived from granitic rocks tend to contrast with those from alkalic rocks in containing, on the whole, a smaller amount of Th and in being relatively enriched in Y over Ce, Ta over Nb, and U over Th. The granite pegmatites generally are quartz-rich, with Zr present chiefly as zircon. A small production of thorite has been obtained from alkalic pegmatites in Norway, but these deposits in general are not potential large-scale sources of thorium. Thorium may possibly be obtained as a byproduct in the utilization of magmatic apatite, analogous to the production of uranium from sedimentary phosphate rock.

Hydrothermal vein deposits containing thorium have become known only during the past few years. They differ from the base-metal sulfide types of veins, in which thorium is lacking in significant amounts, and they show resemblances to the cerium- and thorium-rich pegmatites associated with alkalic rocks. The Powderhorn district, Gunnison County, Colorado,[23] contains veins and mineralized shear zones carrying thorite or thorogummite with calcite, dolomite, quartz, barite, cerian fluorapatite, and bastnaesite. The deposits occur in and near alkalic igneous rocks, including the Iron Hill stock, that are notably rich in rare earths, Ti, Nb, Ba, and Sr. Concentrations of perovskite occur in the area. In the Mountain Pass area, San Bernardino County, California,[24] large veins and irregular bodies containing bastnaesite with calcite, dolomite, barite, parisite, and sahamalite occur in association with alkalic igneous rocks. The deposit contains Th in small amounts as a vicarious constituent. In the Salmon Bay area on Prince of Wales Island, Alaska,[25] veins carrying thorite with carbonates, hematite, and monazite are associated with other veins lacking Th but carrying carbonates with parisite and bastnaesite. Some deposits of bastnaesite, as in the fluorite-barite veins of the Gallinas Mountains, New Mexico,[26] and the contact metamorphic deposit at Bastnaes, Sweden, do not carry appreciable amounts of thorium. Vein deposits containing thorite or thorogummite but lacking rare earths are also known. In the Wet Mountains in Custer and Fremont Counties, Colorado,[27] a very large area contains veins containing a thoritelike mineral together with hematite, quartz, barite, carbonates, and minor fluorite and sulfides. The deposits appear to be related to albite-syenite intrusives. Quartz-hematite veins with a thorite-like mineral and minor monazite and allanite also occur in districts in east-central Idaho and southwestern Montana.[28] These vein deposits of Th and Ce minerals in general are extremely low in U, Zr, Y, Nb, and Ti. They show that the geochemical descent of Th and Ce, like that of U, continues into the hydrothermal stage. The baddeleyite deposits of Brazil are roughly analogues of the Th and U vein deposits, but most of the Zr is retained in high-temperature minerals. The separation of U and (Th,Ce) in the hydrothermal stage remains unexplained. Uranium apparently carries further into the lower-intensity hydrothermal zones, together with S, As, and heavy metals.

Thorium also occurs as a very minor constituent in deposits other than veins and pegmatites, such as with Nb in carbonatites and in a few contact

metamorphic deposits. In the sedimentary cycle, thorium,[29,30] unlike uranium, is not a significant constituent of the carbonaceous marine black shales and apparently does not play an important biogeochemical role. Zirconium is like thorium in this respect and is deposited chiefly as detrital zircon in near-shore clastic sediments. In sea water, uranium is enriched relative to thorium.

Alluvial deposits contain the largest known reserves of thorium. The thorium-containing mineral, monazite, occurs widely distributed as an accessory mineral in igneous and metamorphic rocks and in pegmatites. The content in gneiss and schist sometimes run as high as 0.1 wt % monazite, but efforts to mine and concentrate the mineral directly have been unsuccessful. The high specific gravity, hardness, and general stability of monazite cause it, when freed by weathering, to become mechanically concentrated in alluvial deposits. Important deposits of this kind are found in Travancore, Ceylon, the states of Bahia and Espirito Santo in Brazil, New South Wales, and Queensland. In the United States, alluvial deposits of monazite are found in Florida, the Appalachian region, Idaho, and elsewhere. The monazite is associated with ilmenite, zircon, magnetite, and garnet chiefly, and is separated and concentrated by magnetic methods. Thorite[31] and thorianite are widespread in trace amounts in alluvial deposits. The known deposits of monazite sands are very large, and the world's supply of thorium is now and probably will continue to be largely drawn from them.

REFERENCES

1. Pabst, A., *The Metamict State,* American Mineralogist 37: 137 (1952).
2. Pellas, P., *Order-disorder Transitions in the Crystalline Lattices of Radioactive Minerals,* Comptes Rendus 234: 538 (1952).
3. Pellas, P., *The Spontaneous Disintegration of the Crystal Lattice of Radioactive Minerals,* Comptes Rendus 233: 1936 (1951).
4. Frondel, C., *Hydroxyl Substitution in Thorite and Zircon,* American Mineralogist 38: 1007 (1953).
5. Stieff, L. R., Stern, T. W. and Sherwood, A. M., *Preliminary Description of Coffinite—A New Uranium Mineral,* Science 121: 608 (1955).
6. Christ, C. L., Clark, J. R. and Evans, H. T., Jr., *Crystal Structure of Rutherfordine UO_2CO_3,* Science 121: 472 (1955).
7. Sahama, T. G. and Vähätalo, V., *X-ray Spectrographic Study of the Rare-earths in Some Finnish Eruptive Rocks and Minerals,* Comptes rendus de la société géologique Finlande 14 (1939).
8. Magneli, A. and Blomberg, L., *On the Cerium Fluoride-Uranium Dioxide System,* Acta Chemica Scandinavica 5: 372 (1951).
9. Pudorf, W. and Valet, U., *On Cerium Uranium Oxide and the Mixed Crystal Series UO_2-Ce...,* Zeitschrift für Naturforschung 7a: 59 (1952).
10. Trzebiatowski, W. and Selwood, P. W., *Magnetic Susceptibilities of Urania-Thoria Solid Solutions,* Journal of the American Chemical Society 72: 4504 (1950).
11. Lambertson, A. and Mueller, M. H., *Equilibrium Phases in the System UO_2–ZrO_2,* US Atomic Energy Commission, AECD-3068 (1951).
12. Duwez, P. and Odell, F., *Phase Relationships in the System Zirconia-silica,* Journal of the American Chemical Society 33: 274 (1950).
13. Brauer, G. and Gradinger, H., *Anomalous Mixed Crystals of the Fluorite Lattice Type,* Naturwissenschaften 38: 559 (1951).
14. Guimarães, D., *The Zirconium Ore Deposits of the Poços de Caldas Plateau, Brazil, and Zirconium Geochemistry,* Instituto de tecnologia industrial, Estado de Minas Gerais, Bol. 6 (1948).
15. Bøggild, O. B., *The Mineralogy of Greenland,* Meddelelser om Grønland 149: no. 3 (1953).
16. Luchitsky, V. I., *Alkali Metasomatism in the Region of the Ukranian Massiv,* Doklady Akademiya Nauk SSSR 55: 49 (1947).
17. Wickman, F. E., *Some Aspects of the Geochemistry of Igneous Rocks and of Differentiation by Crystallization,* Geologiska Foreningens i Stockholm Forhandlingar 65: 37 (1943).
18. Hutton, C. O., *Nuclei of Pleochroic Haloes,* American Journal of Science 245: 154 (1947).
19. Brogger, W. C., *Die Mineralien der Syenitpegmatitgange der Sudnorwegischen Augit-und Nephelinsyenit,* Zeitschrift fur Kristallographie 16 (1890).
20. Fersman, A. E., *Minerals of the Kola Peninsula,* American Mineralogist 11: 289 (1926); Neues Jahrbuch fur Mineralogie, Geologie und Paleontologie, Beilage-Band 55: 36 (1926).
21. Fersman, A. E. and Bohnstedt, E. M., *Minerals of the Khibina and Lovozero Tundra,* Lomonosov Institute of Geochemistry, Crystallography, and Mineralogy SSSR (1937).
22. Antonov, L. V., *The Apatite Deposits of the Khibina Tundra,* State Chemical Technical Publication, Leningrad, 7 (1934).
23. Olson, J. C. and Wallace, S. R., written communication.
24. Olson, J. C., Shawe, D. R., Pray, L. C. and Sharp, W. N., *Rare-earth Mineral Deposits of the Mountain Pass District, San Bernardino County, Calif.,* US Geological Survey Professional Paper 261 (1954).
25. Wedow, H., *et al., Preliminary Summary of Reconnaissance for Uranium and Thorium in Alaska, 1952,* US Geological Survey Circular 248 (1953).
26. Glass, J. J. and Smalley, R. G., *Bastnaesite,* American Mineralogist 30: 601 (1945).
27. Christman, R. A., *et al.,* written communication.
28. Trites, A. F. and Tooker, E. W., *Uranium and Thorium Deposits in East-central Idaho and Southwestern Montana,* US Geological Survey Bulletin 988-H (1953).
29. Koczy, F. F., *Thorium in Sea Water and Marine Sediments,* Geologiska Foreningens i Stockholm Forhandlingar 71: 238 (1949).
30. Koczy, F. F., *The Thorium Content of the Cambrian Alum Shales of Sweden,* Sveriges Geologiska Undersokning, Serie C, Arsbok 43, No. 7 (1949).
31. Hutton, C. O., *Studies of Heavy Detrital Minerals,* Bulletin of the Geological Society of America 61: 635 (1950).

Thorium Deposits in the Wet Mountains, Colorado

By Q. D. Singewald and M. R. Brock,* USA

In 1950 the US Geological Survey discovered thorium in veins in the Wet Mountains of Colorado. Subsequent discoveries by prospectors and geologists have established a thorium metallogenic province that trends north-northwestward along the western slope of the range. The known deposits are irregularly scattered through an area about 25 miles long and 10 miles wide.

The Wet Mountains extend about 50 miles south-southeastward from the Arkansas River (Fig. 1) as an en echelon continuation of the Colorado Front Range. To the west is a narrow intermontane valley named the Wet Mountain Valley; to the east lie the Great Plains of the United States. The narrow crest of the central part of the range, adjoining the thorium province, stands at an average altitude of about 9000 feet. The western slope is fairly rugged; local relief ranges from a few hundred feet to more than a thousand feet. Few of the valleys contain perennial streams, for the climate, despite the name of the mountains, is nearly semiarid. Thin, somewhat scrubby stands of evergreen cover many ridges, and good stands cover some of the north-facing slopes.

The prevailing bedrock of the Wet Mountains is a crystalline complex of Precambrian age. The complex is transected by many dikes, some of which may be later Precambrian in age, some Tertiary. It also is transected by at least one stock that is late Precambrian. Sedimentary rocks of Paleozoic and younger age adjoin the eastern flank of the mountains and wrap around the southern end. Tertiary volcanic rocks form a discontinuous belt along the lower western slope and in places cap the southern part of the range crest. An unknown thickness of alluvium covers bedrock throughout the Wet Mountain Valley.

Metal mines, worked mainly during the last century, have been the chief source of mineral wealth derived from the Wet Mountains. They are described by Emmons.[1] Except for one lead mine 10 miles northeast of Rosita, and perhaps several insignificant lead mines farther north, the metal mines are clustered within two districts in the vicinity of Rosita and Silver Cliff, respectively. The aggregate output of these districts has been about $7 million worth of ores containing gold, silver, and lead. These base-metal deposits occur within areas of volcanic rocks and, less abundantly, within surrounding Precambrian terrane. By contrast, thorium-bearing veins have as yet been found only in Precambrian terrane—to the east, northeast, and north of Rosita. Perlite, derived from a glassy member of the volcanic series, is currently mined a few miles southwest of Rosita. Very minor quantities of barite from veins and vermiculite from bodies of reconstituted or altered gneiss have been mined at scattered localities in the Precambrian terrane.

CRYSTALLINE COMPLEX

Essentially all that is known about the crystalline complex in the thorium province is derived from an area of 35 square miles, mapped in detail since 1952. The only previous studies were made by Cross,[2] who described Precambrian rocks found near Rosita and Silver Cliff, but lumped them together on his geologic map, and by Christman, Heyman, Dellwig and Gott,[3] who made plane-table maps of three local areas that contain thorium veins.

The crystalline complex is composed of products of high-grade metamorphism, either sediments alone or sediments interlayered with tuffs, flows, or sills, and products of magmatic intrusion, granitization, or differential melting. These foliated rocks form interlayered sequences whose individual members grade into one another, both along the strike and across it. At few places do the individual members attain thicknesses exceeding several tens of feet. Mappable units are difficult to resolve. In general, wherever one type of rock constitutes more than 80% of the material in a sequence not less than 50 feet thick, the authors and their associates[4] mapped the bedrock as a unit designated by the name of the prevailing rock. Elsewhere, the bedrock was divided into units designated by the names of two or more rocks, each of which constitutes more than 20% of the material in the sequence; these units are not less than 100 feet thick and, generally, are several hundred feet thick. Altogether, the crystalline complex was divided into 24 map units, of which 8 are designated by one rock name, and 16 are designated by two or more rock names. In addition, certain distinctive rocks, such as garnet-rich layers and quartzite, which occur as thin but long layers within both kinds of units, were mapped as "marker beds."

Hornblende-plagioclase gneiss, biotite-quartz-plagioclase gneiss and hornblende-pyroxene-plagioclase gneiss, in order of abundance, are the prevailing products of metamorphism either of sediments alone or of sediments interlayered with tuffs, flows, or sills. All gradations exist from the hornblende-plagioclase

* US Geological Survey.

gneiss to the biotite-quartz-plagioclase gneiss on the one hand, and to the hornblende-pyroxene-plagioclase gneiss on the other. The rocks generally are thinly banded, owing to alternating layers or laminae having slightly different composition and texture. Mafic minerals[5] constitute from about 35 to 85% of rocks that contain both hornblende and pyroxene. The biotite content of rocks essentially free of hornblende and pyroxene averages about 10%. The more leucocratic facies of biotite-quartz-plagioclase gneiss, which are difficult to distinguish in the field from alaskitic granite, contain subordinate microcline.

Garnetiferous gneiss, sillimanitic gneiss, quartzite, and scapolite-pyroxene gneiss are, in their order of abundance, subordinate types of metasedimentary gneiss. Garnet, probably almandite, locally is a prominent constituent in long and narrow layers or lenses of biotite-bearing rock, not only in metasedimentary gneiss, but also in migmatite and alaskitic granite. The layers, ranging from less than a foot to several tens of feet in thickness, commonly serve as distinctive "marker beds". A few can be traced several miles along the strike. At few places is garnet a prominent constituent of hornblende gneiss. Sillimanite commonly is associated with garnet in "marker beds", but is somewhat less widespread than garnet. At some places, sillimanite occurs without garnet. Quartzite, mostly garnetiferous, has been found only as lenses, few of which are more than a hundred feet long or more than 10 feet thick. They commonly are associated with garnet-rich gneiss. The relatively rare scapolite-pyroxene gneiss likewise is restricted to thin layers, lenses, and pods.

Alaskitic granite gneiss and associated migmatite are the most widespread representatives of rocks that may have formed by igneous intrusions, granitization, or differential melting. The alaskitic granite gneiss forms tabular bodies and lenses conformable with the regional foliation. Individual occurrences range from less than a foot to about 500 feet in thickness. Many have relatively sharp contacts, but others grade into the enclosing rocks, particularly into migmatite. The average rock[5] contains about 42% perthitic microcline, 33% quartz, 22% oligoclase, and 3% combined biotite and accessories. In places the alaskitic granite gneiss contains garnet-bearing layers.

Quartz monzonite gneiss and leucogranodiorite gneiss are conformable granitic members of the crystalline complex that are much less common than alaskitic granite gneiss. In addition, a granite, slightly more radioactive than alaskitic granite gneiss, commonly crosscuts the regional foliation. It may have been emplaced during the declining stage of the metamorphic orogeny or later. Pegmatites are widespread, but in general were not mapped. Metamorphosed gabbroic and ultramafic rocks are subordinate members of the crystalline complex. They are closely associated with hornblende-pyroxene-plagioclase gneiss and may be products of local melting. Their contacts in a few places seem to crosscut enclosing rocks, but their long dimensions and internal foliation conform with the regional foliation.

YOUNGER IGNEOUS ROCKS

A nonfoliated albite stock that covers about 3 square miles contains inclusions of the crystalline complex and transects the foliation. The prevailing rock[5] contains 65–80% albite—most of which is antiperthite—less than 25% microcline, and less than 5% quartz. Accessory minerals are hornblende, biotite, zircon, apatite, magnetite, and fluorite. Throughout the stock radioactivity readings with a gamma scintillation detector range from 2–10 times normal background and average about 5 times normal background. Spectrographic analyses show that most of the radioactivity is due to thorium. An age determination by the Larsen zircon method by Jaffe of the US Geological Survey indicates that the stock is about 600 million years old.

Dikes, whose relative ages are incompletely known, cut the crystalline complex and include a considerable variety of facies, but syenite, melanocratic syenite, and basic rocks that range from andesite to basalt, predominate. Field relations suggest that syenite dikes are essentially contemporaneous with early facies of the albite syenite stock and that most basic dikes antedate the syenite dikes. Some basic dikes, however, are younger than syenite dikes. Thus, most dikes probably are late Precambrian in age, but some may be younger, perhaps Tertiary in age.

The syenite dikes are the most common and the most continuous; some have been traced for several miles. The rock generally is fine grained and composed of pink feldspar with only minor amounts of quartz, biotite, hornblende, aegirite, and secondary minerals. The melanocratic syenite dikes include a diversity of fine-grained and porphyritic facies, but in thin section all contain albite and soda-bearing amphiboles or pyroxenes. The basic dikes are predominantly dark-gray, aphanitic to medium-grained rocks containing calcic andesine or sodic labradorite. Many are intensely altered, particularly in proximity to veins. Most syenite dikes and many melanocratic syenite dikes exhibit radioactivity anomalies comparable to those of the albite syenite stock. Basic dikes normally exhibit no anomalous radioactivity.

GEOLOGIC STRUCTURE

Foliation is well developed throughout most of the crystalline complex. In general, the strike is northeast, and the dip is steep to the north at most places, but steep to the south at other places. At some places foliation is obscure in alaskitic granite gneiss, gabbroic and ultramafic bodies, and mafic varieties of hornblendic gneiss. Outcrops generally are not good enough to correlate obscure foliation with local structural details; however, at a few places foliation is obscure in alaskitic granite gneiss along the crests of relatively open minor folds or structural terraces.

The foliation at most places probably is inherited from original bedding. It conforms with differences

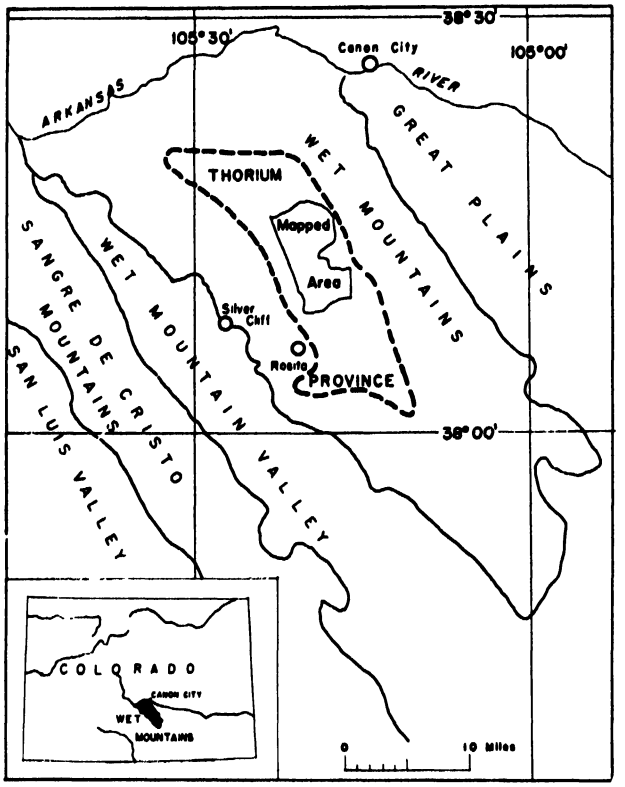


Figure 1. Location of thorium deposits, Wet Mountains, Colorado

in composition between layers of thinly banded rocks. It likewise conforms with long and narrow "marker beds" of distinctive rocks such as quartzite and garnet-sillimanite gneiss. One "marker bed" of garnet-sillimanite gneiss 10–50 feet thick was traced more than 3 miles. On the other hand, at many places where lithologic units grade abruptly and complexly along the strike into other units, particularly within the belts of isoclinal folds, the foliation may represent axial-plane cleavage superimposed upon earlier folds, and may not be inherited from preexisting bedding.

Lineation at many places is exhibited by grooves, crenulations, mineral lenticules, and alignment of elongated minerals. However, lineation is not apparent in most outcrops; perhaps this is due in part to the poor quality of outcrops. Lineations generally are consistent throughout sizeable areas. They are essentially parallel to major fold axes or subperpendicular.

Three longitudinal belts displaying different types of folds have been mapped in the crystalline complex. One belt is dominated by a broad, doubly plunging major anticline on whose limbs are subordinate folds and structural terraces; the lineation, essentially parallel to fold axes, generally plunges less than 40 degrees. Another belt is a homoclinal zone of steep dips in which lineation is mostly wanting. The third belt is one of crumpled isoclinal folds in which lineations is subperpendicular to the strike of the foliation, but essentially parallel to minor fold axes.

The dominant trend of fractures which postdate the metamorphic orogeny is northwest to west, that is, transverse to oblique to the trend of regional foliation. The fracture pattern is represented by dikes, veins, faults, shear zones, and joints. The prevailing trend of dikes ranges from N 50°W to S 70°W, whereas the prevailing trend of veins ranges from N 30°W to N 80°W. Relatively narrow, sinuous zones of fractures may be traced for miles. The horizontal component of displacement along the larger faults may in places be as much as 500 feet. The vertical component cannot be determined.

THORIUM DEPOSITS

Thorium vein minerals—as distinct from thorium-bearing accessory rock minerals, such as zircon—occur as irregularly distributed constituents of veins, as disseminations and small local concentrations in broader areas of shattered rock, and as continuously scattered components of bodies thought to be altered breccia pipes. Only the veins seem to hold economic potentialities at the present time.

Figure 1 outlines the province which thorium-bearing veins were found before 1955. Systematic search has revealed hundreds of thorium-bearing veins in the mapped part. Hundreds of others doubtless will be found in the remainder. Details of the vein pattern are illustrated by Fig. 2. Omitted are all veins that give radioactivity readings less than 3 times normal background count when the gamma-ray scintillation detector is held at hip level. Although a considerable number of veins are scattered erratically through the area of Fig. 2, many are concentrated along sinuous belts that follow major zones

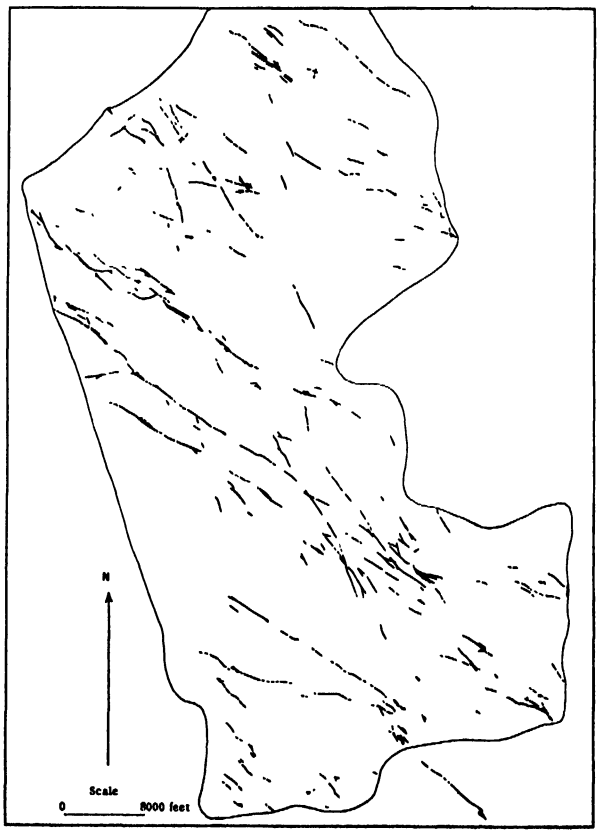


Figure 2. Thorium veins in mapped area, Wet Mountains, Colorado

of discontinuous faults. No correlation has yet been found between the distribution of veins and either the metamorphic structure or the lithology of the crystalline complex.

The veins occupy steeply dipping zones of shattered and altered rock. Most of them are less than 10 feet wide, but a few are as much as 50 feet wide. They may be traced along the outcrop for distances ranging from about 100 feet to 5000 feet. The material in a vein zone near the surface normally is decomposed, friable, and heavily impregnated with yellow, brown, and red oxide minerals. Purplish-red hues among the iron oxide minerals are seen in nearly every strongly radioactive vein but are not diagnostic, because they also appear where veins are not radioactive. The vein rocks at many places emit a strong stinking odor when freshly broken, but the odor disappears in about a minute. Typical vein minerals such as quartz (including smoky quartz), barite, carbonate minerals, and minor amounts of fluorite, sulphide minerals, and copper stain may or may not be present in radioactive veins.

The most widespread product of hypogene alteration in the veins and their walls is pink feldspar, which is commonly accompanied by quartz. In some places feldspathized veins grade laterally into coarse pink pegmatite. Intensely feldspathized rock tends to resist erosion, so the float may obscure the surrounding rock where exposures are poor. The feldspathized rock may have a spongy structure enclosing rounded pellets of limonite. Where hornblendic gneiss adjoins a feldspathized vein, the rock is commonly epidotized.

A second type of fairly widespread hypogene alteration may have been dominantly carbonization. It seems to be particularly common where veins adjoin or lie within basic dikes. The original products have been largely destroyed by weathering, but probably included carbonate minerals, a soda amphibole like arfvedsonite, and perhaps other mafic minerals.

Thorium-rich concentrations occur erratically along veins as pockets, pods, or lenses. Not enough prospecting has been done to predict their sizes and grades. More than 100 selected samples from diverse localities contained from 0.02 to 12.5% ThO_2. Only one vein has uranium in greater than a trace amount. Diamond drilling at one locality[3] delineated two ore shoots for which a cutoff grade was taken as 0.3% ThO_2; one is 200–300 feet long, 6–26 feet thick, and at least 400 feet deep; the other is 160 feet long, 2–10 feet thick, and at least 140 feet deep. These ore shoots are doubtless considerably larger than average.

A reddish-brown thoritelike mineral is visible as blebs and veinlets at a few of the richest localities. Elsewhere, the thorium minerals, masked by limonite, can be detected only by their radioactivity. The thoritelike mineral collected at one locality[5] exhibits intimate inter-growths with barite and specularite under the microscope. The larger, euhedral grains are anisotropic and zoned. Chemical, optical, X-ray, and differential thermal data suggest that the mineral is a hydrated species, probably thorogummite. Age of the thoritelike mineral has not yet been determined.

REFERENCES

1. Emmons, S. F., *The mines of Custer County, Colorado*: US Geological Survey 17th Annual Report, 1895–96, Part 2, 405–472 (1896).

2. Cross, Whitman, *Geology of Silver Cliff and the Rosita Hills, Colorado*: US Geological Survey 17th Annual Report, 1895–96, Part 2, 275–284 (1896).

3. Christman, R. A., Heyman, A. M., Dellwig, L. F. and Gott, G. B., *Thorium investigations 1950–52, Wet Mountains, Colorado*: US Geological Survey Circular 290 (1953).

4. Singewald, Q. D., *et al., Geologic and radiometric maps of the McKinley Mountain area, Wet Mountains, Colorado*: US Geological Survey Mineral Investigations Field Studies Map MF 37 (1955).

5. Christman, R. A., Brock, M. R., Pearson, R. C. and Singewald, Q. D., *Wet Mountain thorium investigations, 1952–1954*: US Geological Survey Open File available for public inspection at Denver and Salt Lake.

Thorium in the Powderhorn District, Gunnison County, Colorado

By S. R. Wallace and J. C. Olson,* USA

In the Powderhorn district, Gunnison County, Colorado, thorium occurs mainly in silicified, iron-stained shear zones, and in carbonate-rich veins. These thorium deposits are closely associated with a composite stock of alkalic igneous rocks at Iron Hill, southeast of Powderhorn, and with similar, and probably related, alkalic igneous rocks in other parts of the district. Larsen[1] demonstrated that Ti, Ba, Sr, and P are relatively abundant in some of the Iron Hill igneous rocks. These elements are also present in greater-than-average concentrations in the thorium-bearing veins. The present study was undertaken to obtain more information on the geologic relation of these and other minor elements—particularly Th, Nb, and the rare earths—to the alkalic igneous rocks, and to evaluate the economic significance of the thorium-bearing deposits.

The thorium deposits of the Powderhorn district (Fig. 1) are in an elongate area about 20 miles long and 6 miles wide that trends northwestward from the vicinity of Iron Hill to the Lake Fork of the Gunnison River, in southwestern Gunnison County.

Thorium was discovered in the Powderhorn district in 1949 on what is now the Little Johnnie group of claims (locality 1, Fig. 1). In 1950, soon after the original discovery was made, Adams and Moore of the US Geological Survey examined the Little Johnnie, Jeanie, and Red Rock claims (localities 2, 3, and 4, Fig. 1). In 1951, during reconnaissance for radioactive materials in the San Juan Mountain region, Burbank[2] examined thorium-bearing deposits in the Lake Fork-Dubois area and in the vicinity of Iron Hill. Unpublished data obtained in these investigations contributed much to the present field study and the preparation of this report. A brief reconnaissance for thorium-bearing deposits was made by Olson during three weeks in July and August 1953, and the Little Johnnie thorium deposit was mapped by S. R. Wallace and J. E. Roadifer in August 1953.

GENERAL GEOLOGY

The Powderhorn district is underlain chiefly by Precambrian metamorphic and igneous rocks. These rocks are cut by small stocks, dikes, and irregular bodies of a variety of alkalic igneous rocks of pre-Jurassic age. Flat to gently dipping strata of the Morrison formation of Jurassic age overlie these metamorphic and intrusive rocks and are in turn overlain unconformably by volcanic rocks of Tertiary age which were deposited on an erosion surface of low relief. The erosion surface beneath the Morrison formation and that beneath the volcanic rocks are locally nearly coincident, and in places the Tertiary volcanic rocks rest directly on Precambrian rocks. Erosional remnants of the Jurassic sedimentary and Tertiary volcanic flow rocks cap many mesas in the interstream areas.

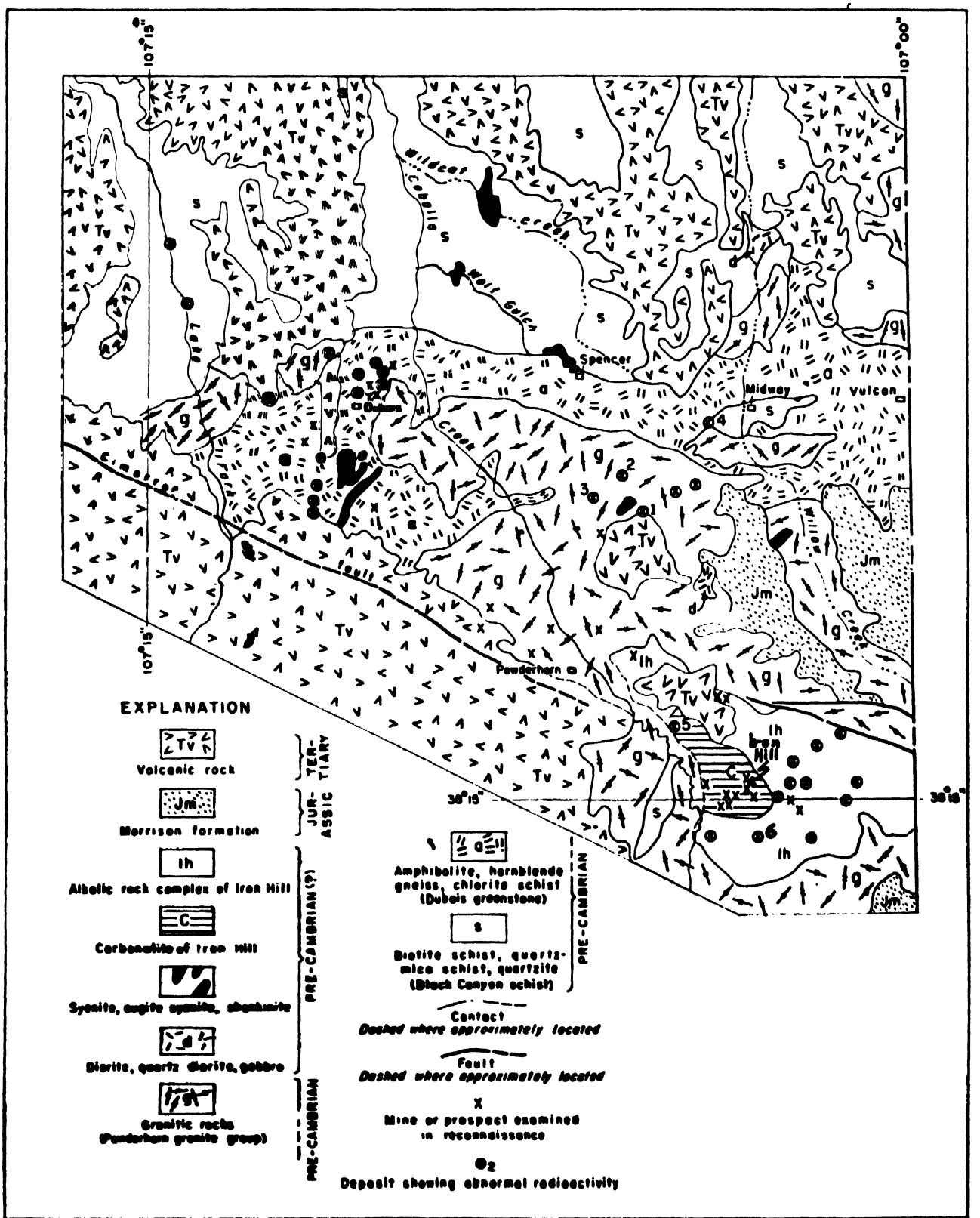
The Precambrian rocks, as mapped by Hunter,[3] are divided (Fig. 1) into the Black Canyon schist, which is dominantly biotite schist, quartzmica schist, and micaceous quartzite; the Dubois greenstone, which consists chiefly of hornblende schist, hornblende gneiss, amphibolite, metadiorite, and chlorite schist; and the Powderhorn granite, which consists of granitic rocks of relatively uniform composition but which includes such diversified textural varieties as schistose metarhyolite porphyry, granite gneiss, coarsely porphyrytic granite, and aplite. The Powderhorn granite cuts and is therefore younger than the Dubois greenstone, but is in turn cut by foliated amphibolite dikes. The porphyritic texture and bipyramidal quartz phenocrysts of the metarhyolite porphyry suggest that this variety was either extrusive or intruded at relatively shallow depth; the other facies of the Powderhorn granite are almost certainly plutonic.

With the exception of some facies of the Powderhorn granite, all the rocks described above are well foliated and have been metamorphosed to a much higher degree than any of the lower Paleozoic sedimentary rocks of central or southwestern Colorado.

Many dikes and small irregular bodies of poorly foliated to massive igneous rock intrude the Precambrian metamorphic and igneous complex. These intrusive rocks include diorite, quartz diorite, gabbro, syenite, augite syenite, shonkinite, and the alkalic rocks of the Iron Hill complex. These rocks all have common chemical and structural features, and probably are genetically related.

The Iron Hill complex is a composite stock that occupies an area of about 12 square miles in the southeastern part of the district. The dominant rock type of the stock is pyroxenite. Dolomitic carbonate rock, the second most abundant rock in the complex,

* US Geological Survey.



Geology modified after Hunter, 1928, U S. Geol. Survey Bull. 777 and Cross and Larsen, 1935, U S Geol. Survey Bull. 843

Figure 1. Generalized geologic map of the Powderhorn District, Colorado, showing localities examined

crops out over an area of about 2 square miles on and adjacent to Iron Hill in the east-central part of the stock. Calcite, apatite, phlogopite, magnetite, aegirite, and sodic amphibole are common accessory minerals in the carbonate rock, and locally they are abundant. The other rocks in the stock are uncompahgrite, ijolite, soda syenite, nepheline syenite, nepheline gabbro, and quartz gabbro.

The carbonatite is generally massive but locally has a conspicuous, steeply plunging lineation formed mainly by streaks of apatite along shear planes. Persistent carbonate veins similar in composition to the main Iron Hill carbonate mass cut the pyroxenite, ijolite, uncompahgrite, and quartz gabbro; locally the massive carbonatite bodies are cut by thin pyroxenite and micaceous dikes. Thus carbonate rocks are both older and younger than some of the igneous rocks of the complex. Larsen[1] favored the concept that the main carbonatite mass was formed hydrothermally in the throat of a volcano, though it may have been intruded as a carbonate magma or it may be an inclusion of Precambrian marble.

The Iron Hill complex probably is pre-Jurassic in age, because Larsen[1] found that the heavy mineral suite of basal Morrison strata in the vicinity of Iron Hill contained minerals characteristic of those found in the Iron Hill alkalic rocks. The Iron Hill stock and similar intrusive rocks throughout the district, and the related thorium-bearing deposits, are younger than the main period of Precambrian metamorphism in the district, may possibly be later Precambrian.

The metamorphic rock complex is overlain unconformably by thin remnants of sandstone and siltstone of the Morrison formation of Jurassic age, which were deposited on a nearly flat surface. Volcanic rocks of the Alboroto rhyolite of the Potosi volcanic series of Miocene age lie unconformably on the Morrison formation, and in turn are overlain unconformably by rhyolite of the Hinsdale formation of Pliocene(?) age.[4] The sedimentary and volcanic rocks are found chiefly as erosional remnants on mesas and ridges, and have been removed from most of the district by erosion.

STRUCTURE

The foliation and individual layers of the Precambrian metamorphic rocks strike generally within 45 degrees of east and dip steeply throughout most of the district. Many of the dikes and veins in the district were emplaced parallel to this foliation and layering. The Mesozoic and Cenozoic sedimentary and volcanic rocks dip gently northward except locally where disturbed by faults.

The largest known fault in the region (Fig. 1), the Cimarron fault of Hunter,[3] is a southward-dipping normal fault that has a throw of more than 1500 feet in the Powderhorn district. It extends at least 35 miles northwestward from Powderhorn but has not been mapped southeast of Powderhorn; its probable location in the valley of Cebolla Creek is marked by hot springs and soring deposits.

MINERAL DEPOSITS

Mineral deposits of three distinct ages occur in the Powderhorn district. Precambrian quartz-chlorite-tourmaline veins containing pyrite, chalcopyrite, and sphalerite, near Dubois, Spencer, Midway, and Vulcan, were mined during the period 1870–1900 for minor amounts of gold and silver they contain, and a small quantity of sulfur was produced from massive sulfide bodies that replace chloritic schist near Vulcan. Iron and manganese oxides, vermiculite, and minerals containing titanium, rare earths, thorium, and niobium are associated with the alkalic igneous rocks and are present in sufficient quantity to encourage some prospecting. Narrow, discontinuous veins, fissures, and joint fillings in the volcanic rocks of Tertiary age have yielded a small amount of manganese oxides; these deposits are probably related to the Tertiary volcanism.

The known thorium deposits in the Powderhorn district are of three principal types: (1) mineralized shear zones (veins) in Precambrian metamorphic rock; (2) layered, carbonate-rich veins filling fissures, particularly in and near the Iron Hill stock; and (3) weakly radioactive zones in nontabular masses of carbonate rock such as the Iron Hill mass. The radioactivity appears to be due almost entirely to thorium and its daughter products. Analyses of 33 samples for uranium and 4 samples for radium showed a maximum of 0.005% uranium and 2.7×10^{-11}% radium. In contrast, the ThO_2 content of 45 samples of various types of radioactive material averaged more than 0.3%, and a selected sample from the Little Johnnie vein contained more than 4% ThO_2.

The mineralized shear zones that cut the Precambrian complex include the most highly radioactive deposits of the district. The shear zones range in width from less than a foot to as much as 18 feet, and in length from a few tens to many hundreds of feet. The Little Johnnie vein has been traced intermittently for more than 3500 feet along strike, and it probably extends for another 1000 feet. Although outcrops are few, exposures in trenches and the pattern of anomalous surface radioactivity between trenches suggest that the zone may consist of several closely spaced en echelon shears.

The mineralized parts of the shear zones are discontinuous, variable in thickness, and commonly contain masses of relatively unmineralized wall rock. The deposits consist of closely spaced irregular veinlets and seams of quartz, iron oxides, alkali feldspar, thorium in the form of thorite or hydrothorite, and other minerals that have been introduced into the fractured rocks. Near the veinlets, the wall rock is greatly altered and commonly shows some replacement by the introduced minerals. In places the mineralized zones contain veinlike masses of coarse-grained barite or carbonate containing minor amounts of pyrite, galena and sphalerite.

Most of the mineralized shears dip steeply and many are nearly vertical, but their strike varies from

one part of the district to another. In general the veins on and near the Little Johnnie claims strike east to northeast, whereas the strike of those in the Dubois-Lake Fork area ranges from northwest to northeast. With the exception of a few exposures underground in adits at Dubois the thorium deposits have not been exposed at depth. However, the length and tabular form of the deposits suggest that many of them persist to depths of hundreds of feet. Thorium-bearing shear zones are exposed in the bottom of Lake Fork Canyon, 1000 feet below exposures of similar veins on the mesa to the east, and the Little Johnnie vein is exposed through a vertical range of more than 700 feet.

Well defined carbonate veins are particularly common in the Iron Hill complex, where they tend to have a crude radial arrangement with respect to the central mass of carbonate rock. The veins range from a few feet to more than 3500 feet in length and from several inches to as much as 15 feet in width; locally the veins contain fragments of wall rock. The great length of some of these veins, the rather even widths, and generally sharp walls suggest that they were emplaced in persistent fractures. Many of the veins have a foliation or banding shown by the concentration of mica, amphibole, and pyroxene crystals in streaks parallel to the walls of the vein. Euhedral prisms of aegirite more than 2 cm long embedded in calcite and arranged perpendicular to the walls in one vein suggest that open filling was a dominant process of vein formation.

Abnormal radioactivity is found in at least two localities in nontabular bodies of the carbonate rock of Iron Hill, at locality 5 (Fig. 1) near the north end of the Iron Hill carbonatite mass, and locality 6 (Fig. 1), in a satellitic mass of carbonate rock about 0.5 mile south of the southwest edge of the Iron Hill carbonatite body. Rare-earth-bearing apatite, mica, and either magnetite or martite are present in the carbonate at these localities.

MINERALOGY

The Precambrian rocks cut by the mineralized shear zones have been strongly fractured, silicified, and iron stained. The Little Johnnie vein which cuts quartz-biotite schist, metarhyolite porphyry, and amphibolite, is typical of many deposits of this type and is described below. Thin sections of the vein material show potash feldspar, albite, and quartz as the dominant constituents. Typically, these are intimately mixed in a fine-grained aggregate clouded with fine hematite, goethite, and some allophane. Euhedral crystals of hematite as much as 0.5 mm across are common, and many are partly altered to goethite. Associated with the hematite and goethite are small subhedral to anhedral masses of thorite or hydrothorite. Apatite, as a felted mat of needles in the feldspar, is abundant in one thin section studied but is rare in two other sections that were examined. Coarse-grained barite and carbonate are abundant in a few places in the vein but were not identified in thin section. Some of the barite fluoresces pink. Accessory minerals in the vein include pyrite, galena, sphalerite, clinozoisite (?), tourmaline, fluorite, and rutile. Small euhedral crystals of a uniaxial positive mineral were tentatively identified as xenotime and probably account for much of the yttrium content of the veins.

The mineralogy of the carbonate-rich veins varies considerably in different veins and in different parts of a single vein. Dolomite is the principal constituent of most of the veins, but calcite, ankerite, and siderite are present in many veins and predominate at some places. Accessory minerals present include apatite, pyrite, chalcopyrite, sphalerite, galena, fluorite, quartz, opal, chalcedony, albite, microcline, orthoclase, phlogopite, several pyroxenes and amphiboles, and other minerals.[1] Barite, bastnaesite, cerite (?), and synchisite (?) and minor constituents. Many of the veins are stained yellow by iron oxides.

RELATION TO THE ALKALIC IGNEOUS ROCKS

Most of the known thorium deposits are near Dubois, near the Little Johnnie claims, and in the Iron Hill complex (Fig. 1), and in each of these areas alkalic igneous rocks are present. Near the Little Johnnie vein the alkalic rocks comprise several small dikes of syenite that consist almost entirely of alkali feldspar; a small stock of augite syenite[3] that contains biotite, microcline, sphene, calcite, and garnet; and a large dike of pigeonite gabbro that contains accessory apatite, orthoclase, and sodic amphibole. Fracture surfaces in the gabbro are coated with films of anatase and brookite associated with minor amounts of aegirite, alkali feldspar, and quartz. Three small carbonate veins and a vein or dike of sodic amphibole rock about 2 inches wide were found on the Little Johnnie claims. The carbonate veins are stained yellowish brown by iron oxides and contain abundant apatite and accessory potash feldspar, quartz, and a green pleochroic pyroxene. The sodic amphibole rock contains abundant pleochroic blue amphibole intergrown with lesser amounts of zeolites, apatite, carbonate, and sodic pyroxene. Dahllite, brookite, aegirite, and zeolites occur in vugs. A comparison of the mineralogy of these rocks and veins with that of the thorium-bearing veins shows that many minerals are common to both.

The relative abundance of certain elements in both the alkalic igneous rocks and the thorium deposits provides a further correlation between the intrusives and associated veins. Larsen[1] demonstrated that Ti, P, Ba, and Sr are present in greater-than-average concentrations in many of the Iron Hill igneous rocks, and spectrographic analyses by the U. S. Geological Survey laboratories has shown that Nb and rare earths are contained in some of the minerals of the alkaline rocks. Rare earths are relatively abundant in apatite in the Iron Hill carbonatite, and in apatite and perovskite from the pyroxenite. The Nb content of the perovskite ranges from 0.x to 0.cx%, and the brookite from the gabbro on the Little Johnnie claims contains 2% Nb.

Table I. Abundance of Certain Minor Elements in Samples of Mineralized Shear Zones and Carbonate Veins

	Number of samples in which element exceeds 0.1%	
*Element**	*Mineralized shear zones (6 samples analyzed)*	*Carbonate veins (8 samples analyzed)*
Ba	6	8
Ti	5	4
Sr	0	4
Th	4	0
La	0	4
Ce	0	4
Nd	0	4
Sm	1	0
Y	3	0
Nb	1	1
P	0	3
V	0	2
Zr	0	2

* Spectrographic analyses by Havens and Barnett, US Geological Survey.

Table I gives the results of semiquantitative spectrographic analyses of vein material from the thorium-bearing deposits. It is apparent that these elements are present in greater-than-average amounts in both the thorium deposits and the associated alkalic igneous rocks, and the spatial and geo-chemical relations of the thorium-bearing veins and the alkalic rocks definitely indicate a genetic tie between them.

The abundance of potash in many of the alkalic rocks outside the Iron Hill complex, in contrast to the relative abundance of soda and lime in the igneous rocks within the complex, has been pointed out by Larsen.[1] Thorium appears to be associated with both the potassic and the soda and lime rocks, but, as shown on Table I, it seems to be more abundant in veins related to potassic rocks. Table I reveals other contrasts between the carbonate-rich veins of the Iron Hill complex and the mineralized shear zones in other parts of the district. Veins in and near the soda- and lime-rich rocks of the Iron Hill complex generally contain more carbonate, Sr, and P than do the mineralized shear zones outside the Iron Hill stock. It may also be significant that the ratio of cerium-group to yttrium-group rare earths is much greater than one in the carbonate veins and the rare-earth-bearing minerals of the Iron Hill rocks but is less than one in the samples of mineralized shear zones in other parts of the district.

EFFECTS OF WEATHERING

The sedimentary rocks of Jurassic age and the Tertiary volcanic rocks were deposited on erosion surfaces of low relief that were closely coincident;[2] generally flat lying Tertiary volcanic rocks rest either directly on Precambrian rocks or on nearly horizontal beds of the Morrison formation. The vein material in deposits near these surfaces has thus been subjected to at least one and possibly two periods of extensive weathering and erosion prior to exposure by the present erosion cycle, which has cut deep canyons in the older surfaces.

During either or both of the premid-Tertiary erosion cycles the veins were jasperized. At some places, the carbonate of the vein material is extensively replaced by jasper as much as 50 to 100 feet below the old surfaces. Several deposits show some evidence of increase in amount of radioactivity, and presumably an increase in thorium content, with depth. The apparent variation may indicate dispersal of some thorium by jasperization, leaching, and oxidation of vein material at and near the present surface, and at least part of this alteration has occurred during the current cycle of erosion.

CONCLUSIONS

Two principal types of thorium-bearing deposits occur in the Powderhorn district: (1) silicified and iron-stained mineralized shear zones in Precambrian rocks; and (2) carbonate-rich veins, filling persistent fissures, which are especially abundant in and near the Iron Hill composite stock. Both types of deposit contain relatively high concentrations of several or all of the following elements: Ti, P, Ba, Sr, Th, Nb, and rare earths; carbonate- and alkali-bearing minerals are common in many of the deposits. The veins are associated with alkalic igneous rocks of pre-Jurassic age that contain abnormal amounts of the elements listed above as characteristic of the veins. The content of minor elements in both the igneous rocks and the thorium-bearing deposits is reflected in their similar accessory mineral assemblages. The spatial and geochemical associations of the alkalic igneous rocks of the district with the thorium-bearing deposits indicate a genetic relationship.

REFERENCES

1. Larsen, E. S., *Alkalic rocks of Iron Hill, Gunnison County, Colorado,* US Geological Survey Professional Paper 197–A: 1–64 (1942).
2. Burbank, W. S. and Pierson, C. T., *Preliminary results of radiometric reconnaissance of parts of the northwestern San Juan Mountains, Colorado,* US Geological Survey Circular 236 (1953).
3. Hunter, J. F., *Pre-Cambrian rocks of Gunnison River, Colorado,* US Geological Survey Bulletin 777 (1925).
4. Cross, W. and Larsen, E. S., *A brief review of the geology of the San Juan region of southwestern Colorado,* US Geological Survey Bulletin 843 (1935).

Uranium- and Thorium-Bearing Minerals in Placer Deposits in Idaho

By J. H. Mackin and D. L. Schmidt,* USA

Placer deposits containing radioactive minerals were investigated in several parts of the Rocky Mountains of central Idaho by the US Geological Survey during the summers of 1952–4.[1] The principal radioactive placer minerals are monazite, euxenite, and thorite; valuable associated minerals are columbite, and xenotime. The study was undertaken primarily to determine the origin of deposits drilled concurrently by the US Bureau of Mines. Earlier reports on gold placers in central Idaho are cited by Reed[2] and Capps.[3]

GENERAL GEOLOGY

The placer deposits lie within and around the borders of the Idaho batholith, a complex of granitic rock units ranging from diorite to granite, mostly Cretaceous in age.[4,5] The batholith and its wall rocks are overlain unconformably by several groups of volcanic rocks: early Tertiary Challis volcanics in the eastern part;[6] mid-Tertiary Columbia River basalt on the west and southwest;[7] and Snake River basalt of Pliocene to Recent age on the south.[8]

Three major topographic elements comprise the physiographic setting of the deposits. The first is a rolling upland surface, with a local relief of 2000 feet (600 m), preserved in divide areas between broad open valleys that stand 5000 to 6000 feet (1500 to 1800 m) above sea level. This late mature surface is sharply trenched by young canyons of the major streams; the canyon cycle was initiated by regional uplift in late Tertiary time.[9] The third element is the north-trending range, with crest lines from 8000 to 10,000 feet (2400 to 3000 m), commonly asymmetric in cross section, and associated on one or both sides with deeply alluviated basins. There is reason to believe that ranges of this type were formed by block-fault movements that occurred from time to time during the Tertiary and continued into the Pleistocene. These three topographic elements may be sharply distinct, or they may blend from place to place depending on the extent of headward erosion of the canyon cycle and the recency of block faulting.

Detail of relief in the higher parts of the region is due largely to the effects of alpine glaciation. Areas above 9000 feet (2800 m) are generally characterized by matterhorn topography. In the 7000 to 9000 (2200–2800 m) altitude zone, individual and coalescing cirques are cut in the flanks of rounded summits. Lower parts of the late mature upland were not glaciated during the late Pleistocene.

Moraines and outwash deposits on floors of some of the upland valleys indicate two late Pleistocene glacial stages. The younger of the two is represented by hummocky, boulder-strewn morainal ridges, clearly late Wisconsin. The deposits of the older stage are characterized by subdued morainal forms and a degree of weathering suggesting an early Wisconsin age. A few widely scattered deposits of deeply decomposed till indicate a much greater extent of alpine glaciers during early Pleistocene time, but subsequent erosional modification of the region has been so complete that the effect of early Pleistocene glaciers on the geology of the placer deposits is negligible. For this reason, areas beyond the limits of early Wisconsin glaciers will be referred to as nonglaciated.

An essential requirement of a commercial placer deposit of the Idaho suites of radioactive minerals is a depth and extent of material capable of supporting a large scale dredging operation over a period of years. Detailed investigations were therefore limited to thick alluvial fills, each of which is due to some local reversal of the normal process of stream downcutting. The principal causes of accumulation of the valley fills, and examples of each are: (1) block faulting during Pleistocene time (monazite placers in the Cascade area); (2) late Pleistocene glacial derangement of drainage (euxenite-monazite placers of Big Meadow in the Bear Valley area; and (3) blocking of drainage lines by Pleistocene basalt flows (thorite placers in the Hailey area) (Fig. 1). A contributing cause of valley fill was an increase in the loads of streams due to accelerated downslope movement of the weathered mantle under periglacial conditions during Pleistocene glacial stages.

RADIOACTIVE MINERALS IN BEDROCK

Monazite is the most widespread radioactive mineral in the granitic rock of the Idaho batholith. Reconnaissance pan sampling of minor streams and of weathered granitic rock over most of the southern part of the batholith indicates that monazite is more often present than not and that its gross distribution is nonuniform. The distribution of the monazite placer deposits drilled by the US Bureau of Mines, at Cascade near the western border of the batholith,

* US Geological Survey.

at Bear Valley in the interior, and at Victor and Stanley near the east border, indicates the scatter of the richer bedrock source areas (Fig. 1).

In the drainage basins from which the monazite of the Cascade placers was derived the mineral occurs as an accessory in a porphyritic granitic rock in the quartz diorite-quartz monzonite compositional range. The distribution is exceedingly erratic in detail, ranging from essentially zero to as much as 0.3 pound per cubic yard (0.18 kg/m^3, 0.01%) within a few tens of feet in apparently uniform granitic rock. There is no evident spacial relationship between the distribution of the monazite and pegmatite or aplite dikes, or quartz veins. The common associated heavy accessories are magnetite, ilmenite, garnet, apatite, and zircon; there is no consistent relationship in the abundance of any of these minerals with the abundance of monazite.

The gross yield of a given drainage basin, as indicated by stream panning, appears to be a function of the number and richness of the local segregations of monazite in the granitic rock—the term segregation being used with a descriptive rather than a genetic meaning. The gravel of small streams heading in rich source areas may contain as much as 10 pounds of monazite per cubic yard (6 kg/m^3). By the same gross standard of tenor of stream deposits, the belt of migmatitic gneiss into which the granitic rock grades along the western border of the batholith is very nearly barren of monazite. However, local quartz-feldspar pods in the gneiss contain as much as 0.5 pound per cubic yard (0.3 kg/m^3, 0.02%). Massive monazite replacements in phosphatic marble in the migmatite zone along the eastern border of the batholith, described by Abbot[10] have not been seen in the area covered by this study.

Euxenite occurs in trace amounts in several localities widely scattered over the batholith. The only commercial placers now known in Bear Valley are supplied from a 6-square-mile (15-km) area of quartz diorite. The euxenite occurs as an accessory mineral in the granitic rock and in associated pegmatite dikes. The distribution in the granitic rock is spotty—pan samples of deeply weathered rock in a single exposure may range from a trace to 0.05 pound of euxenite per cubic yard (0.03 kg/m^3, 0.002%), with the good values sharply localized within an outcrop area of a few square feet. As with monazite, the yield of a given small drainage basin depends on the number and richness of the segregations. Associated heavy minerals commonly include monazite, magnetite, ilmenite, and zircon, and may include apatite, allanite, columbite, xenotime, and spinel. Well washed gravel in favorably situated small streams may contain as much as three pounds of euxenite per cubic yard (2 kg/m^3).

As far as is now known throite occurs in significant amounts only in an inlier of the Idaho batholith, or a satellite intrusion, in the vicinity of Hailey, Idaho. The thorite is an accessory mineral in quartz monzonite, with the same habit as the euxenite of Bear Valley, that is, it occurs in small segregations in rock not distinguishable megascopically from the surrounding rock. The segregations may contain as much as one pound of thorite per cubic yard (0.6 kg/m^3, 0.04%), while the adjacent quartz monzonite averages 0.005 pound per cubic yard (0.003 kg/m^3, 0.0002%). Common associated heavy accessories are magnetite, sphene, hornblende, and apatite. Less abundant accessories include ilmenite, garnet, zircon, allanite, anatase, and rutile. Gravel deposits of small streams draining the richest source area contain as much as 0.3 pound of thorite per cubic yard (0.2 kg/m^3).

The origin of the radioactive minerals is an open question. The field relations and relations observed in thin sections favor the view that they were formed at the same time as the enclosing rock, rather than by later hydrothermal solutions. Monazite is associated with euxenite in the Bear Valley area, but the monazite-rich rock of the Cascade, Victor, and Stanley areas contains only trace amounts of euxenite or none at all. Euxenite and thorite have the same habits of occurrence as accessories in granitic rock, but there is no thorite in the euxenite-rich rock of the Bear Valley area, and no euxenite in the thorite-rich rock of the Hailey area. The thorite-rich rock of the Hailey area contains no monazite. In view of the favorable scatter of the areas studied in detail and the reconnaissance sampling done between the areas, any systematic distribution of the radioactive minerals within the batholith should be apparent. But the batholith is a composite mass, consisting in part of granitic rocks of metasomatic origin and in part of orthomagmatic intrusions emplaced at different times. Much more extensive and detailed study of the distribution of heavy-mineral suites in the batholith, particularly with respect to the boundaries between units of different rock type, origin, and age, is needed before any definitive statement can be made as to the occurrence and origin of the radioactive minerals.

EFFECT OF GLACIATION ON THE SUPPLY OF PLACER MINERALS

The effective concentration of heavy minerals in placer deposits requires: (1) disintegration of the source rock sufficient to free the heavy minerals; (2) residual concentration of the heavy minerals by removal of the readily soluble and some of the light minerals by weathering and erosion; and (3) an accelerated movement of the thus enriched mantle to the streams.[11] Primarily for these reasons, the distribution of late Pleistocene glaciers is thus a critical factor in the localization and tenor of the Idaho placer deposits.

Gravel in the deposits of streams draining nonglaciated areas commonly consists of vein quartz and various resistant dike-rock types; the granitic rock, which makes up more than 99% of the drainage basin, is represented only by coarse sand. In the Bear Valley area, for example, alluvium deposited

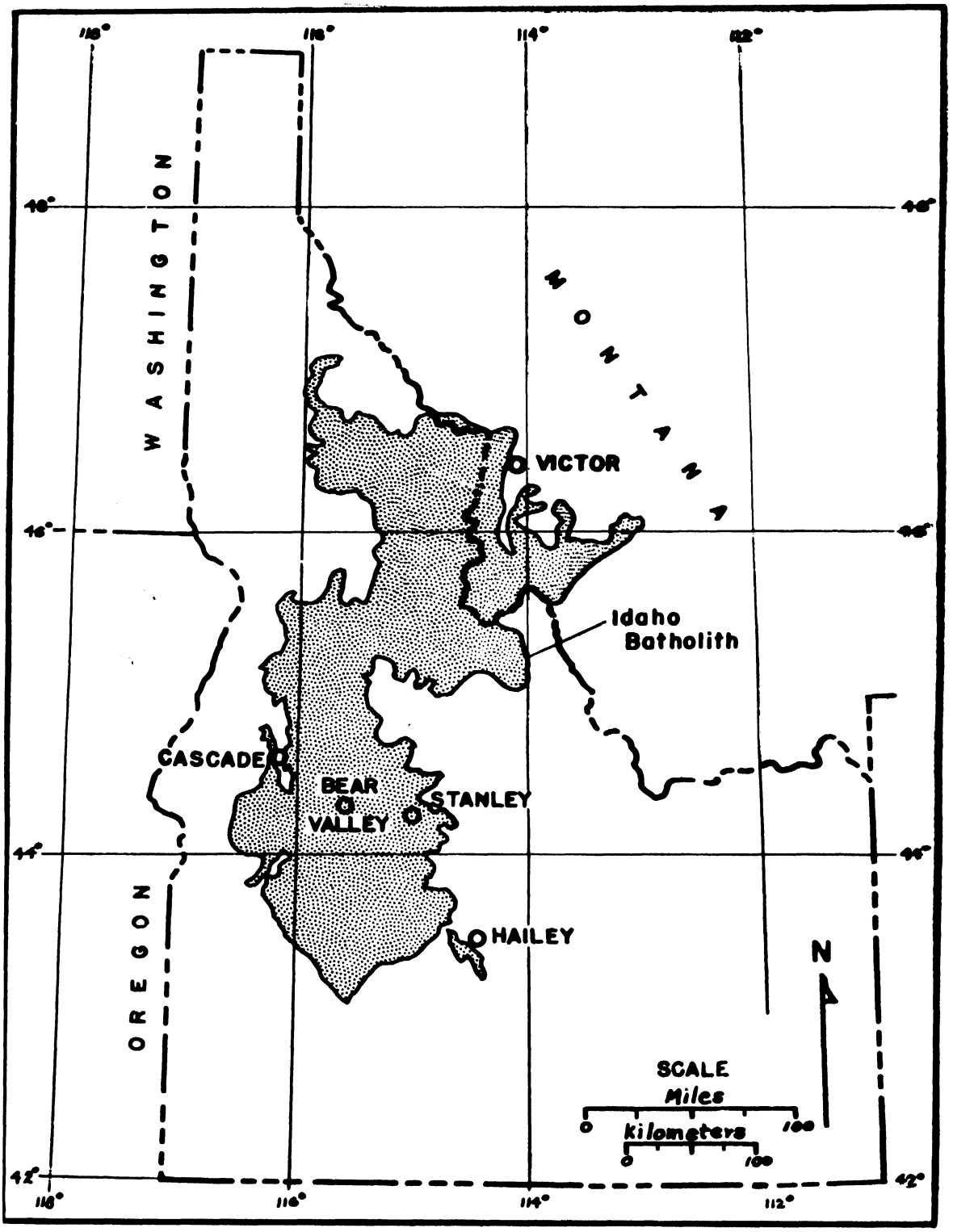


Figure 1. Index map of Idaho

by minor streams entering Big Meadow from non-glaciated terrane during the early Wisconsin glacial stage averages 30 pounds of heavy mineral concentrate per cubic yard (18 kg/m^3). This high concentration is believed to be due to the thorough weathering of the bedrock during mid-Pleistocene time, and a quickened downslope movement of the enriched mantle under periglacial climatic conditions during the early Wisconsin. On the other hand, outwash deposits formed by streams entering Big Meadow from early Wisconsin glaciers, and the morainal deposits of these glaciers, consist predominantly of subrounded fragments of granitic rock, and average only 20 pounds of heavy-mineral concentrate per cubic yard (12 kg/m^3); probably this concentration is lower than in the alluvium from the neighboring

nonglaciated area because some of the heavies are still locked up in the granitic pebbles. Late Wisconsin moraines and outwash deposits from the same drainage basins average 10 pounds of heavy concentrates per cubic yard (6 kg/m^3). The difference between the amount of heavy mineral concentrate in early and late Wisconsin deposits is probably due to the fact that a deep regolith, formed during a long period of preWisconsin weathering, was available to the early Wisconsin glaciers, while erosion by the smaller late Wisconsin glaciers was confined within cirque basins that had been, shortly before, scoured in fresh bedrock by early Wisconsin ice.

Panning of large numbers of samples of deposits derived from nonglaciated drainage basins, early Wisconsin deposits, and late Wisconsin deposits, gives comparable average results in the other areas covered by this study. The ratio of the amount of total heavy-mineral concentrate in the three types of material is approximately 3:2:1.

EFFECT OF AGGRADATION ON THE TENOR OF THE PLACER DEPOSITS

Changes in stream velocity accompanying seasonal variations in discharge cause cycles of scouring and redeposition of the alluvial materials comprising the channel floor, each time with a winnowing of the materials on the basis of particle size and, within any given size range, on the basis of specific gravity and shape.[12] Because the vigor of this process varies greatly from place to place in the channel, and because of sidewise shifting and changes in alignment of the channel, the deposit is an aggregate of lenses differing markedly in degree of sorting. The lenses of gravel may contain as much as 100 times the amount of heavy-mineral concentrate as adjacent lenses of sand.

In streams that swing back and forth across valley floors for a long period of time with little change in grade, repeated reworking of the valley-floor alluvial deposit tends to develop concentrations of heavy minerals far higher than the average proportions of these minerals in the detritus annually delivered from the slopes of the drainage basin. In aggrading streams, on the other hand, this type of sorting is less effective because some part of the load handled each year is deposited in the accumulating fill where it is not subject to reworking. As the amount of material thus deposited in a given segment of the stream per year approaches the amount of material shed into that segment each year from the local valley sides or from the next upvalley segment, the winnowing action approaches zero. For this reason, other things being equal, the concentration of heavy minerals tends to be higher in deposits of graded streams than in deposits of aggrading streams, and in the latter, the concentration tends to be inversely proportional to the rate of aggradation. In the Cascade area, for example, deposits of modern streams that are stable or slowly degrading are consistently higher in heavy-mineral concentrate than aggradational deposits in the same area formed during Pleistocene time by similar streams.

DOWNVALLEY CHANGES IN COMPOSITION OF THE HEAVY-MINERAL SUITES

Changes in the total concentrate and in the proportions of the different heavy minerals downstream from the source area are due principally to selective transportation, dilution, selective attrition, and selective weathering during periods when the detritus is temporarily at rest on the valley floor. Commonly two or more of these processes are in operation in the same stream at the same time. The following discussion is based on observations of stream segments in which it was possible, under favorable conditions, to arrive at an approximate evaluation of each of the different processes.

In the selective sorting process outlined earlier the average rate of movement of the heavy minerals along the stream bed, over a period of years, is slower than that of the light minerals in the same size range. But in a graded stream, in which the channel deposits mantling the valley floor are reworked over and over again as the stream shifts laterally, this "running ahead" of the light minerals does not cause a change in the composition of the sand fraction of the bed load in a downstream direction. The heavy minerals move more slowly into a given segment of the valley, but they also move more slowly through and away from that segment, and the average composition of the sand fraction of the channel deposits is the same as though all the grains moved at the same rate.

In the aggrading stream, on the other hand, the heavy-mineral grains, which are last lifted and first deposited in the seasonally expanding and contracting channel, actually lag behind the light grains because the raising of the level of the stream bed means that the deposits are not subject to continuous reworking. There is, in other words, a "permanent withdrawal from circulation" of the slower moving portion of the bed load, and a resultant decrease in the proportion of the heavies in the sand fraction in a downvalley direction.

Monazite serves best to bring out this relationship because the other factors, such as attrition, which affect the survival of this mineral are negligible in any limited travel distance. In the Bear Valley and Cascade areas, where drilling data permit a comparison, the content of monazite decreases by 50% in a distance of a mile (1.6 km) in Pleistocene valley-fill deposits, while there is no significant change in the content of monazite in the same distance in modern valley-floor deposits formed by graded streams.

Reduction by dilution in the percentage weight of a given placer mineral in the heavy-mineral concentrate may be due to the entry of side streams, which erode rocks low in the heavy minerals, or to the sidewise cutting of the trunk stream in bedrock or in older deposits containing lesser amounts of that mineral. The quantitative effects of dilution by side streams are obvious and need no discussion. The effect of exchange between the bed load and the materials comprising the banks is well shown on

Bear Creek, where the reduction in the percentage weight of monazite is about twice as rapid in a segment where the creek is cutting laterally in barren glacial outwash as where the stream is meandering in its own alluvial deposits. It is evident that any general evaluation of the dilution effects of exchange must be in terms of the rate of bank cutting.

Monazite is in all respects the most durable of the radioactive placer minerals of central Idaho. In the Cascade area, for example, this mineral can be traced in alluvial deposits from a well-defined source for a distance of 25 miles (40 km) through areas from which local contributions of monazite to the stream are negligible. Monazite grains in pan samples in headwater rills in the source area are euhedral crystals and angular fragments of crystals in the 0.2–1.0 mm size range. The grains are very slowly rounded in transit along the streams. The median grain size decreases only by an estimated 50% in 25 miles (40 km) of stream travel, and an unknown but perhaps considerable part of this decrease in size may be due to selective transportation rather than to attrition. Even at this distance from the source, some of the grain boundaries are crystal faces.

Euxenite panned from residual soil in the Bear Valley area is in the form of euhedral crystals and angular fragments of crystals with a very wide range in grain size, from 0.1 to 5.0 mm. The grains in the soil commonly carry a tan coating of gummitic material of the order of 0.01 mm in thickness; the fact that the degree of coating decreases downward through the soil profile indicates that it is due to weathering. It is removed from the edges and flat surfaces of the grains within the first 1000 feet (300 m) of travel along stream beds, remaining only in re-entrant angles of irregular microfissures that characterize this mineral.

The average size of the larger euxenite grains decreases by 3 to 4 times, from 5.0 mm to 1.5 mm, within the first mile (1.6 km) of movement along the stream beds. Five miles (8 km) from the source area the average larger grain size is 0.8 mm, and very few of the larger grains show crystal faces. In another five miles (8 km) the larger grains are reduced to about 0.5 mm. The next 15 miles (24 km) of travel causes little further reduction in size. The very rapid decrease in the size of the larger grains in the first ten miles (16 km) of transportation (from 5 mm to 0.5 mm) is due primarily to breakage under the impact of pebbles and boulders—the tendency of euxenite to shatter readily is probably due in part to microfissuring associated with the metamict state of the mineral. Because the finer particles produced by shattering move with the suspended load, the percentage weight of euxenite in the placer deposits decreases much more rapidly in a downvalley direction than the percentage weight of the less brittle heavies, as monazite.

The minerals of the thorite group occur in the residual soil and placer deposits of the Hailey area as crystals and fragments of crystals, euhedral to subrounded, ranging from 0.1 to 1.5 mm in greater dimension. The minerals vary widely in physical properties; the several varieties, probably including uranothorite and orangite, cannot be identified by sight in the pan concentrates. Field estimates of tenor were therefore based largely on scintillation-counter readings. A sharp decrease in tenor downvalley from the source area is certainly due in part to attritional wear, but it is also due in part to dilution and other factors. The laboratory studies needed for an evaluation of the factors have not been completed.

Although there are variations from place to place, magnetite and ilmenite are present in approximately equal amounts in residual soils and headwater stream deposits in the granitic terranes, where these two minerals usually make up about 90% of the total heavy-mineral concentrate. But placer deposits formed by trunk streams draining the same areas may contain only a few per cent of magnetite in a heavy-mineral concentrate consisting predominately of ilmenite. Because magnetite is the least valuable of the heavy minerals, its drastic reduction in percentage weight in the concentrate has the effect of a natural beneficiation, and is therefore a matter of considerable practical importance.

A first clue to the manner of destruction of the magnetite is provided by the fact that a stream entering a wet mountain meadow with a magnetite-ilmenite ratio of 1 :1 may lose nearly all of its magnetite within a mile (1.6 km) of meandering on the meadow floor. Upstream from the meadow the magnetite is in the form of angular to subrounded crystals and grains with or without a film of hematite developed by oxidation in the normal weathering process. Samples of gravel taken from below the water table under the meadow-peat layer show no magnetite, or show only deeply pitted, skeletal grains with no hematite coatings—the associated sand and gravel are notably bleached. Numerous pH determinations of the meadow ground water range from 6.2 to 5.5 and average 6.0, in contrast with a fairly consistent 7.1 for the stream water. The relationships indicate that the magnetite is dissolved by the semi-stagnant acid water under the peat that mantles the flood plain. The vigor of the process is suggested by the fact that, at places where the meadow water is aerated as it seeps out from fresh meander cuts in the bleached gravel, a thick layer of ochreous ooze accumulates within a period of a few months. It should be noted that the reduction in the amount of magnetite along the channel is not in any sense due to destruction of the mineral in the channel environment—it is due wholly to exchange, incident to lateral shifting of meanders in alluvium, in which the magnetite is destroyed by acid water.

Several lines of evidence, too involved for discussion here, indicate that in a wet-meadow peat environment, the percentage of magnetite in the heavy-mineral suite in a gravel deposit may be reduced very nearly to zero in a few hundred years.

AVERAGE HEAVY-MINERAL COMPOSITION OF THE PLACER DEPOSITS

The heavy-mineral composition of the placer deposits is dependent on the mineral content of the source rock and on several physiographic factors bearing on concentration, namely, preliminary eluvial concentration by selective weathering, differences in the effectiveness of channel concentration in graded and aggrading streams, selective transportation, dilution, selective attrition, and selective weathering during periods when the detritus is temporarily at rest on the valley floors. In the Bear Valley area, alluvial fills formed as a result of glacial derangement of drainage contain the following quantities of heavy minerals in pounds per cubic yard (kg/m^3) : euxenite 1.0 (0.6) ; monazite 0.5 (0.3) ; columbite 0.2 (0.1) ; zircon 0.05 (0.03) ; garnet 5 (3) ; ilmenite 20 (12) ; and magnetite 5.0 (3.0). In the same terms, the heavy-mineral content of deposits in valleys blocked by Pleistocene basalt flows in the Hailey area is as follows: thorite 0.5 (0.3) ; zircon 0.5 (0.3) ; sphene 1.0 (0.6) ; garnet 0.1 (0.06) ; and magnetite 10 (6.0). The Cascade deposits, which accumulated in a basin formed by block faulting during Pleistocene time contain: monazite 1.5 (0.9) ; zircon 0.2 (0.1) ; garnet 5.0 (3.0) ; ilmenite 40 (24) ; and magnetite 1.0 (0.6).

REFERENCES

1. Mackin, J. H. and Schmidt, D. L., *Placer Deposits of Radioactive Minerals in Valley County, Idaho* [abstract], Geological Society of America Bulletin 64, 2: 1549 (1953).
2. Reed, J. C., *Geology and Ore Deposits of the Warren Mining District, Idaho County, Idaho,* Idaho Bureau of Mines and Geology, Pamphlet 45 (1940).
3. Capps, S. R., *Gold Placers of the Secesh Basin, Idaho County, Idaho,* Idaho Bureau of Mines and Geology, Pamphlet 52 (1938).
4. Ross, C. P., *Some Features of the Idaho Batholith,* Sixteenth International Geological Congress Report: 369–385 (1936).
5. Anderson, A. L., *Multiple Emplacement of the Idaho Batholith,* Journal of Geology 60: 255–265 (1952).
6. Ross, C. P., *Geology and Ore Deposits of the Bayhorse Region, Idaho,* US Geological Survey Bulletin 877: 1–161 (1938).
7. Kirkham, V. R. D. and Johnson, M. M., *The Latah Formation in Idaho,* Journal of Geology 37: 483–504 (1929).
8. Stearns, H. T., Crandall, L. and Steward, W. G., *Geology and Ground-Water Resources of the Snake River Plain in Southeastern Idaho,* US Geological Survey, Water-Supply Paper 774 (1938).
9. Fenneman, N. M., *Physiography of Western United States,* McGraw-Hill Co., Inc., New York: 185–196 (1931).
10. Abbot, A. T., *Monazite Deposits in Calcareous Rocks, Northern Lemhi County, Idaho,* Idaho Bureau of Mines and Geology, Pamphlet 99: 21–22 (1954).
11. Jenkins, O. P., *New Technique Applicable to the Study of Placers,* California Journal of Mines and Geology 31, no. 2: 153–210 (1935).
12. Mackin, J. H., *Concept of the Graded River,* Geological Society of America, Bulletin 59: 463–512 (1948).

Monazite in Southeastern United States

By W. C. Overstreet, N. P. Cuppels and A. M. White,* USA

Monazite-bearing crystalline rocks follow two narrow belts in southeastern United States.[1] A long western belt leads northeastward from the inner edge of the Coastal Plain deposits in central Alabama across the Piedmont of Georgia, South Carolina, and North Carolina to the inner edge of the Coastal Plain sediments in northeastern Virginia. A short eastern belt extends northward from central North Carolina to the western belt in Virginia. The two belts are 550 and 200 miles long south of their junction and 50 miles long northeast of the junction.

Detrital monazite derived from crystalline rocks in the western belt has wide geographic distribution in the Piedmont and Coastal Plain. Monazite was mined on a small scale from colluvial and alluvial placers in the Carolinas along the western belt between 1887 and 1917 in which year the domestic industry succumbed to lower priced, imported monazite. Little is known of alluvial placers along the eastern belt or of the role of the belt as a source for monazite found in Coastal Plain sediments.

MONAZITE IN SEDIMENTARY ROCKS

Detrital monazite has been found in residual soil mantling monazite-bearing crystalline rocks in the Piedmont, in colluvial and alluvial sediments deposited in or downstream from the belts, and in Cretaceous to Recent sediments across the Coastal Plain.

Residual deposits consist of clayey sand and rock fragments that have accumulated on interstream divides through the disintegration of saprolite. Residual deposits grade down slope into poorly sorted, unconsolidated, colluvial sediments the most typical and widespread of which are sheet-wash deposits that unconformably overlie the crystalline rocks. Colluvium is commonly a clayey sand and is underlain by a thin layer of quartz pebbles. The colluvial deposits range widely in stratigraphic position and age: they grade into, are truncate dby, or lap upon alluvial fill in the valleys; some are of possible pre-Wisconsin age,[2] and other deposits are obviously forming at the present time.

Processes forming colluvial sediments and residual deposits have produced an initial concentration of monazite greater than that obtaining in bedrock, and where these deposits are reworked by the streams the resulting alluvium is of higher tenor than sediment derived directly from saprolite. Rarely, some colluvial sediments are eluvial placers that contain monazite in concentrations 10 to 15 times greater than its abundance in the underlying rock.

Placers in alluvial sediments deposited in valleys along the western monazite belt in North and South Carolina are the historic source of monazite in southeastern United States. Within the belt the valleys are typically small; large valleys are common on either side of the belt, but those on the west are barren of monazite, and the ones on the east, which have collected part of their fill from the belt, are poor in monazite. Sediments filling the valleys are finer grained in the eastern and southern parts of the belt than in the western and northern parts. Age of the alluvium, as determined by pollen and C^{14} analyses, is post-Wisconsin except for a few late Pleistocene deposits that survive in isolated upland depressions where they have escaped erosion. Sand and silt make up about 65% of the alluvium, clay is 25% of the total, and gravel is 10%.

Stream sediments possess a rude uniformity in stratigraphic sequence that, from top to bottom, commonly is: sandy silt; silt; sand; clay; gravel; then bedrock. These units vary in composition and appearance, but some properties are consistent.

The sandy silt is red-brown to brown and has the most uniform composition and distribution of the sediments in the monazite belt. Where it is particularly well stratified it is generally more sandy than at its massive exposures. A layer of buff, brown, or gray silt, whose color varies horizontally in a few feet underlies the red-brown sandy silt. Particles the size of silt and clay are dominant, and, as depth below the flood plain increases, the amount of clay increases. Sand is the most abundant sediment, but it is neither the most persistent nor the most uniform. It is buff, brown, gray, or white in color and ranges in grade through all classes from granule sand to very fine sand. At most places it occurs as lenticular or prismatic bodies, but it may be absent, or it may be the only sediment in a valley. The clay near the bottom of the sedimentary sequence has the widest range of physical characteristics. In some places it is blue gray and has a uniform texture; elsewhere it is a dark gray or black muck containing abundant fragments of fresh or carbonized wood and peaty vegetal debris. Clay in many exposures contains fine, white sand and scattered, angular quartz pebbles. It almost invariably overlies the basal gravel, or if that is absent, lies on bedrock. At the bottom of

* US Geological Survey.

the sequence is a quartz-pebble gravel with minor amounts of feldspar and rock fragments bound in a matrix of white, yellow, or buff sandy clay. All degrees of angularity are represented among the components with subangular to subrounded fragments most abundant. Distribution of the gravel is irregular; in any valley the gravel is persistent but irregular in thickness close to the head of the stream, but farther downstream it is discontinuous and thin.

The paucity of coarse sediments results from the scarcity of coarse detritus available for alluvial deposition in the Piedmont, where deep chemical weathering has reduced most of the rock to saprolite. Saprolite underlies 85% of the valley floors and is even more abundant along the valley walls. In these areas only rare fragments of unweathered rock and quartz from veins and pegmatite are available to form gravel.

The richest concentrations of monazite in the belt are in gravel and coarse sand near the base of the sedimentary sequence, but monazite is present in the alluvium from grass roots at the top of the fill to bedrock at the bottom. Silt and clay carry only small concentrations of monazite, which explains the low average tenor of large downstream flood plains where gravel may be buried under 20 feet or more of fine-grained sediment. The abundance of monazite can be related to the way the sediment was deposited: the least monazite is in sediments dropped from suspended load in water spread out on flood plains during periods of overbank flooding; the most monazite is in coarse material left in the channels during normal stream action.

The mineralogic composition of concentrate taken from alluvium is determined by the kinds of rocks in the distributive province of the stream and by the mode of deposition of the sediment from which the concentrate is recovered. What might be called an average concentrate from the monazite belt consists, in order of abundance, of ilmenite, garnet, monazite, sillimanite, zircon, and rutile. If the stream drains areas underlain by metamorphic rocks of lower rank than those typical of the belt, or includes some intrusive masses of basic igneous rocks, minerals such as staurolite, kyanite, epidote, magnetite, and hornblende enter the concentrate. Along the margins of the belt the increase in these minerals is notable. The mode of deposition of the sediment from which the concentrate is recovered influences the relative abundance of the heavy minerals: at the same point in a stream, sediment deposited from suspended load will contain higher proportions of the semiheavy minerals than will sediment moved in the traction load. Thus a silt or clay will contain proportionately more sillimanite, kyanite, epidote, staurolite, garnet, and hornblende than will coarse sand or gravel from the same part of the stream.

Monazite placers in the Carolinas were mined by hand in the late 1800's and early 1900's. Even though the industry failed in 1917, none of the stream beds were permanently depleted by mining because every rain swept additional monazite into the valleys. Surface runoff from cultivated fields in monazite-rich areas replenished some streams with enough monazite to permit their channels to be profitably rewashed every few years. Streams with narrow valleys bordered by tilled hillsides could be mined every year, and sundry small creeks were reworked after every hard rain.

Weathered and unweathered crystalline rocks in the Piedmont plateau are overlain to the east and south by loosely consolidated Cretaceous and Tertiary sediments of the Atlantic Coastal Plain. These nearly horizontal beds of sand, silt, clay and marl have an exceedingly sinuous contact with the crystalline rocks along the Fall Line. Locally, where the Coastal Plain sedimentary beds have been removed and an old, weathered surface of the crystalline rock re-exposed to erosion, the inland edge of these beds makes a northwest-facing scarp.[3] The Cretaceous and Tertiary sediments have served as intermediate hosts for monazite between the crystalline source rocks and alluvial and littoral placers on the Coastal Plain.

Alluvial placers are in Wisconsin(?) and later fluvial deposits in the valleys of streams draining Cretaceous sediments near the landward side of the Coastal Plain. These fluvial deposits are debris reworked from the Cretaceous sediments and contain the same heavy minerals—but in greater abundance —than the Cretaceous sand. Ilmenite, rutile, monazite, zircon, staurolite, kyanite, and sillimanite are the dominant minerals; magnetite is rare; and epidote, hornblende, and garnet are absent.

The littoral placers are late Pleistocene to Recent deposits of well sorted sand that generally rest about 30-50 feet above sea level but include deposits as low as the present beaches and as high as 250 feet above sea level. They are on the seaward part of the Coastal Plain and preserve recognizable features of beaches, dunes, spits, and bars.

The composition of heavy-mineral suites from the Coastal Plain deposits, especially Pleistocene and Recent sediments, has recently been investigated over wide areas by Dryden and Miller[4] who report that Cretaceous, Tertiary, and the older Pleistocene deposits lack hornblende, epidote, and garnet, but that these minerals are common, often dominant, in younger Pleistocene and Recent deposits. According to Dryden and Miller, the most probable explanation for the absence of epidote, hornblende, and garnet from the older sediments is the leaching of these minerals from the source rocks in the Piedmont by profound weathering with possibly some postdepositional leaching. A study of modern saprolite in the Piedmont shows that, though hornblende and garnet are vulnerable to saprolitic weathering, both are present in exposed saprolite. Epidote appears to be unaffected. Thus deep weathering of the Piedmont could have reduced the quantity of garnet and hornblende entering the Coastal Plain and possibly could have deprived the sediments of these minerals. The effect of leaching subsequent to deposition is shown

in the reduced proportion of hornblende, epidote, and garnet in Pleistocene deposits over that in modern sediments in the same valleys in the western monazite belt. The relative importance of the two processes has not been evaluated.

Ilmenite deposits with scant monazite are the only commercial placers that are being worked in the Coastal Plain at the present time. None of the colluvial, alluvial, or littoral deposits are monazite placers. Except in rare areas where the deposits have been reworked, monazite constitutes less than 0.1% of the sediment. In general the proportion of monazite to other heavy minerals is greatest in alluvial placers along small streams draining crystalline rocks in the western monazite belt, but the highest-tenor, large-volume deposits are the alluvial placers in streams that rework Cretaceous sediments at the west edge of the Coastal Plain. The littoral placers have the lowest proportion of monazite.

MONAZITE IN CRYSTALLINE ROCKS

The discussion will be restricted to the western monazite belt. The geology of the eastern belt is practically unknown.

The western monazite belt possesses regional tectonic and metamorphic symmetry. It lies in a zone of injection gneiss whose northwestern edge is discontinuously bounded by a narrow belt of phyllite and low-grade metamorphic rocks called the Brevard schist.[5] Its southeastern edge is partly defined by somewhat similar low-grade metamorphic rocks called the Pine Mountain series in Georgia[5] and the Battleground schist, Kings Mountain quartzite, and Blackburg schist[6] in North and South Carolina. Neither of these narrow belts of low-rank metamorphic rocks continues the full length of the monazite belt: they are absent or unrecognized northeast of central North Carolina. Both the Brevard schist and the Pine Mountain series are separated from the zone of injection gneiss by faults. The Brevard schist and the Battleground schist, Kings Mountain quartzite, and Blackburg schist are regarded as groups of synclinally depressed younger sediments resting unconformably on the older injection gneiss, but, though the structure appears to be well defined, the unconformities and age relations are not so clear. The Pine Mountain series, which is anticlinally folded, is thought to be younger[7] than the injection gneiss of the monazite belt.

The zone of injection gneiss includes metamorphosed sedimentary rocks, metamorphosed basic rocks in part of igneous origin, intrusive granitic bodies, and diabase dikes. No indisputable relict bedding has been generally recognized though it has been seen locally and is suggested by compositional layering in the metamorphosed sedimentary rocks. Basement rocks on which the gneisses rest have not been discovered.

The original sediments deposited in the zone of injection gneiss were not uniform in composition. Northeastward along the strike psammitic sediments appear in the pelites, and westward across the strike there is an increase in the abundance of calcareous sediments and basic volcanic rocks. Some layers, probably originally arkosic, are richer in potash than others.

These original sediments were affected by a progressive regional metamorphism that increases westward across the strike to the central core of a metamorphic climax, then declines. The central core, which is at least 300 miles long and 20–25 miles wide, is the area of highest grade regional metamorphism attained in the Piedmont: the sillimanite-garnet subfacies of the amphibolite facies. Where conditions of less temperature and pressure obtained between the central core and the Brevard schist and Battleground schist, the regional metamorphism produced muscovite schist and biotite-muscovite schist from sediments of the same composition that became sillimanite schist in the core. These lower rank rocks are characterized by such accessory minerals as staurolite, kyanite, epidote, and magnetite, whereas in rocks at the core the typical accessory minerals are sillimanite, ilmenite, rutile, garnet, and monazite. Bordering the sillimanitic core are rocks of the staurolite-kyanite subfacies of the amphibolite facies, and in the northeastern part of the western belt at the border between North Carolina and Virginia the rocks decline in metamorphic grade to the greenschist facies.

The injection gneiss complex is formed by the intrusion of masses of concordant, gneissic, synkinematic quartz monzonite and related bodies of pegmatite and quartz veins into sillimanitic and isofacial sillimanite-free rocks at the core of the belt. Intruded into the rocks of the staurolite-kyanite subfacies between the sillimanitic core and the Brevard schist and Battleground schist are concordant to discordant, massive to gneissic, postkinematic plutons. They are mainly quartz monzonite in composition and were introduced under temperatures and pressures that were lower than those reached at the core during emplacement of the synkinematic rocks. The widespread injection phenomena typical of the sillimanitic core are absent from the staurolite-kyanite zones.

The injection gneiss formed by the synkinematic plutons and the sillimanitic or isofacial rocks at the core of the belt are the chief sources of monazite in the Piedmont. The surrounding lower rank metamorphic rocks are poor sources of monazite; it is sparse and sporadically distributed in the postkinematic rocks. Striking differences in the composition of monazite from the synkinematic plutons and the eastern postkinematic plutons have been detected, but the composition of monazite from the western postkinematic plutons has not been determined.

It seems probable that the origin of the western monazite belt is closely related to the tectonic and metamorphic history of the area. The attitude of the sillimanite zone and its flanking staurolite-kyanite zones between the narrow synclinal depressions of the Brevard and Battleground schists suggests a broad, much contorted geanticline. The sillimanite zone and the monazite belt are parallel and coincident: the highest concentrations of monazite are

in the core of the sillimanite-garnet zone; as the staurolite-kyanite zones are entered, monazite decreases markedly in abundance, and in the greenschist facies no monazite-bearing rocks are found. In the sillimanite-garnet zone magnetite is virtually absent; it makes a strong entry in metamorphic rocks in the staurolite-kyanite zone and in posttectonic granitic rocks intruded in the zone, and is a prominent accessory in the greenschists. From these mineralogic and spatial relations the following hypothesis for the origin of the western monazite belt is suggested.

The western monazite belt and its flanking staurolite-kyanite zones represent the metamorphosed product of a sequence of marine sediments that has been folded into a northeasterly elongated geanticline. It is an uplift of tightly compressed isoclinal folds that are generally overturned to the northwest. In the core of the geanticline, where syntectonic rocks were emplaced at the peak metamorphic pulse reached in the Piedmont, the conditions of temperature and pressure promoted precipitation of the rare-earth phosphates during crystallization of the granitic rocks and metamorphic differentiation of the sediments. Thus the tectonic and metamorphic pulses established the position and trend of the belt by promoting the conditions under which monazite crystallizes. In the staurolite-kyanite zone the temperatures and pressures obtaining during emplacement of late syntectonic and posttectonic granitic rocks did not promote the precipitation of monazite: most of the available rare earths and thorium were collected by other accessory minerals, such as epidote, biotite, and garnet, and the phosphorus formed apatite.

Ages of zircon and monazite from quartz monzonite in the core of the belt and at its margins conform to structural interpretations and suggest that the granitic rocks at the margins were emplaced after those in the core. Zircon and monazite from the metamorphosed sedimentary rocks are the same age as those from the syntectonic quartz monzonite.[8] It is inferred that any detrital zircon and monazite in the schists recrystallized under the conditions of temperature and directed stress that were reached at the climax of regional metamorphism, and, since the climax and the introduction of the syntectonic quartz monzonite was synchronous, the radiometric ages of zircon and monazite from diverse sources would be the same.

The ages of zircon and monazite from the syntectonic quartz monzonite and from metamorphosed sediments in the sillimanite-garnet zone are consistently Early Ordovician (about 400 million years). Zircon from a posttectonic quartz monzonite in the eastern staurolite-kyanite zone (about 285 million years) and from two areas of posttectonic granite in the western staurolite-kyanite zone (about 300 million years) are probably Devonian in age. Thus it is inferred that the most intense metamorphism in the Piedmont was achieved in Early Ordovician time. Subsequent movements allowed intrusion of the posttectonic granitic rocks and the injection of Triassic diabase dikes. Because the posttectonic rocks are underformed it appears that no late Paleozoic orogeny disturbed the western monazite belt.

SUMMARY

Placers in streams draining monazite-bearing crystalline rocks are likely to be poorer sources for monazite than fluvial placers formed by reworking detrital monazite deposited in an earlier cycle of erosion.

The apparent preferential precipitation of monazite in syntectonic quartz monzonite and associated injection gneiss in areas where regional metamorphism has attained the highest grade of the amphibolite facies suggests that monazite occurs elsewhere in areas of injection gneiss that are at the sillimanite-garnet subfacies whether they are sillimanitic or isofacial sillimanite-free gneisses.

REFERENCES

1. Mertie, J. B., Jr., *Monazite deposits of the southeastern Atlantic states*, US Geol. Survey Circ. 237 (1953).
2. Cain, S. A., *Pollen analysis of some buried soils, Spartanburg County, South Carolina*, Torrey Botanical Club Bull. 71: 11–22 (1944).
3. Lang, W. B., King, P. B., Bramlette, M. N., McVay, T. N., Bay, H. X. and Munyan, A. C., *Clay investigations in the southern states 1934–35*, US Geol. Survey Bull. 901 (1940).
4. Dryden, Lincoln and Miller, G. A., written communication (1954).
5. Stose, G. W. and Smith, R. W., *Geologic map of Georgia*, Georgia Division of Mines, Mining and Geology (1939).
6. Keith, Arthur and Sterrett, D. B., *Gaffney-Kings Mountain, S. C.–N. C.*, US Geol. Survey Geologic Folio 222 (1931).
7. Hewett, D. F. and Crickmay, G. W., *The warm springs of Georgia, their geologic relations and origin, a summary report*, US Geol. Survey Water-Supply Paper 819 (1937).
8. Jaffee, H. W. and Gottfried, David, oral communication.

Geology and Monazite Content of the Goodrich Quartzite, Palmer Area, Marquette County, Michigan

By R. C. Vickers,* USA

Monazite is now the principal source of thorium and rare earths. Although beach and stream placers supply practically all of the monazite used today, deposits of monazite in consolidated sediments (ancient placers) may also be of economic importance because of the relatively high value of monazite concentrates. For example, at a price of 18 cents per pound for monazite concentrates (March 1954), rocks containing 20 pounds of monazite per ton would be comparable in value to copper ores being mined in the United States containing about 0.75% copper or to the taconites that are beneficiated for their iron content in the Lake Superior region.

Beach and stream gravels throughout the world have received considerable attention during the past several years because of the increased demand for such minerals as ilmenite, monazite, rutile, and zircon. Consolidated gravels, on the other hand, are usually not regarded as an economic source of these minerals. However, several rich concentrations of monazite in sedimentary rocks have been found recently in the United States by uranium prospectors. The purpose of this paper is to describe one of these ancient monazite placers which may have present economic importance.

The Palmer area in Marquette County, Michigan, is a part of the Marquette iron-bearing district of the Lake Superior region. Abnormal radioactivity in specimens of pebble conglomerate on rock dumps at several abandoned iron mines in the Palmer area was detected in 1951 by geologists of the US Atomic Energy Commission. The locality was brought to the attention of the author during a detailed study of the known occurrences of radioactive minerals in northern Michigan. Preliminary sampling and laboratory work indicated that most of the radioactivity is caused by detrital grains of thorium-bearing monazite in the matrix of the conglomerate and that samples contained as much as 5% monazite. Further work in the area provided information concerning the areal extent, thickness, and grade of the monazite-bearing strata.

GEOLOGY

The Palmer area is on the south limb of the Marquette trough, a westward-plunging synclinorium about 40 miles long and from 1 mile to 6 miles wide. This synclinorium contains middle Precambrian (Huronian) rocks that are mainly quartzite, slate, iron-formation, and dolomite. The Palmer area is a downfaulted block of Huronian sedimentary rocks about 4 miles long and three-quarters of a mile wide separated from the main part of the Marquette synclinorium by an east-trending fault. Within this fault segment the rocks generally dip northward. Most of the bedrock is covered by glacial deposits.

According to Van Hise and Leith[1] the sequence of Precambrian rocks in the Palmer area is as follows:

Series	*Formation*	*Approximate thickness (ft)*
Upper Huronian	Goodrich quartzite	850
Middle Huronian	Negaunee iron-formation	1000
	Ajibik quartzite	150
Archean	Palmer gneiss	–

In the Palmer area the Goodrich quartzite is composed of a locally developed, basal, cobble, or boulder conglomerate, which grades upward into interbedded coarse-grained quartzite and pebble conglomerate. The lithologic character of the basal conglomerate is dependent upon the character of the subjacent formation. In part of the area the basal part of the Goodrich quartzite is predominantly cobbles and boulders of granite and schist derived from the lower Precambrian to the south and abundant jaspilite derived from the underlying Negaunee iron-formation. In some places the basal part of the Goodrich contains enough specular hematite fragments to constitute ore. Except for the development of boulder and cobble conglomerate at the base of the formation, the Goodrich quartzite consists almost entirely of alternating beds of coarse quartzite and arkosic quartz-pebble conglomerate. The observed pebble conglomerate beds range from about 1 inch to 2 feet in thickness and are separated by beds of coarse sand, which are from 1 foot to 10 or more feet in thickness. These lithologic relationships are based on outcrops of only the lower 200 feet of the Goodrich. The lower part of the quartzite is fairly well exposed in the Palmer area, but only one exposure is definitely more than 200 feet above the base. Because monazite is most abundant in beds of pebble conglomerate and because gamma-ray logs show an increase in monazite content in the middle and upper parts of the formation, the percentage of pebble beds

* US Geological Survey.

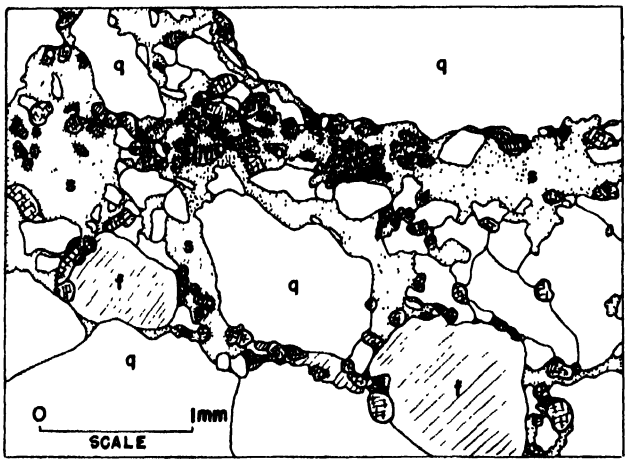


Figure 1. Sketch of a photomicrograph (27) of Goodrich quartzite showing quartz (q), interstitial monazite (m), and altered feldspar (f). Stippled areas (s) are mainly sericite, chlorite, and hematite

is believed to increase similarly in those parts of the formation.

The maximum thickness of Goodrich quartzite penetrated by diamond drilling in the Palmer area is about 1100 feet. The true stratigraphic thickness of the formation is not known because no sediments younger than the Goodrich quartzite were penetrated in the diamond drilling in the area, and no information is available on possible folding.

MINERALOGY

The monazite occurs as rounded to subrounded detrital grains in the matrix of quartz-pebble conglomerate. The brownish-red to honey-colored monazite grains are generally 0.10 to 0.20 mm in diameter. The identification of the monazite was confirmed by X-ray powder diffraction photographs. Locally the monazite grains make up more than 50% of the matrix in the conglomerate, and several lenses of monazite grains as much as 2 mm thick were noted in thin sections. Heavy minerals other than monazite in the Goodrich quartzite are mainly hematite, magnetite, ilmenite, and rutile (Fig. 1).

A sample of monazite (about 92% pure) was extracted from composite chips of several glacial boulders and selected mine-dump specimens. The sample is believed to be representative of the monazite in the Palmer area. The monazite was concentrated by gravity separation on a Wilfley table after grinding to minus 100 mesh, and then was further purified magnetically. Chemical analyses (calculated to 100% of the monazite) showed 8.3% ThO_2 and 0.22% UO_2. The specific gravity of several grains was 4.63.

MONAZITE CONTENT

The monazite content of all samples of Goodrich quartzite in this report was determined by comparing the beta-gamma activity of the material with prepared standards. The standards were prepared by separating out relatively pure monazite from a composite of several glacial boulders and mine-dump specimens of Goodrich quartzite and then remixing various proportions of the monazite with the crushed rock from which the monazite had been separated. A graph was then plotted which showed a straight-line relationship between the monazite content of the standards and their radioactive content. This method of monazite determination was used because a study of alpha-sensitive stripping film on thin sections of the quartzite indicated that almost all radioactivity was due to monazite. The accuracy of determining the amount of monazite by measuring the radioactivity of a sample was checked by two other methods and the results are tabulated below:

Method	*Monazite (pounds per ton)*
Radioactive content (from graph)	34
Grain count of heavy-liquid fraction (plus 2.96 specific gravity)	37
Gravity (Wilfley table) and magnetic (Frantz isodynamic separator) concentrate	35

DISTRIBUTION AND GRADE OF MONAZITE

The stratigraphic position, lateral extent, and grade of the monazite-bearing beds is known from: (1) samples of outcrops that are mainly restricted to the lower 200 feet of the formation; (2) gamma-ray logs of three diamond-drill holes that penetrate an apparent thickness of 1100 feet of the Goodrich quartzite; (3) analyses of several diamond-drill core samples; and (4) mine-dump and glacial-boulder samples.

In most of the outcrops examined, the monazite is concentrated in narrow beds of pebble conglomerate, 1 inch to 2 feet thick, separated by beds of coarse-grained quartzite 1 foot to 10 or more feet thick. Chip-channel samples of the lower part of the quartzite contained a weighted average of about 3 pounds of monazite per ton. However, gamma-ray logging suggests that most of the monazite occurs more than 300 feet above the base of the formation. A sample of pebble conglomerate from the only outcrop that is believed to be more than 300 feet above the base of the formation contained 21 pounds of monazite per ton. A scintillation-counter survey of the outcrop containing the pebble conglomerate bed indicated an average monazite content of about 6 pounds per ton. Specimens of core representing about 3% of the total core from two diamond-drill holes, aggregating 1530 feet, were scanned with a scintillation counter, and several monazite-bearing specimens were found which contained as much as 50 pounds of monazite per ton. Locally derived glacial erratics and mine-dump samples contained as much as 90 pounds of monazite per ton, but material of this grade was not observed in outcrop or in drill-core specimens. Samples of Goodrich quartzite containing more than 20 pounds of monazite per ton were found on mine dumps for a distance of about 1.5 miles along the strike of the formation.

The average grade of monazite-bearing quartzite that would be amenable to open-pit mining methods is not accurately known. Small tonnages of material

containing more than 20 pounds of monazite per ton are present, and the author believes that large tonnages are available that would contain about 10 pounds of monazite per ton. Additional exploration would be necessary to determine the amount and grade of monazite-bearing rock present.

ORIGIN OF THE MONAZITE AND CONCLUSIONS

Although the Goodrich quartzite crops out over an area of several hundred square miles in northern Michigan, concentrations of monazite have been found mainly in an area of about three square miles. Outside the Palmer area, small local concentrations of monazite may be found in an outlier of Goodrich quartzite about 12 miles to the southeast. The quartzite in this area is arkosic and overlies older granite.

Because monazite in the Goodrich quartzite seems to be restricted to a relatively small area, the mineral is believed to be derived from a local source. Because of the increase in the size and angularity of the monazite grains in the area southeast of Palmer, the source of the monazite may be to the southeast, which is an area underlain mainly by abnormally radioactive porphyritic granite. Monazite, allanite, and zircon were observed in thin sections of specimens of granite taken about 7 miles southeast of Palmer, but the monazite in the few granite specimens examined was finer grained than in the Goodrich quartzite.

Concentrations of monazite may be expected in consolidated sediments in other areas, formed perhaps under much the same conditions as present-day monazite placers. Sandstones and conglomerates derived from a monazite-bearing source rock would warrant attention. Both present-day and ancient monazite placers are commonly small relative to the area covered by the strata in which they are contained; detailed reconnaissance must be done before a particular area can be classified as unfavorable. The presence of monazite in consolidated sediments may also be used as a guide to concentrations of zircon, rutile, ilmenite, or other heavy minerals that might be recovered in addition to the monazite.

Owing to the small amount of thorium in many monazites, an economically important deposit of monazite in consolidated sediments may not be sufficiently radioactive to attract attention. For example, a monazite deposit containing 20 pounds of monazite per ton would have a radioactivity equivalent to material containing about 0.02% uranium, if we assume that the monazite contains about 7.5% thorium and 0.20% uranium and that the ratio of other radioactive minerals to monazite is very low.

During the intensive search for uranium deposits, the possibility should not be overlooked that the abnormal radioactivity of sandstones and conglomerates and their metamorphic derivatives may be caused by potentially valuable concentrations of thorium-bearing monazite or other radioactive detrital minerals.

REFERENCES

1. Van Hise, C. R. and Leith, C. K., *The Geology of the Lake Superior Region*, US Geological Survey Monograph 52: 251–265, plate 17 (1911).

Uranium in Terrestrial Sedimentary Rocks in the United States Exclusive of the Colorado Plateau

By W. I. Finch,* USA

Uranium deposits are widespread in terrestrial sedimentary rocks in northeastern and western United States outside of the Colorado Plateau. Large uranium deposits occur in the Cretaceous sandstone formations in the Black Hills region of South Dakota and Wyoming and in Tertiary sandstone, arkose, and tuffaceous formations in Wyoming, Texas, and Nevada (Fig. 1). Small deposits occur in terrestrial formations of many ages in western and northeastern United States.

Each deposit or group of deposits here decribed is plotted according to the age of the host rock in Fig. 1, lithology of the host rock in Fig. 2, and the chief ore metals in Fig. 3. The types of lithology are: (1) sandstone (minor mudstone, includes sandstone and conglomerate that may contain some interbedded mudstone and arkosic or tuffaceous material); (2) arkose or water-laid tuff; and (3) mudstone, siltstone, or limy clastic sediments. Chemical precipitates (mainly limestone) and vein deposits in terrestrial rocks are not discussed in this paper. The relative abundance of uranium, vanadium, and copper is used to classify the deposits in Fig. 3. The metals are listed in order of abundance for each type of deposit. In spite of this arbitrary classification, vanadium minerals are the main ore minerals in some uranium (vanadium and copper minor) deposits because vanadates contain about 3 times as much uranium as vanadium. Generally, the major ore minerals in uranium (vanadium and copper minor) deposits are uranium silicates, phosphates, and arsenates. The uranium content in all the deposits described in this report is generally greater than 0.10% U_3O_8.

PALEOZOIC ROCKS

Uranium deposits occur in Devonian and Pennsylvanian formations in eastern Pennsylvania, in the Permian formations in southwestern Oklahoma, and in Pennsylvanian and Permian formations in central Colorado and New Mexico (Fig. 1). These deposits occur in widely distributed localities in different stratigraphic zones. In general, these deposits occur in fluviatile sandstone, and they contain more copper than uranium in the West and mostly uranium in the East (Figs. 2 and 3). Copper deposits have been known in many of these localities for a long time, but most of the uranium deposits have been discovered only in the past decade.

In Pennsylvania, the uranium (vanadium and copper minor) deposits occur in coarse graywacke conglomerate near the base of the Pottsville formation of Pennsylvanian age on the north limb of the Panther Valley syncline and in graywacke sandstone near the top of the Catskill formation of Devonian age on the south limb of the Panther Valley syncline.[1] Although only four deposits are known in a small area of poor exposures, deposits of larger size may be present. The ore minerals are disseminated in deposits that are lenticular masses a few feet to several hundred feet across. The uranium minerals in the deposits in the Pottsville formation are carnotite, tyuyamunite, and uranophane, whereas the uranium minerals in the deposits in the Catskill formation are autunite, kasolite, and uranophane. Carbonaceous material is rare in both formations.

In Oklahoma, uranium occurs in the Garber sandstone of Permian age on the gently dipping south flank of the Wichita uplift in Tillman, Cotton, and Jefferson Counties, Oklahoma.[2] Although the Garber sandstone is generally referred to as part of the Permian red beds, the copper- and uranium-bearing beds are nearly always light-colored lenses. The uranium deposits consist either of copper and uranium minerals in fine-grained sandstone and siltstone or of uranium associated with asphaltic arkosic sandstone. The main minerals in the copper-uranium deposits are torbernite, autunite, uranophane, malachite, and azurite in heavily iron- and manganese-stained sandstone. Replacement of wood fragments is common.

These deposits are small; similar deposits of uranium probably occur with the copper in Permian red beds in the adjacent part of northern Texas.

Colorado and New Mexico copper-uranium deposits occur in upper Paleozoic sandstone in four widely separated spots that form an arc about the eastern border of the Colorado Plateau (Fig. 1). In Mora County, New Mexico, copper and uranium minerals occur in light-colored, medium-grained arkosic sandstone lenses in the normally red sequence of the steeply dipping Sangre de Cristo formation of Pennsylvanian and Permian (?) age.[3] Copper deposits with little or no uranium occur in carbonaceous shale, limestone, and siltstone beds that are interbedded with the sandstone. The copper-uranium de-

* US Geological Survey.

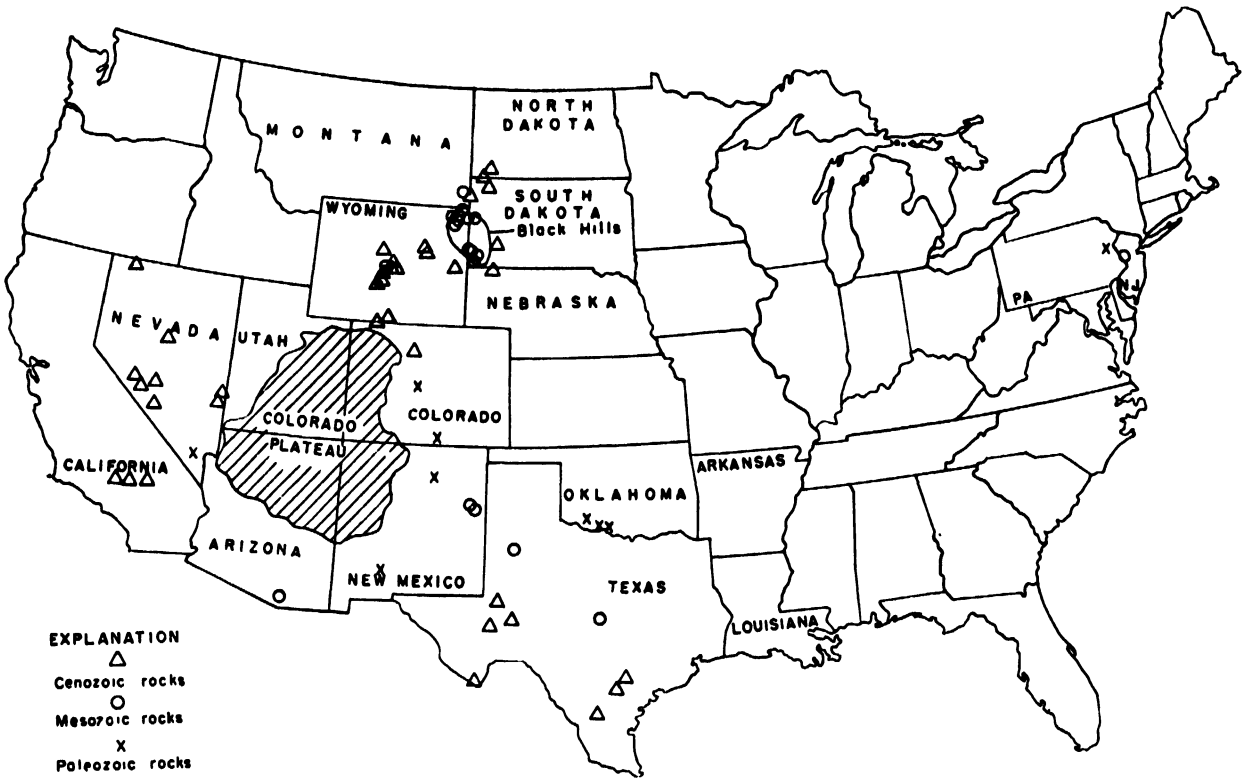


Figure 1. Index map showing distribution and stratigraphic position of uranium deposits in terrestrial sedimentary rocks in the United States exclusive of the Colorado Plateau

posits are associated with carbonized plant remains, gray and black clay galls, and small thin lenses of hematitic altered sandstone. The uranium minerals are metatyuyamunite and uraninite. Chalcocite, chalcopyrite, other sulfides, and uraninite replace carbonaceous material. A similar deposit of copper and uranium in the Sangre de Cristo formation has been reported in the Cuchara Camp, Huerfano County, Colorado.[5]

Another deposit of copper and uranium has been

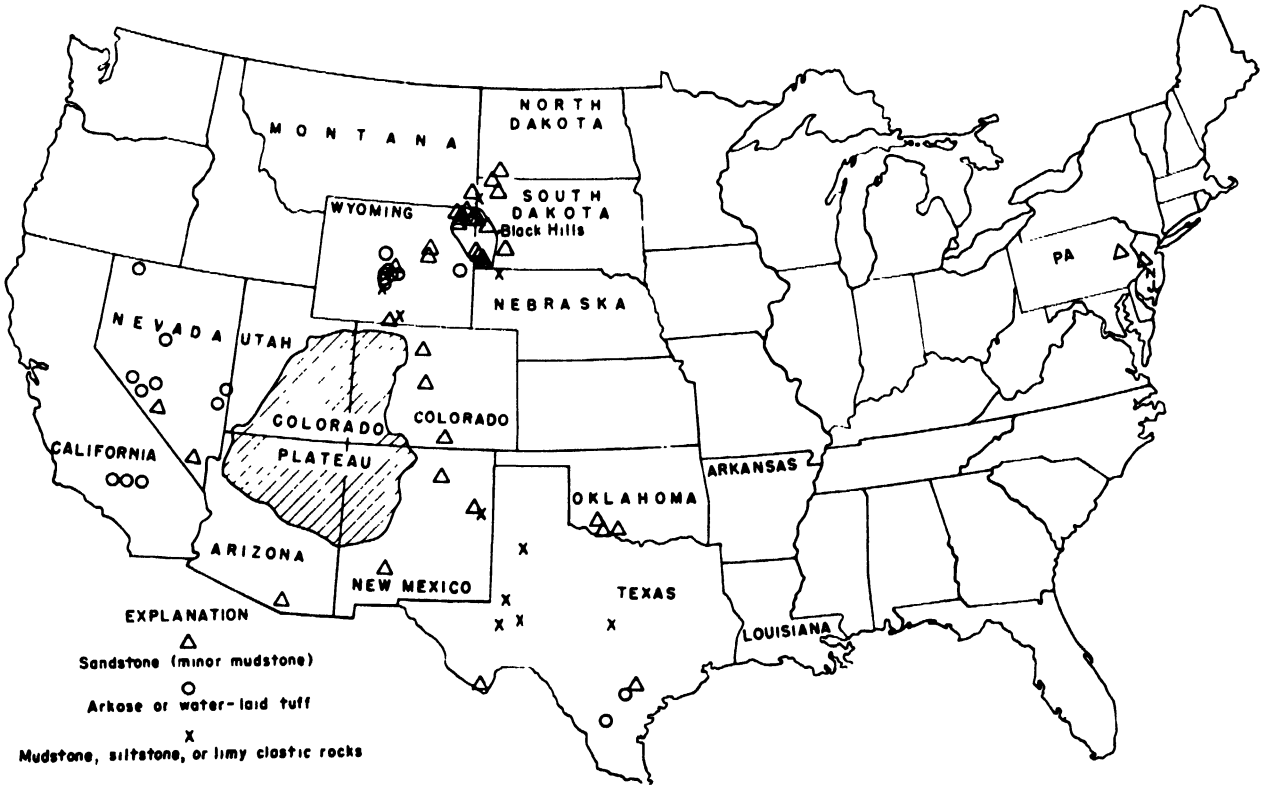


Figure 2. Distribution of uranium deposits by the lithologic character of the host rock

reported in sandstone of the Abo formation of Permian (?) age in Sierra County, New Mexico.

In Park County, Colorado, a copper-vanadium-uranium deposit occurs in the Maroon formation of Pennsylvanian and Permian age on the northeast flank of the Garo anticline. Tyuyamunite and carnotite are disseminated or fill fractures in three beds of medium- to coarse-grained sandstone. Malachite, volborthite, red and black vanadium minerals, and limonite are associated with the uranium minerals. The deposits are a few tens of feet in width and range from a few feet to several hundred feet in length.

MESOZOIC ROCKS

Large uranium deposits occur in sandstone of Cretaceous age in the Black Hills region of South Dakota and Wyoming (Fig. 1). Isolated small deposits occur in Triassic rocks in Pennsylvania, New Jersey, and Texas, in Jurassic rocks in Wyoming and New Mexico, and in Cretaceous rocks in Arizona. In general, the deposits in the Black Hills region occur in sandstone and contain more vanadium than uranium. The other deposits occur in sandstone, siltstone, or limy siltstone and contain less vanadium and copper than uranium. The deposits in these Mesozoic rocks were discovered in 1951 or later and as a rule are not yet well developed.

In the Black Hills region, vanadium-uranium deposits occur in the Inyan Kara group of Cretaceous age, which encircles the Black Hills uplift. The Inyan Kara group, comprising the Fall River, Fuson, and Lakote formations, has been folded into gentle anticlines and monoclines subsidiary to the major uplift. The Fall River sandstone in the upper part of the Inyan Kara group contains most of the large deposits. The ore-bearing rocks are generally lenticular light-colored, fine-grained sandstone, either thinly interbedded with dark-colored shales or irregularly bedded with mudstone.

Although these deposits contain more vanadium than uranium (ratio of V_2O_5 to U_3O_8 commonly 3:1), some of them consist mainly of carnotite, whereas others contain large amounts of corvusite. The deposits are generally tabular layers of disseminated minerals, but some concretions and "rolls" occur locally. Limonite, hematite, calcite, and manganese oxide are associated with much of the ore. The deposits range from bodies a few feet across that contain a few tons of ore to bodies several hundred feet across that contain many thousand tons of ore.

The most favorable areas for large deposits in the southern part of the Black Hills are where sandstone lenses that contain abundant mudstone or shale coincide with structural terraces.[6] Similar favorable conditions probably exist in the northern part of the region. The deposits in the Black Hills region are similar to the vanadium-uranium deposits in the Morrison formation of Jurassic age on the Colorado Plateau.

Uranium is also found in several other places. It occurs in the Newark group of Triassic age in Bucks County, Pennsylvania, and Hunterdon County, New Jersey. These deposits, which are below ore grade, occur as lenticular masses in sandstone and contain more uranium than vanadium or copper; the uranium minerals, torbernite and uranophane, are disseminated and are associated with limonite and clay. Uranium occurs in carbonaceous siltstone of the Dockum group of Triassic age in San Saba and Lubbock Counties, Texas. A small uranium deposit occurs in the Morrison formation of Jurassic age in

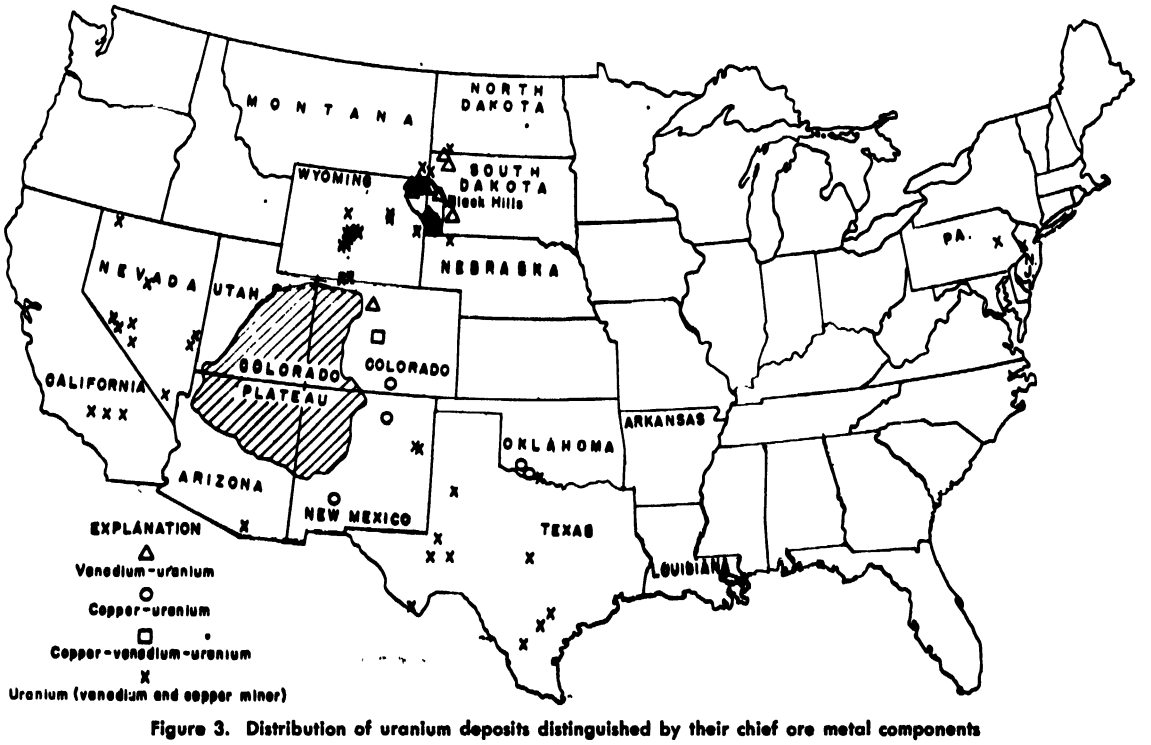


Figure 3. Distribution of uranium deposits distinguished by their chief ore metal components

central Wyoming near the large deposits in the Tertiary rocks (Fig. 1). Several deposits occur in sandstone or limy sandstone beds of Late Jurassic age in Quay County, New Mexico. Carnotite or tyuyamunite is the main ore mineral. A uranium deposit has been reported recently in arkosic sandstone beds near the base of the Cretaceous in Santa Cruz County, Arizona. Kasolite is disseminated in the rock.

CENOZOIC ROCKS

Uranium occurs in Cenozoic rocks in the Wyoming basins and the northern Great Plains region, in the Texas coastal plains, and in the Nevada basins and California lake beds. In the Wyoming basins and northern Great Plains region, uranium and vanadium-uranium deposits occur mainly in sandstone (commonly tuffaceous and muddy) and arkose formations that range from Paleocene to Pliocene in age. In the Texas coastal plains region, uranium (vanadium and copper minor) deposits occur in tuff and sandstone formations of Eocene and perhaps Oligocene age. In Nevada and California, uranium deposits occur in tuffaceous sandstone of the Miocene and Pliocene lake beds.

Economic deposits were discovered in Tertiary rocks in the Wyoming basins in 1951, and in the northern Great Plains, Texas coastal plains, and Nevada basins in 1954. Large areas of similar rocks in the United States remain untested. The mineralogy habits, and apparent geologic controls of these deposits differ somewhat from those in the Mesozoic sandstone formations of the Black Hills and of the Colorado Plateau.

Uranium deposits occur in Tertiary rocks in an elongate area 160 to 200 miles wide and over 500 miles long and which extends in a northeasterly direction from Colorado across Wyoming into Nebraska, and South and North Dakota.

In general, the deposits occur in progressively younger Tertiary rocks going northeastward in this area. The deposits are in the Fort Union formation of Paleocene age in southwest North Dakota and nothwest South Dakota; in the Wasatch and Wind River formations of Eocene age in central Wyoming; in the White River formation of Oligocene age in southwest South Dakota, northwest Nebraska, and easternmost Wyoming; and in the Browns Park formation of Miocene(?) age and North Park formation of Pliocene(?) age in southern Wyoming and northern Colorado. Within the Tertiary rocks the largest deposits are in rocks of Paleocene and Eocene age. In general, the deposits may be divided into three types: Type I—deposits in carbonaceous sandstone associated with uranium-bearing lignite beds; Type II—small concretionary deposits in sandstone; and Type III—poorly defined tabular disseminated deposits in sandstone, arkose, or mudstone.

Type I deposits occur in the Fort Union formation of Paleocene age in southwest North Dakota and northwest South Dakota. In the same area, and in southeast Montana, Type I deposits also occur in the Arikaree formation of Miocene age and in the Hell Creek formation of Late Cretaceous age. Most of these deposits occur in sandstone interbedded with uranium-bearing carbonaceous shales and lignite beds.[7] The uranium minerals are commonly yellow (meta-autunite I and metatyuyamunite) and are disseminated in the rock. The deposit in the Arikaree is in thin lenses of fresh-water limestone and siltstone. Denson, Bachman, and Zeller[8] have suggested that the deposits in the lignite region are genetically related to the disseminated uranium present in the superjacent beds of volcanic ash.

Type II deposits occur in a red lenticular sandstone facies of the Wasatch formation of Eocene age in the Pumpkin Buttes area of central Wyoming. These deposits consist of uranium that is mainly in the form of uranophane and carnotite in nodules a few inches across and commonly several feet long. Nodules of iron and manganese oxides are commonly uranium bearing. Many of the uranium-bearing nodules are replacements of fossil wood and some contain uraninite. These deposits are thought to have oxidized in place, and their deposition is thought to have been caused mainly by carbonaceous material.

Type III deposits include the remaining deposits in Tertiary rocks in this area. The uranium minerals, which are mainly uranium silicates and phosphates, are disseminated in poorly bedded arkose, sandstone, and siltstone. The ore bodies are poorly defined tabular bodies. Uraninite, carnotite, and liebigite have been found in some of these deposits. Carbonaceous material is sparse. These deposits range from bodies a few feet across that contain a few tons of ore to bodies several hundred feet across that contain many thousands of tons of ore. The known deposits, which are mainly those that crop out, appear to be analogous in origin to caliche, and the configuration of some may be related to Recent topographic and ground water conditions. Others are probably related to obscure sedimentary and structural features and may be primary deposits that have oxidized more or less in place.

Uranium deposits in Tertiary rocks occur in tuff and tuffaceous sandstone formations of late Eocene or early Oligocene age in southeastern Texas and in a limy sandstone formation of Pliocene age in west Texas. The small deposits in west Texas, which contain less vanadium than uranium, consist of metatyuyamunite in vugs in limy sandstone.

The large uranium (vanadium and copper minor) deposits in southern Texas occur in the flat-lying Jackson formation of Eocene age and perhaps in the overlying beds of Oligocene age. The ore-bearing beds consist of poorly bedded and mostly unconsolidated marine, brackish-water, near-shore, and continental beds of light-colored tuff, sand, and sandy clay. These deposits were discovered only recently, and their mineralogy is not well known. Yellow and green uranium minerals, probably uranium phos-

phate and silicate minerals, occur along fractures, bedding planes, and disseminated in the rock. Large amounts of arsenic and molybdenum occur with the uranium, according to Riley of the US Geological Survey (personal communication). The best mineralized rock appears to be associated with hydrated iron oxides, bentonite, and rocks that are characterized by mixed and irregular bedding. Carbonaceous material is rare and commonly shows no spatial association with the ore. The deposits range from bodies a few feet across that contain a few tons of ore to bodies several hundred feet across that contain many thousand tons of ore. The deposits appear to have been concentrated by ground water from a disseminated volcanic source.

Uranium deposits occurring mainly in tuff in the Miocene lake beds of Nevada and southern California have been known for many years but economic deposits were not discovered until 1954.

In Nevada, uranium (vanadium and copper minor) is disseminated in water-laid sandy, clayey, or arkosic tuff of Miocene lake beds. Uranium minerals are rare, as the uranium appears to be contained in an indistinguishable phosphate mineral, possibly fluorapatite. Yellow uranium minerals have been reported in a few localities. The high-grade ore is most common along weak to strong shear zones and fractures and is associated with limonite. Carbonaceous material, gypsum, calcite and other minerals commonly associated with uranium deposits in terrestrial sedimentary rocks are generally absent. The deposits range from bodies a few feet across that contain a few tons of ore to bodies several tens of feet across that contain a few hundred tons of ore. The uranium is thought to have been concentrated by ground water.

Small quantities of autunite and gummite occur in tuffaceous sedimentary rocks in the Rosamond formation (local usage) of Miocene age in the Rosamond prospect near Mojave, Kern County, California.[9] Uranium minerals occur mainly on fracture and joint surfaces and to a lesser extent, disseminated in tuffaceous rocks adjacent to faults. Several similar deposits occur west of the Rosamond prospect in Kern and Mojave Counties, California.

SUMMARY AND CONCLUSIONS

Large uranium deposits occur in sandstone formations of Cretaceous age in the Black Hills region of South Dakota and Wyoming and in formations of Tertiary age in the Wyoming basins and northern Great Plains, Texas coastal plains, and Nevada basins. Small deposits occur in terrestrial sedimentary rocks in California, Arizona, New Mexico, Colorado, Oklahoma, Pennsylvania, and New Jersey.

Although most of the deposits are scattered throughout much of western United States, several regional relationships are indicated by this review. Deposits in upper Paleozoic rocks occur circumferentially about the eastern border of the Colorado Plateau. The Black Hills region contains large deposits clustered in the southern and northern parts of the Black Hills uplift. Deposits in Tertiary rocks of the Wyoming basins and northern Great Plains region lie in a northeast-trending belt about 175 miles wide and 500 miles long. The ore-bearing formations in this belt become progressively younger from north to south. Within the Tertiary rocks, the largest deposits occur in rocks of Paleocene and Eocene age.

In general, the deposits in Paleozoic and Mesozoic formations occur in sandstone (minor mudstone) that was deposited by streams, and they contain greater amounts of vanadium or copper than uranium. On the other hand, the deposits in Cenozoic formations occur in arkose, tuff, and tuffaceous sandstone that were deposited in closed basins or lakes, by streams, or under near-shore conditions. These Cenozoic deposits most commonly contain less vanadium or copper than uranium.

REFERENCES

1. Klemic, Harvey and Baker, R. C., *Preliminary Summary of uranium occurrences in Carbon County, Pennsylvania,* US Geological Survey Circular 350 (1954).
2. Beroni, E. P., in *Geologic investigations of radioactive deposits,* semiannual progress report, June 1, 1954, to November 30, 1954, US Geological Survey Trace Elements Investigations Report 490, US Atomic Energy Commission, Technical Information Service, Oak Ridge, Tennessee (1954).
3. Tschanz, C. M., in *Geologic investigations of radioactive deposits,* semiannual progress report, June 1, 1953, to November 30, 1953, US Geological Survey Trace Elements Investigations Report 390, US Atomic Energy Commission, Technical Information Service, Oak Ridge, Tennessee (1953).
4. Tschanz, C. M., in *Geologic investigations of radioactive deposits,* semiannual progress report, December 1, 1953, to May 31, 1954, US Geological Survey Trace Elements Investigations Report 440, US Atomic Energy Commission, Technical Information Service, Oak Ridge, Tennessee (1954).
5. Baltz, E. H., Jr., in *Geologic investigations of radioactive deposits,* semiannual progress report, June 1, 1954, to November 30, 1954, US Geological Survey Trace Elements Investigations Report 490, US Atomic Energy Commission, Technical Information Service, Oak Ridge, Tennessee (1954).
6. Gott, G. B. *et al.,* in *Geologic investigations of radioactive deposits,* semiannual progress report, June 1, 1954, to November 30, 1954, US Geological Survey Trace Elements Investigations Report 490, US Atomic Energy Commission, Technical Information Service, Oak Ridge, Tennessee (1954).
7. Gill, J. R., in *Geologic investigations of radioactive deposits,* semiannual progress report, June 1, 1954, to November 30, 1954, US Geological Survey Trace Elements Investigations Report 490, US Atomic Energy Commission, Technical Information Service, Oak Ridge, Tennessee (1954).
8. Miller, R. L. and Gill, J. R., *Uranium from coal,* Scientific American, 191, no. 4: p. 36–39 (1954).
9. Walker, G. W., *Rosemond uranium prospect, Kern County, California,* California Division of Mines Special Report 37 (1953).

Uranium-Vanadium-Copper Deposits of the Colorado Plateau Region

By R. P. Fischer,* USA

The Colorado Plateau region comprises the adjoining parts of Colorado, Utah, Arizona, and New Mexico and encompasses an area of more than 100,000 square miles. The uranium-vanadium-copper deposits in the region are widely distributed and have many common geologic characteristics. They have been the principal source of uranium and vanadium in the United States.

Rocks exposed in the region consist mainly of sedimentary beds that are nearly flat lying. Most of the ore deposits are in sandstone strata of continental origin. The ore minerals impregnate and partly replace the host rock, and they form ore bodies that are dominantly tabular and roughly parallel to the sandstone bedding. As the common geological characteristics of this group of deposits differ considerably from the habits of many other types of metalliferous deposits, they present peculiar problems of localization, genesis, and ore finding.

In the past the uranium deposits of the Colorado Plateau have been commonly referred to as "carnotite deposits." Carnotite was discovered in 1898 in southwestern Colorado, but only a small amount of ore was mined during the next decade. From 1910 to 1923, however, these deposits were intensively mined for their radium content; some vanadium was produced as a byproduct. Mining operations were centered in Colorado, but a small amount of ore was obtained from Utah. Only a small amount of carnotite ore was mined from 1923 until 1936. Intensive mining was resumed in 1936 and continued through the war years; at first, operations were concentrated in Colorado, but then spread to Utah and finally to northern Arizona. Vanadium was the desired metal during this period, but some byproduct uranium was produced during World War II. From 1945 to 1948 mining activity was again at a low level, as demands for vanadium were small and there was no market for uranium ore.

In 1948, when the US Atomic Energy Commission announced its uranium ore-buying program, only 15 small mines were operating; at the end of 1954, however, there were several hundred producing mines.[1] Centers of important production have spread westward into central Utah and southward into Arizona and the northwest part of New Mexico (Fig. 1). Uranium, of course, is the metal of principal value, and vanadium and perhaps a little copper are now being produced as byproducts.

The vanadiferous sandstone deposits in the Entrada sandstone have yielded a large amount of vanadium, and, in recent years, a little byproduct uranium. During recent years, also, the silver-bearing sandstone deposits in the Chinle formation at Silver Reed, Utah,[2] have yielded a little uranium ore.

The uranium-vanadium-copper deposits of the Colorado Plateau region have been studied by many geologists. Coffin[3] prepared the first detailed report on the deposits of southwestern Colorado; general descriptions of the deposits in the Plateau region were published by Hess[4] and Fischer.[5] The US Geological Survey began a comprehensive study of these deposits in 1939 and continued this work through World War II. During the war also, Union Mines Development Corporation made intensive geologic studies under government contract. Since 1947 the US Geological Survey has conducted physical exploration and geologic studies on behalf of the US Atomic Energy Commission, which has also done exploration and geologic study with its own staff and through contracts with universities since 1948. Industry has also employed many geologists during recent years. All told, probably more than 1000 man years of geologic work has been done in these deposits.

GEOLOGY AND GEOLOGIC HISTORY OF THE REGION

Structurally the Colorado Plateau region has been relatively stable since Precambrian time. Paleozoic sedimentary formations, which are of both marine and continental origin, are widely distributed and fairly thin. The only major deformation in the region during the Paleozoic was that which formed the Uncompahgre element of the late Paleozoic ancestral Rocky Mountains. It resulted in a broad uplift of considerable elevation that projected northwestward into the east-central part of the region. The uplift was bordered on the southwest by the Paradox basin, in which accumulated several thousand feet of evaporites and detrital sediments. Several elongate salt domes or anticlines, trending northwest parallel to and bordering the southwest flank of the Uncompahgre uplift, formed during late Paleozoic time. Salt and gypsum continued to invade and warp the sedimentary formations until the middle of the Mesozoic era, and movement recurred during Tertiary time.

* US Geological Survey.

Continental sedimentation dominated the Mesozoic era until Late Cretaceous time. Rocks deposited consist mostly of sandstone and shale, and they also form widely spread individual units that are fairly thin, totalling only a few thousand feet in thickness. During the Late Cretaceous the region sank slowly, largely as a unit, and received a layer of shale and sandstone beds, of marine and continental origin, several thousand feet thick. Deformation, presumably of Laramide age at the close of Cretaceous and during early Tertiary time, is expressed in the region by several broad folds and sharp flexures, but these features are not yet exactly dated, nor are the subsequent events of Tertiary deformation, intermontane sedimentation, and erosion.

Igneous activity in the Plateau region is of moderate intensity and comprises both intrusive and extrusive action. The intrusions consist mostly of the injection of medium-sized stocks and laccoliths into the sedimentary cover in the central and eastern parts of the region; these are dated on rather vague evidence as early Tertiary or perhaps Late Cretaceous. Volcanic extrusions are abundant along and beyond the western, southern, and eastern margins of the region; most are of middle to late Tertiary age but some activity continued even into Recent time.

DISTRIBUTION

Hundreds of uranium-bearing deposits are known in the Colorado Plateau,[5] but most of them are small. The maps (Figs. 1, 2, and 3) show only the more productive deposits, those which are reported to have yielded 1000 tons or more of ore as of January 1, 1954.[5] All three maps are compiled on the same base, and all show the same deposits. The symbols on Fig. 1 indicate the stratigraphic position of the deposits, those on Fig. 2 the classification of the deposits by the lithologic character of the host rock, and those on Fig. 3 the classification by metal components. Note that in the explanation on Fig. 1 the Entrada sandstone is listed above the Todilto limestone rathe rthan below it, where it should be from the standpoint of stratigraphic position. This arrangement was used, however, because it is more compatible with the arrangement of classes on Figs. 2 and 3.

Deposits or occurrences of uranium with vanadium or copper are known in nearly all sedimentary formations exposed in the Colorado Plateau region; these formations range from late Paleozoic to middle Tertiary in age. Nearly all of the more productive deposits, however, are restricted to five formations —the Shinarump conglomerate and Chinle formation of Triassic age, and the Entrada sandstone, Todilto limestone, and Morrison formation of Jurassic age (Fig. 1).

The Shinarump conglomerate is composed of light-colored conglomeratic sandstone interbedded with gray and red siltstone and mudstone; all beds are lenticular. The sandstone beds are poorly sorted and they contain argillaceous material in the form of thin lenses, pebbles, and fragments of mudstone; fossil wood is also abundant. Sandstone lenses commonly fill channels cut in underlying rocks. Most of the ore deposits are in the thicker parts of these channel-fills.

The Shinarump averages 50 to 75 feet thick in northern Arizona and in southern and central Utah, though it is absent in a few places. It is absent or poorly developed in east-central Utah, Colorado, and New Mexico. The Shinarump accumulated as a stream and flood-plain deposit on a broad alluvial plain.

The Chinle formation is composed mainly of red and gray shale and siltstone; light-colored sandstone beds, in part conglomeratic, are also present, as are thin layers of limestone and limestone conglomerate. Fossil wood is fairly common. The Chinle formation extends nearly everywhere throughout the Plateau region and averages several hundred feet thick. The formation probably accumulated mostly under flood-plain conditions. Most of the Chinle uranium deposits are in conglomeratic sandstone beds, but a few are in highly argillaceous beds.

The uranium deposits in the Shinarump and Chinle formations show an interesting relationship in stratigraphic position with respect to the unconformity between these formations and the underlying Moenkopi formation, as described by Williams and others,[6] Where the Shinarump is present (northern Arizona and southern Utah), it is the host rock; northward, where the Shinarump is absent, progressively younger beds of Chinle on-lap the Moenkopi and are ore-bearing. Of these Chinle beds, the Moss Back member, a conglomeratic sandstone similar in lithologic character to the Shinarump, contains most of the larger known deposits. Williams and his coworkers[6] conclude that most of the uranium deposits in Triassic rocks lie within 50 feet of the unconformity on top of the Moenkopi.

The Entrada sandstone extends almost throughout the Plateau region. In Colorado, New Mexico, and Arizona, it is a massive, crossbedded, fine-grained, clean, light-colored sandstone and averages 50 to 100 feet in thickness. Westward from Colorado the formation thickens gradually to about 1000 feet in central Utah and is composed of a red, fine-grained, earthy sandstone. Much of the Entrada sandstone was probably deposited by wind action. No fossil wood or other organic material has been recognized in the Entrada where it is typically developed. Several large vanadium deposits have been mined from the Entrada sandstone in western Colorado; one of these deposits (at Rifle) is also partly in an underlying sandstone that might be the Wingate sandstone.

Where the Todilto limestone is ore-bearing in northwestern New Mexico it averages about 20 feet thick and is a dark, thinly and irregularly bedded, dense to recrystallized limestone. It has the same lithologic character and approximately the same thickness in northeastern Arizona and in the western part of the San Juan Mountains of southwestern Colorado, but eastward in New Mexico and Colorado

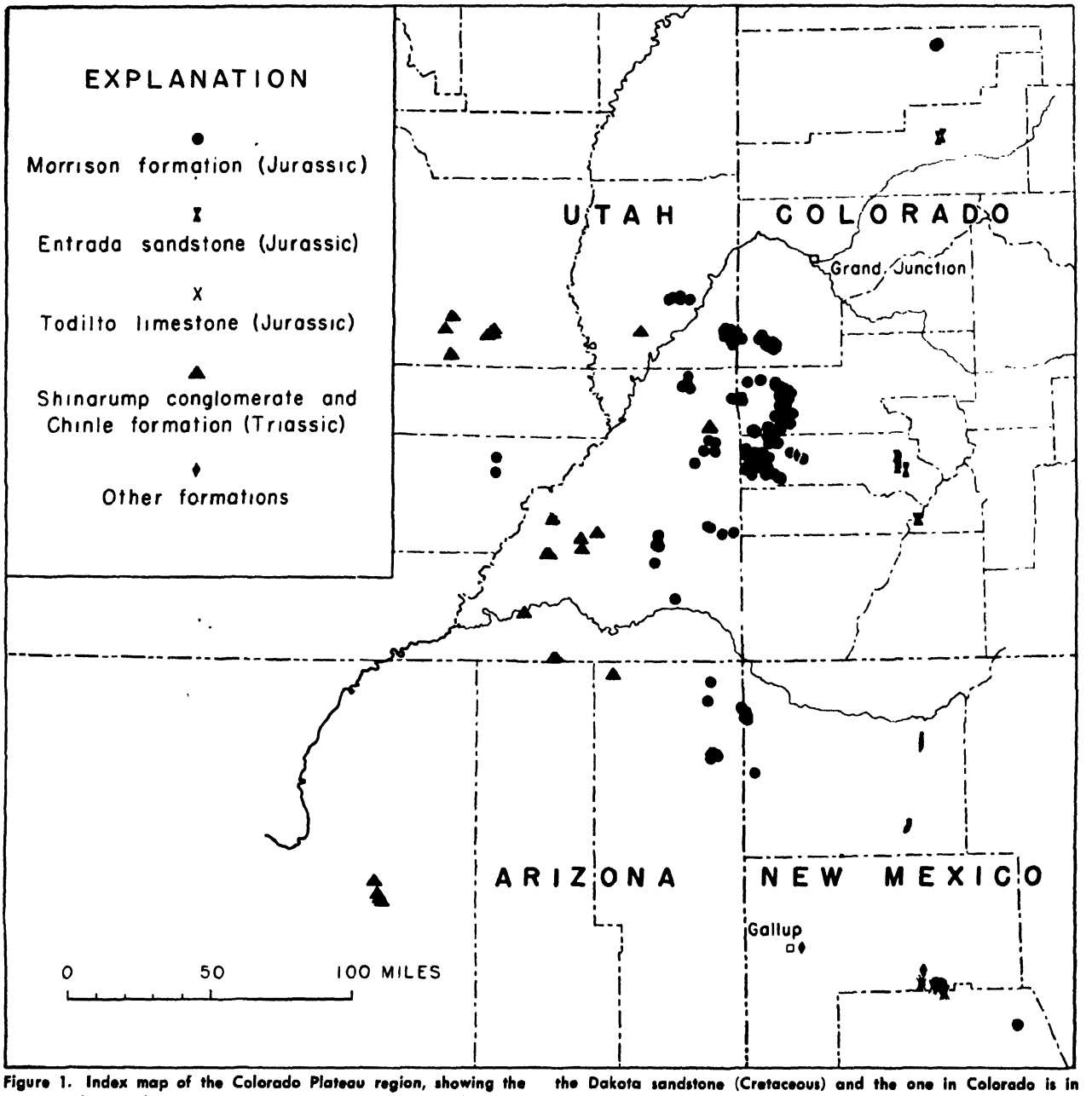


Figure 1. Index map of the Colorado Plateau region, showing the more productive deposits, the stratigraphic positions of which are indicated by symbols. Of the three deposits shown by the diamond-shaped symbol ("other formations"), the two in New Mexico are in the Dakota sandstone (Cretaceous) and the one in Colorado is in the Hermosa formation (Pennsylvanian). Compiled with the aid of R. T. Chew, III, and H. S. Johnson. Deposits shown are taken from Finch,[5] yielded 1000 tons or more of ore as of January 1, 1954

it thickens somewhat and contains gypsum. The Todilto is absent in Utah and the northern and extreme western parts of Colorado. The limestone facies of the Todilto contains some carbonaceous material but no recognizable fossil wood. The formation probably was deposited in brackish water.

The Morrison formation formerly covered most of the Plateau, but pinches out near the southern and western edges; it extends east and north beyond the region. The Morrison averages about 600 to 900 feet thick. Four members are recognized, which will be described in ascending order. For a more detailed discussion of Morrison stratigraphy the reader is referred to a report by Craig and others.[7]

The Salt Wash member occupies the southeastern quarter of Utah, the southwestern part of Colorado, and the extreme northern part of Arizona. It averages about 250 feet in thickness and consists of light-colored, medium-grained sandstone interbedded with mudstone. The sandstone strata are lenticular, irregularly bedded, and contain some mudstone in the form of thin lenses, pebbles, and fragments; fossil wood is fairly abundant. Most of the ore deposits are in the uppermost sandstone strata and in or near the central, thicker parts of the lenses. Sandstone near ore bodies is colored light yellow brown with iron oxide near the surface and is pale gray and contains finely disseminated pyrite below the zone of oxidation; away from ore bodies the sandstone is dominantly pale red. The mudstone in the Salt Wash is domi-

nantly red, which is apparently the original color, but near ore deposits the mudstone immediately below and above the sandstone and the mudstone within the sandstone is altered to gray.[8]

The Salt Wash was deposited from streams meandering over a broad flood plain. It was derived mainly from pre-existing sedimentary beds exposed in highlands southwest of the area of Salt Wash deposition. Because the southwestern part of the region was closer to the source of sediments, the Salt Wash there contains much sandstone. In the eastern and northern parts of the region the Salt Wash has more mudstone relative to sandstone. In the central part, where ore deposits are most abundant in the Salt Wash, the unit contains about equal amounts of sandstone and mudstone.

The Recapture and Westwater Canyon members of the Morrison formation are similar in character, consisting of light-colored sandstone and varicolored shale or mudstone. Each unit averages a few hundred feet in thickness. Both are present in northwestern New Mexico, where they contain a few small ore deposits, but they extend only a short distance into Arizona, Utah, and Colorado. These members also accumulated under stream and flood-plain conditions.

The Brushy Basin member extends over all the Plateau region, except perhaps the southwestern part, and it averages 300 to 400 feet in thickness. It is composed mainly of variegated mudstones and siltstones, which contain some thin beds of limestone; thick lenses of sandstone, in part conglomeratic, are present in places, especially in New Mexico, where they contain large deposits of uranium.[9] Fossil wood is common. The Brushy Basin was also deposited in a stream and flood-plain environment, but one in which sandstone accumulated in lesser amounts than during the deposition of the other Morrison beds. Brushy Basin type sediments extend far east and north of the Colorado Plateau region and constitute the entire Morrison formation.

CLASSIFICATION

As described above, the lithologic character of the host rock differs among the ore deposits in the Colorado Plateau region. Differences within a single formation are generally small, but major differences occur between some formations. Deposits can be classified into four categories according to the lithologic character of their host rock, as described below and indicated by symbols on Fig. 2.

1. Sandstone-mudstone, which includes deposits in sandstone that is interbedded with mudstone and that also contains mudstone lenses and pebbles, but not enough finely divided argillaceous material to occupy all the pore spaces between sand grains; plant fossils are common. Of the deposits shown on Fig. 2 this class includes all those in the Morrison formation, most of those in the Shinarump and Chinle formations, and one of the two Dakota deposits in New Mexico.

2. Sandstone, which includes deposits in "clean" sandstone. Only Entrada deposits belong to this class.

3. Limestone, which includes all deposits in the Todilto limestone and the deposit in the Hermosa formation in southwestern Colorado.

4. Mudstone, siltstone, and argillaceous sandstone, which includes deposits in rock that is more argillaceous than the first class, sandstone-mudstone; in the argillaceous sandstone probably all or nearly all of the pore space between sand grains is occupied with argillaceous matrix; plant fossils are common. Some of the deposits in the Chinle formation belong to this class, as does one of the Dakota deposits in New Mexico.

The ore deposits may also be classified by the relative amounts of uranium, vanadium, and copper that they contain. A classification of the deposits by their metal components is given below and shown on Fig. 3.

1. Vanadium-uranium deposits, having from 1 to 20 parts V_2O_5 to 1 part U_3O_8. Nearly all deposits in the central part of the Plateau region belong to this class (Fig. 3). Included are all Morrison deposits shown except two in New Mexico, and about a third of the Triassic (Shinarump and Chinle) deposits (Fig. 1). Further, this class includes nearly all deposits in the sandstone-mudstone category (Fig. 2).

2. Vanadium (uranium) deposits, having from 20 to 40 parts V_2O_5 to 1 part U_3O_8. The deposits along the eastern margin of the Plateau region in Colorado belong to this group (Fig. 3). All these deposits are in the Entrada sandstone (Fig. 1), which contains all deposits in the sandstone category (Fig. 2).

3. Copper-uranium deposits, in which the copper content generally exceeds uranium by a few times. This group is restricted to the White Canyon area in southeastern Utah (Fig. 3). All deposits are in the Shinarump conglomerate (Fig. 1), and all are classed as sandstone-mudstone deposits (Fig. 2). The habits of these deposits, incidentally, closely resemble the habits of the so-called "Red Beds copper deposits".[2]

4. Uranium (vanadium-copper) deposits, in which the uranium (specifically U_3O_8) is more abundant than vanadium (V_2O_5) and copper. Except for two deposits in east-central Utah, all deposits in this category are along the southern and western margins of the Plateau region.

INTERPRETATIONS OF DISTRIBUTIONS AND CLASSIFICATION

The distribution of these deposits geographically and stratigraphically and their differences in metal components suggest a combination of regional and stratigraphic-lithologic influences on the concentration of the ore metals. Although some broad patterns may be discerned, not all relations can yet be completely explained.

The productive deposits in Triassic rocks are all in Arizona and Utah (Fig. 1), and most of them are in lenses of conglomeratic sandstone, either in the

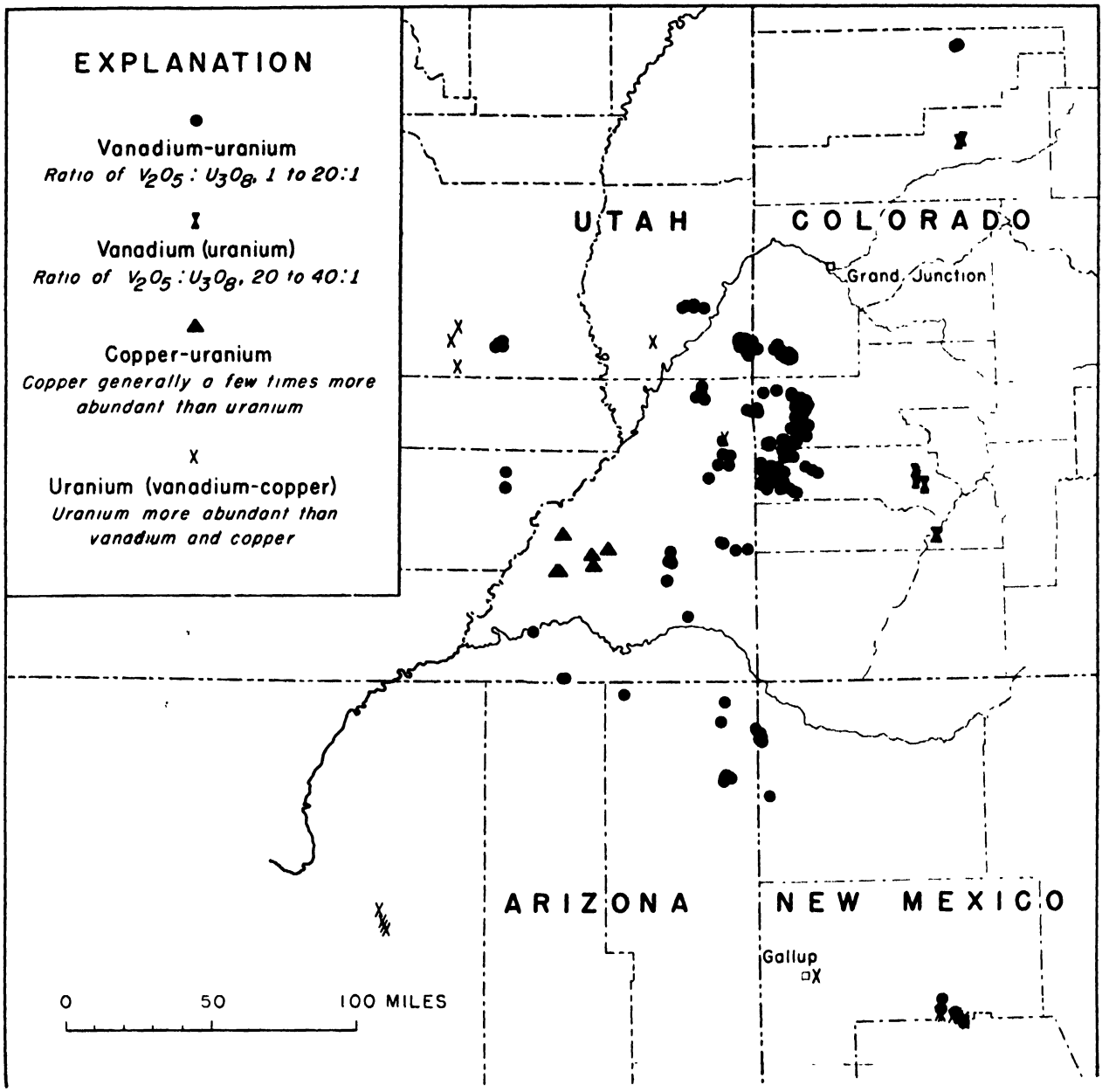


Figure 2. Map showing classification of deposits by the lithologic character of the Host Rock. Compiled with the aid of R. T. Chew, III, and H. S. Johnson. Deposits shown are taken from Finch, and had yielded 1000 tons or more of ore as of January 1, 1954

Shinarump conglomerate or in the lower part of the Chinle formation. These apparently favorable sandstone beds are either absent or poorly developed in northwestern New Mexico and western Colorado.

Nearly all of the more productive deposits in the Salt Wash member of the Morrison formation are in eastern Utah, western Colorado, and northeastern Arizona. They are approximately in the central part of the area of Salt Wash deposition, and where the unit has about equal amounts of sandstone and mudstone, which appears to be a generally favorable environment for these deposits. Westward the Salt Wash becomes sandier and eastward more shaly. Where the Brushy Basin contains ore deposits in New Mexico it also contains about equal amounts of sandstone and mudstone; elsewhere the Brushy Basin contains more mudstone than sandstone.

The more productive deposits in the Entrada sandstone are restricted to the eastern edge of the Plateau region in Colorado, and productive deposits in the Todilto limestone are known only in New Mexico. No satisfactory explanation is yet available to suggest why these deposits are so restricted in distribution.

Most of the deposits of the "uranium (vanadium-copper)" class shown on Fig. 3 are along the southern and western margins of the region and, geographically, are the most remote from the Entrada deposits, which contain a high ratio of vanadium to uranium—essentially an opposite metal ratio. This relationship suggests a zonal arrangement of rela-

tively high vanadium in the eastern part of the region and low vanadium in the southern and western parts. On the other hand, however, a comparison of the lithologic character of the high vanadium-low uranium Entrada deposits with the high uranium-low vanadium deposits in Utah and Arizona also suggests a possible lithologic influence that may have assisted in localizing the relative amounts of the metals in these deposits. As will be described under the section "Mineralogy and Mineral Habits", vanadium minerals mainly occupy open pores in sandstone whereas uranium minerals commonly replace fossil wood. The clean sandstone of the Entrada offers the open pores for the growth of vanadium minerals but contains no fossil wood, which might be needed to concentrate uranium. In contrast, five of the nine high uranium-low vanadium deposits in Utah and Arizona (Fig. 3) are in highly argillaceous rock (Fig. 2), which might not have the open pores for vanadium minerals, but the rock does have fossil wood, with which much of the uranium is associated. Detailed studies should be made to determine whether these metal differences are the result of zonal or lithologic influences, or perhaps even to other factors.

Regardless of whether the low-vanadium deposits in Utah and Arizona are influenced by zonal or lithologic relations, the southeastern part of the Plateau region appears to be a low-vanadium area, for all of the productive deposits in New Mexico are relatively low in vanadium, no matter what the type of host rock or the stratigraphic position. Although some of the deposits in this area are shown in Fig. 3 to be in the vanadium-uranium class, these actually contain a little more V_2O_5 than U_3O_8, in contrast to most of the other vanadium-uranium deposits, which contain several times more V_2O_5.

The restricted distribution of the copper-uranium deposits (Fig. 3) is certainly the most striking geographic relationship evident among the deposits in the Plateau region. There seems to be no likely stratigraphic or lithologic influence to assist in explaining the localization of this class of deposit.

MINERALOGY AND MINERAL HABITS

In addition to uranium, vanadium, and copper, the deposits contain small amounts of iron and manganese and trace amounts of lead, cobalt, nickel, molybdenum, chromium, arsenic, and selenium; some fine-grained disseminated fluorspar is associated with ore bodies in the Todilto limestone. Only uranium, vanadium, and copper, however, form constituent parts of ore-forming minerals.

The early ore minerals consist of low-valence oxides and silicates of uranium and vanadium; copper sulfides are present in places. In the oxidized zone near the surface, these minerals are altered to higher valent oxides of vanadium and to vanadates and other secondary uranium and copper minerals. For a more detailed description of the mineralogy of these deposits, the reader is referred to a report by Weeks and Thompson.[10]

Characteristically the ore minerals are fine grained and intimately mixed, so that complete identification and detailed relations are difficult to establish. Nevertheless, the principal ore minerals can be recognized and the gross relations are established. The mineralogy and mineral habits differ somewhat according to the lithologic character of the host rock and the metal components of the deposit.

In sandstone the early ore minerals mainly occupy pore spaces between sand grains. They also form rich replacements of carbonized fossil wood, commonly pseudomorphing cell structure, and perhaps partly replacing the sandstone enclosing the wood. The minerals also impregnate or replace shaly seams and mudstone fragments in the ore-bearing sandstone. Later or secondary minerals occupy the pore spaces, pseudomorph fossil wood, and coat walls of open fractures. In limestone, the early minerals are finely disseminated; later minerals replace these and coat open fractures and bedding planes. In highly argillaceous rock the early minerals replace fossil wood and form small disseminated grains; later minerals replace the earlier ones and coat fractures and bedding planes.

The uranium and vanadium oxides commonly replace fossil wood and to a lesser extent the sand grains and perhaps argillaceous material; fine disseminations in pore spaces also occur. The vanadium silicates dominantly fill the pores in the sandstone and partly impregnate or replace argillaceous material. The copper sulfides replace fossil wood, occupy pore spaces, and partly replace sand grains.

On oxidation of deposits containing an appreciable amount of vanadium, practically all the uranium combines with vanadium to form vanadates (carnotite and tyuyamunite); likely the available vanadium is derived from the vanadium oxides, for the vanadium silicates appear to be very stable. In deposits with little or no vanadium, the uranium, and copper if it is present, alter to secondary silicates, carbonates, sulfates, phosphates, and arsenates.

The metals show little tendency to migrate during oxidation of deposits containing appreciable vanadium, and under common conditions there is no evidence of secondary concentration or depletion of the metals at or near the surface. More movement of uranium, as well as copper, occurs near the surface in deposits low in vanadium, but even so the migration of metals is generally not conspicuous.

ORE BODIES

With but few exceptions, ore bodies have much the same habits regardless of their metal components, their lithologic and structural environments, and their stratigraphic position.

Ore bodies range from small masses only a few feet across to those several hundred feet across. The larger ore bodies are mainly tabular, forming layers ranging from a few feet to as much as 20 feet or more in thickness. The long axes of these layers lie essentially parallel to bedding, hence they are commonly referred to as the "bedded type," but in detail

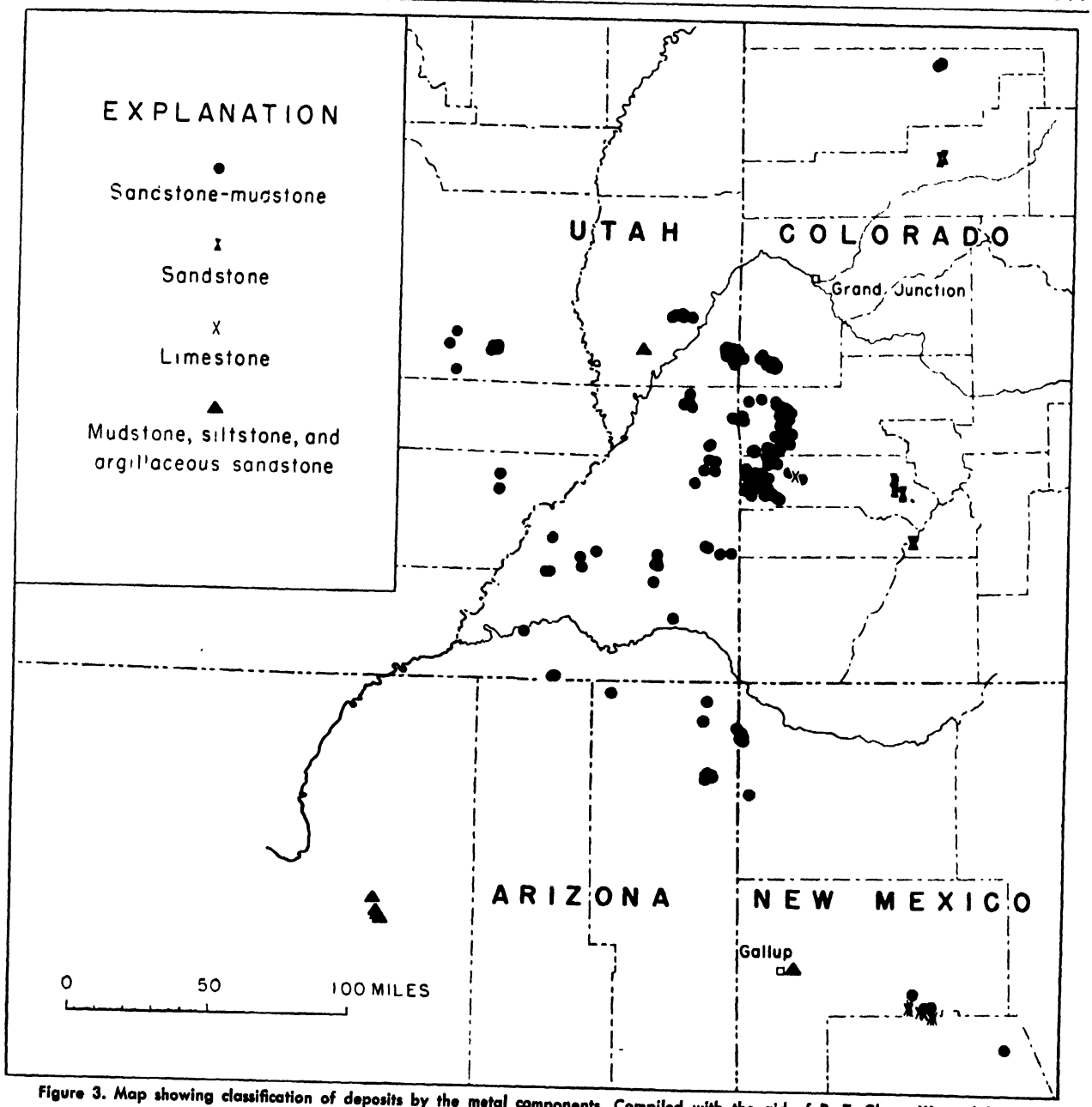


Figure 3. Map showing classification of deposits by the metal components. Compiled with the aid of R. T. Chew, III, and H. S. Johnson. Deposits shown are taken from Finch and are those that had yielded 1000 tons or more of ore as of January 1, 1954

the layers are undulant and cut across bedding. Some ore bodies, especially some of those in the Todilto limestone, are distinctly elongate in one dimension parallel to bedding and approximately equidimensional in width and height. Only a few deposits are known that have a dimension across bedding greater than along bedding.

Although the tabular bodies in sandstone are quite irregular in outline, they tend to be slightly elongate. The elongate direction is usually parallel to the direction of the course of the stream that deposited the sandstone lens or channel-fill containing the ore body, as shown by sedimentary structures such as crossbedding and current lineation and by the orientation of fossil logs. In addition, the peculiar elongate concretionary masses in the ore bodies, and which are commonly called "ore rolls," have a dominant orientation in the same direction.[11] These rolls usually form the thickest parts of ore bodies and in some cases the richest parts. Some of the more elongate ore bodies in sandstone consist of single rolls.

Some of the ore bodies in the Todilto limestone are tabular and irregular in outline but many are distinctly elongate. Typically these elongate bodies follow along lines of deformation in the limestone, some of which correspond in direction to the trends of structure resulting from regional deformation.[12]

Throughout the Plateau region ore bodies tend to be clustered in groups, a relationship that is clearly evident on the map prepared by Finch.[5] Clusters range in size from those only a few thousand feet across to those a few miles across. Distances be-

tween clusters may range from a few thousand feet to many miles. The ground between clusters may contain a few deposits, but most of them are small. In the entire region there are only a few deposits of economic importance that do not appear to be one of a cluster.

Within clusters, individual ore bodies may have well defined edges and may be separated from neighboring bodies by barren rock. Other bodies may be less well defined and layers of mineralized rock too thin or too low grade to be mined profitably may extend some distance beyond minable ore and may even connect with nearby ore bodies. A cluster and its individual ore bodies generally are elongate in a common direction.

MINERAL BELTS

Four rather narrow, elongate areas in which the uranium deposits have a closer spacing, larger size, and higher grade than adjoining areas have been recognized and described; the term "mineral belt" has been applied to each.

The Uravan mineral belt[13] is in southwestern Colorado and contains deposits in the Morrison formation. It is about 50 miles long and 1 to 5 miles wide; its over-all trend is northward, but at the north end it curves west and at the south end it curves southwest. Individual deposits and clusters of deposits within the belt are elongate normal to the local trend of the belt. A few miles east and north of the belt the ore-bearing beds change slightly in lithologic character—the sandstone is more thinly and evenly bedded and finer grained. This change probably expresses differences in the geologic environment at the time when these beds accumulated. The belt crosses, at different angles, three northwest trending synclines and anticlines; at least two of these anticlines are salt structures that originated in late Paleozoic time.

Finch[14] describes three belts of deposits in Triassic formations in Arizona and Utah. One is called the Monument Valley belt; it is about 8 miles wide and 40 miles long and trends northwestward from the northern edge of Arizona into south-central Utah. The deposits are in the Shinarump conglomerate, in conglomeratic sandstone lenses that fill channels; all deposits belong to the vanadium-uranium class. The Shinarump is less lenticular southwest of the belt and locally absent northeast of the belt. The East White Canyon belt is in southeastern Utah. It trends westward and ranges from 2 to 8 miles in width and is 30 miles or more long. All of the productive deposits are in channel-filling lenses in the Shinarump and are of the copper-uranium class. The southern edge of the belt borders the area where the Shinarump is locally absent; north of the belt the channel-filling lenses are small and less continuous than those in the belt. The Moab belt extends from central Utah eastward into east-central Utah, where it swings southeastward and perhaps continues into Colorado. It is 10 to 20 miles wide and at least 130 miles long. All of the more productive deposits are in the Chinle formation, and they include both vanadium-uranium and uranium (vanadium-copper) types. The boundaries are recognized partly on pinch-outs of the Moss Back member of the Chinle, partly in changes in the character of the channel-filled lenses, and partly on other lithologic differences.

These belts partly parallel and partly trend at angles to the major structural features resulting from regional deformation.

LOCALIZATION

In formations composed of sands and muds laid down in stream and flood-plain environments, such as the Shinarump, Chinle, and Morrison formations, the uranium-vanadium-copper deposits show a close association with certain conditions and structures of sedimentary origin. Stratigraphic units consisting of fairly thick sandstone strata interbedded with about equal amounts of mudstone are generally favorable for deposits over broad areas. Most deposits are in or near the thicker, central parts of sandstone lenses;[8] some lenses fill distinct channels.[15] Individual deposits and clusters tend to be elongate parallel to the flow direction of the stream that deposited the lens, as shown by crossbedding, current lineation, and the orientation of fossil logs. Carbonized plant fossils are generally more abundant in and near deposits than in the surrounding barren rock.[8] Deposits are commonly in sandstone where the bedding is mixed and where mudstone pebbles and carbonaceous material is fairly abundant, as might develop in stream channels at places of local turbulence, such as scours and bends;[16] such bodies of sandstone are commonly called "trash pockets." To explain those observed relations, most geologists assume that the ore-bearing solutions migrated along the beds that now contain the deposits, following the more permeable channels, and dropping their metals where conditions favored the precipitation of ore minerals.

The influence, if any, of sedimentary conditions and structures in the Todilto limestone and the Entrada sandstone on the localization of ore deposits is not clearly evident at our present state of knowledge.

A few uranium ore deposits in the Plateau region are localized along fractured zones, in which the vertical distribution of ore minerals clearly demonstrates the vertical movement of metals. At Temple Mountain[17] in central Utah, uranium and vanadium minerals are distributed along a strong fracture zone for several hundred feet above and below the Moss Back (Chinle) sandstone, which contains highly productive deposits of the so-called "bedded type." The broken rocks in the fractured zone are intensively altered, presumably by thermal solutions. Similar relations, though with less alteration and perhaps with a less conspicuous vertical distribution of minerals, occur at Richardson Basin in east-central Utah and along Roc Creek in southwestern Colorado. These fractured zones have not yielded much ore, though some of that mined at Roc Creek was very rich.

In a few other places in the Plateau region, uranium minerals have been deposited along faults, but not in amounts sufficient to make ore.[18]

Near Laguna, in northwestern New Mexico, uranium ore has been mined from a brecciated, pluglike structure that has been called a breccia pipe. The structure is roughly circular in plan, about 25 feet in diameter, and the core has collapsed about 20 feet. Host rock is a thick sandstone bed in the Morrison formation. The ore, some of which is high grade, is mainly coffinite with abundant pyrite; the ore minerals replace sandstone near fractures and partly fill the fractures.

Numerous "bedded" uranium ore bodies in sandstone in the Plateau region are cut and displaced by faults; a breccia of mineralized rock and a small amount of secondary minerals are common along these faults. Most geologists who have mapped these bodies believe the faulting is post-ore, though some have expressed contrary opinions. Many of the ore bodies in the Todilto limestone follow along lines of wavy or crumbled bedding; it is not yet entirely clear whether these structures resulted from penesyngenetic crumpling or regional deformation, though some of them correspond in direction to the regional fracture pattern.[12]

Many uranium deposits in the region are within a few miles of the major structural features; most of these features are folds, some of which are faulted. Butler[19] originally suggested that the anticlinal folds influenced the migration of the ore-bearing solutions and thus played a part in localizing these deposits, and many geologists today adhere to this idea. Other geologists interpret this apparent relationship to be mainly the result of better exposure along these structures, and they place significance on many deposits that are more remote from these structures. Much more study and exploration will be required before these differences are resolved.

Igneous activity, consisting of intrusions and extrusions, has been intensive in places along the eastern, southern, and western margins of the Plateau region, and several moderate-sized stocks and laccoliths, with associated dikes and sills, have intruded the sedimentary rocks in the central and eastern parts of the Plateau region. Some typical uranium deposits are close to these intrusive masses, and a few deposits are actually cut by igneous bodies, but as none of these deposits near igneous rock differ significantly in character from the many deposits that are remote from exposed igneous rocks, geologists in general are not inclined to relate the deposits directly to known igneous masses. On the other hand, some uranium is concentrated in or near volcanic vents (diatremes) in the southern part of the Plateau region,[20] but these deposits do not appear to be closely related to more common uranium deposit.

Vein deposits of precious and base metals of hydrothermal origin are common in some of the centers of igneous activity along the margins of the Colorado Plateau region, especially in the San Juan Mountains area of southwestern Colorado. A few similar veins also occur within or near the intrusive masses in the Plateau region.

Some of the veins in the San Juan Mountains area contain small amounts of pitchblende and some have roscoelite, the vanadium-bearing mica, intergrown with quartz gangue. Pitchblende-bearing veins are being mined at Marysvale, Utah, just west of the Plateau region.

AGE OF THE DEPOSITS

Radioactive age determinations of uranium ores from Triassic and Jurassic rocks in the Plateau region show an average age of about 60,000,000 to 70,000,000 years,[21] which is considerably younger than the estimated ages of the host rocks, and which corresponds closely to the estimated time of Laramide deformation of the Late Cretaceous or early Tertiary and to the age of the pitchblende-bearing veins of the Front Range in central Colorado. Unfortunately the geologic events that occurred in the region at this time are not well recorded, largely because sedimentary beds of that age and younger are absent over most of the region. It seems reasonable to assume, however, that this deformation took place shortly after the deposition of the thick marine sediments of Late Cretaceous age, that the ore-bearing rocks were still deeply buried but likely were being deformed by folding and perhaps faulting, and that likely igneous activity was beginning in places bordering the region and even within the region.

EXPLANATIONS OF ORIGIN

Expressed opinions regarding the origin of these deposits have practically run the gamut of possibilities of ore formation, but they can be generalized into three concepts.

1. Penesyngenetic or early epigenetic, during periods of active ground-water circulation shortly after the accumulation of the beds enclosing the deposits; the metals presumably were derived by secretion from associated rocks. This idea was conceived to avoid the possible difficulties of obtaining active circulation during deep burial in Late Cretaceous time and the apparent lack of influence of later structures on localization.

2. Later epigenetic, by vertical and lateral secretion, accompanying the resumption of active ground-water circulation during and following Laramide deformation; part of the required energy may have been from heat derived from contemporaneous igneous and hydrothermal activity. It was conceived to explain the wide distribution, and assemblage of metals common in sediments, and the lack of habits common to many types of metalliferous deposits.

3. Hydrothermal, derived from widely active, deep-seated sources by solutions rising along available vertical pathways and spreading laterally along favorable beds, or perhaps even by a process of "crustal sweating" of thermal solutions. It was conceived to explain the wide distribution of similar deposits, the low-intensity and apparent low-tempera-

ture character of mineralization, and the lack of habits typical of many hydrothermal deposits.

Each of these three ideas have some inherent points that assist in explaining certain of the observed habits of these deposits; none offers an explanation that appears to be the simple and complete answer. The metals presumably are available from the associated strata, either early or late, provided there are opportunities for solutions, transportation, and concentration. The penesyngenetic idea, however, must be eliminated if the relations on which the age determinations are made require the introduction of the metals 60,000,000 to 70,000,000 years ago, rather than a rearrangement and the migration of daughter products at that time. With our present knowledge of the geologic history of the Plateau region the determined age of the deposits is not incompatible with either the later epigenetic or hydrothermal ideas. Some geologists find it difficult to accept either of these ideas, however, in view of the lack of a more apparent influence by regional structures on the localization of the deposits.

REFERENCES

1. Johnson, J. C., *Statement Presented at the Hearings Before the Joint Committee on Atomic Energy, January 31, February 1, 3, and 4, 1955,* US Government Printing Office (1955).
2. Fischer, R. P., *Sedimentary Deposits of Copper, Vanadium-Uranium and Silver in Southwestern United States,* Economic Geology 32: 906–951, (1937).
3. Coffin, R. C., *Radium, Uranium, and Vanadium Deposits of Southwestern Colorado,* Colorado Geological Survey Bulletin 16 (1921).
4. Hess, F. L., *Uranium, Vanadium, Radium, Gold, Silver, and Molybdenum in Sedimentary Deposits, in Ore Deposits of the Western States (Lindgren volume),* 450–481, American Institute of Mining and Metallurgical Engineers (1933).
5. Finch, W. I., *Preliminary Geologic Map Showing the Distribution of Uranium Deposits and Principal Ore-bearing Formations of the Colorado Plateau Region,* US Geological Survey Mineral Investigations Field Studies Map MF 16 (1955).
6. Williams, G. A., Albee, H. F., Cadigan, R. A., Raup, Omer, *et al.,* written communication.
7. Craig, L. C., Holmes, C. N., Cadigan, R. A., Freeman, V. L., *et al., Preliminary Report on the Stratigraphy of the Morrison and Related Formations of the Colorado Plateau Region,* US Geological Survey Bulletin 1009 (in press).
8. Weir, D. B., *Geologic Guides to Prospecting for Carnotite Deposits on the Colorado Plateau,* US Geological Survey Bulletin 988–B (1952).
9. Hilpert, L. S. and Freeman, V. L., *Guides to Uranium Deposits in the Gallup-Laguna Area, New Mexico,* US Geological Survey Circular (in preparation).
10. Weeks, A. D. and Thompson, M. E., *Identification and Occurrence of Uranium and Vanadium Minerals from the Colorado Plateau,* US Geological Survey Bulletin 1009–B (1954).
11. Fischer, R. P., *Vanadium Deposits of Colorado and Utah,* US Geological Survey Bulletin 936–P (1942).
12. Gilkey, A. K., *Fracture Pattern of the Zuni Uplift,* US Atomic Energy Commission RME–3050, Technical Information Service, Oak Ridge, Tennessee (1953).
13. Fischer, R. P. and Hilpert, L. S., *Geology of the Uravan Mineral Belt,* US Geological Survey Bulletin 988–A (1952).
14. Finch, W. I., *Geology of Uranium Deposits in Triassic Rocks of the Colorado Plateau,* US Geological Survey Bulletin (in preparation).
15. Witkind, I. J., *Localization of Uranium Minerals in Channel Sediments at the Base of the Shinarump Conglomerate, Monument Valley, Arizona,* US Geological Survey Bulletin (in preparation).
16. Stokes, W. L., *Some Stratigraphic, Sedimentary, and Structural Relations of Uranium Deposits in the Salt Wash Sandstone,* US Atomic Energy Commission RME–3102, Technical Information Service, Oak Ridge, Tennessee (1954).
17. Keys, W. S., P/41, *Deep Drilling in the Temple Mountain Collapse, San Rafael Swell, Emery County, Utah,* Vol. 6, Session 6B, these Proceedings.
18. Shoemaker, E. M. and Newman, W. L., written communication.
19. Butler, B. S., *et al., The Ore Deposits of Utah,* US Geological Survey Professional Paper 111 (1920).
20. Shoemaker, E. M. P/48, *Occurrence of Uranium in Diatremes on the Navajo and Hopi Reservations, Arizona, New Mexico, and Utah,* Vol. 6, Session 6B, these Proceedings.
21. Stieff, L. R., Stern, T. W. and Milkey, R. G., *A Preliminary Determination of the Age of Some Uranium Ores of the Colorado Plateau by the Lead-Uranium Method,* US Geological Survey Circular 271 (1953).

Some Examples of Uranium Deposits in the Upper Jurassic Morrison Formation on the Colorado Plateau

By Philip H. Dodd,* USA

The uranium deposits discussed below were chosen as illustrations of the geologic features which are common but controversial. The areas are: 4 B mine and vicinity, Poison Canyon mine, Basin Number One mine, and the area of the Wedding Bell group, all of which are in the Morrison formation of Jurassic age (Fig. 1).

A test pit sunk by Tom Talbert in 1881 is the first recorded mining of Colorado Plateau uranium-vanadium deposits. By 1910 deposits had been discovered in many of the districts which are productive today. From 1910 to 1923 the Morrison deposits were mined for radium and vanadium. With cheaper vanadium production in South America and pitchblende in the Belgian Congo, most of the properties were closed. A renewed demand in 1936 for vanadium opened the mines and production continued through 1945, recessed then renewed in 1948 in response to the urgency for domestic production of uranium.

Craig and others[1] have defined the extent and lithofacies of the Upper Jurassic Morrison formation (Fig. 2) and its four component members all of which bear ore at various stratigraphic horizons. Controls localizing the ore deposits are imperfectly understood. No genetic connection between lacolithic intrusives and the ore deposits has yet been established. Major tectonic structures such as faults, shear zones, and flexures have not been satisfactorily demonstrated as controls. Sedimentary structures, while having limited regional control, do appear to influence the shape of individual orebodies. Sedimentary facies may make one locality more favorable than adjacent areas. Interfaces between fast and slack water deposits and presence of abundant carbonaceous material are accepted factors related to ore localization. Empirical criteria of limited reliability for recognition of zones favorable for orebodies—light tan and light gray sandstone, green to gray alteration of adjacent mudstone, finely disseminated pyrite or limonitic alteration, and concentrations of coalified plant debris—are in use.

Epigenetic origin of the deposits is suggested by a number of factors: late Cretaceous or early Tertiary age determined by uranium and lead isotope studies,[2] occurrence in formations ranging in age from Pennsylvanian through Tertiary,[3] deposits containing low-valent uranium and vanadium minerals not in equilibrium with the zone of oxidation, and replace-textures of ore in fossil wood and bone.

4 B MINE AND VICINITY

The 4 B mine (Figs. 1, 2) is located on Mesa 4½[4,5] where deposits were discovered by drilling in 1951 and 1952.

Geology

Stratigraphy

At the site of the Lukachukai mountains, 3000 feet of fluviatile, lacustrine, and eolian sediments were deposited in the Triassic and Jurassic periods. These include the ore-bearing fluviatile deposits of the Salt Wash sandstone member of the Morrison formation of Upper Jurassic age. About 6000 feet of marine and continental sediments were deposited prior to the Laramide deformation and erosion which stripped Cretaceous and early Tertiary rocks from the Lukachukai Mountains. The Pliocene (?) Chuska formation rests on the Laramide unconformity and is intruded by basalt.

Three facies of Salt Wash (Fig. 3), representing different depositional environments, were mapped by Masters.[5] The Salt Wash on the northwestern end of the Lukachukai Mountains is thick massive sandstone with relatively few mudstone lenses. This facies grades into an intermediate zone of interbedded lenticular sandstone and mudstone which grades southeast into a floodplain facies of mudstone, siltstone, and occasional thin and discontinuous sandstone lenses. As shown on Fig. 3, the orebodies appear to be confined to the zone of interbedded sandstone and mudstone which trends north to northeast across the mountains. Masters[5] believes the calcium carbonate content of the member increases from west to east as does the abundance of carbonaceous plant fossils.

Structure

The northwest plunging Lukachukai anticline dips southwest 10 to 30 degrees, reversing the gentle 1½ degree northeast dip off of the Defiance uplift. This anticline and the syncline which lies immediately to the south, are assumed to be of Laramide age.

Mesa 4½ is on the south flank of the syncline where the dip averages 1½ degrees northeast (Fig. 3). Detailed mapping on the north side of the

* US Atomic Energy Commission.

Lukachukai Mountains disclosed minor terraces but none of these correlate with concentrations of orebodies.

Ore Controls

The ore deposits on Mesa 4½ are restricted to lenticular light gray or very light tan sandstone. Often the orebodies are adjacent to zones of barren red sandstone within the same lens (Figs. 4, 5). Sandstone isopach maps, and structure contour maps drawn on the base of the ore-bearing unit, demonstrate that the light gray color coincides with areas of thick sandstone. The light gray may represent an alteration from red sandstone, a color change restricted to permeable zones and possibly related to ore introduction. On Mesa 4½, as in other mining areas, the orebodies occur as irregularly spaced, roughly aligned groups (Fig. 4). The individual pods of ore are irregular in shape, tabular, and often are elongate parallel to the sedimentary trend and to adjacent ore pods (Fig. 5).

Beam[4] mapped fracture concentrations associated with orebodies in the 4 B mine and 709 mine (Fig. 5). He states, "fractures in ore are closely-spaced, well-defined planes with nearly vertical dips. Fractures in barren ground are wider spaced, poorly defined planes and have, generally, lower dips." If barren drifts were mapped in the same detail as the orebodies, only a poor correlation between concentration of fractures and the distribution of orebodies would be seen; all ore pods are not fractured and conversely all intensely fractured zones are not mineralized. Cross sections of the generally flat and tabular orebodies (Fig. 6), fail to indicate a vertical distribution of ore that might be expected if it is intimately controlled by concentrations of fractures.

Beam believes zones of carbonate-impregnated sandstone are associated with the ore. The carbonate bodies are flat tabular masses from a few inches to 6 feet in thickness and up to 160 feet long. They generally parallel the bedding but in detail may be discordant. The carbonate ranges from relatively pure nearly colorless calcite to red and black, the colors probably due to a mixture of iron, manganese, and vanadium oxides; some of the carbonate may be ankerite and siderite. The carbonate occurs interstitial to sand grains which are slightly corroded. Masses of carbonate 1 to 10 inches across form a poikilobastic texture. Ore appears to be nearly always in contact with such carbonate concentrations either overlying or underlying it.

Mineralogy

Mineralogical study of the 4 B mine is in progress and data yet allows only generalizations. The ore is mostly oxidized and the following oxidized ore minerals have been identified: metatyuyamunite, pascoite, melanovanadite, hummerite, rossite, and metarossite.[6] Traces of uraninite have been tentatively identified as partial replacement of fragments of carbonaceous material. It is probably true that the ores before oxidation were of the uraninite-montrosite type. Fine-grained hematite and goethite are abundant, particularly as coatings of mudstone galls; they often resemble pseudomorphs after pyrite.

The average vanadium-uranium ratio on Mesa One is 2:1 while the average on Mesa Five is 7:1. The average vanadium-uranium ratio of samples taken from drill cores on Mesa 4½ in the vicinity of the 4 B mine is 5.2:1. It appears that there is a tendency toward vertical zoning of metal ratios on Mesa 4½. Cross sections by Crew and Lowell illustrate (Fig. 7) a slight stratigraphic spread of ore deposits within the same general ore-bearing unit. Using the zones delineated by them it is found that the upper (No. 2) zone has a ratio V:U::1.6:1, the middle (No. 3) zone has a ratio of 6.2:1 and the lower (No. 3) zone has a ratio of 9.3:1. It is not known whether this zoning is a primary or a secondary feature. The histogram in Fig. 7 demonstrates that although the arithmetic mean ratio of metals for Mesa 4½ is 5.2:1, that 45% of the samples had a ratio of less than 2:1. This may more nearly represent the metal ratios of the primary unoxidized ore.

POISON CANYON MINE

The Poison Canyon mine is in southern McKinley County, New Mexico about ten miles north of the town of Grants.

Geology

Stratigraphy

Commercial uranium deposits are located in the Todilto limestone, Morrison formation, and Dakota sandstone on the northeast flank of the Zuni uplift which extends 55 miles between Grants and Gallup, New Mexico. The flanks of the pre-Cambrian core of the Zuni uplift is successively overlain by the Abo, Yeso, Glorieta, and San Andreas formations of Permian age; the Chinle formation and Windgate sandstone of Triassic age; and the Carmel, Entrada sandstone, Todilto limestone, Summerville formation, Bluff sandstone, and Morrison formations of Jurassic age; and the Dakota sandstone, Mancos shale, and Mesa Verde formations of Cretaceous age (Konigsmark[7]). Three members of the Morrison formation are recognized: the basal Recapture shale member, Westwater sandstone member (ore-bearing) and the Brushy Basin shale member (ore-bearing).

Structure

The Zuni uplift is a broad northwest trending anticline on the southern edge of the San Juan basin. The sedimentary rocks of the northeast flank generally dip 1 to 10 degrees north and northeast. Subsidiary folds are related to faults either as drag folds or as monoclines reflecting faults in the crystalline basement. The Bluewater fault west of Poison Canyon strikes west of north, is vertical, and has a displacement of 570 feet. Lesser faults have a similar trend. Conjugate sets of joints are vertical

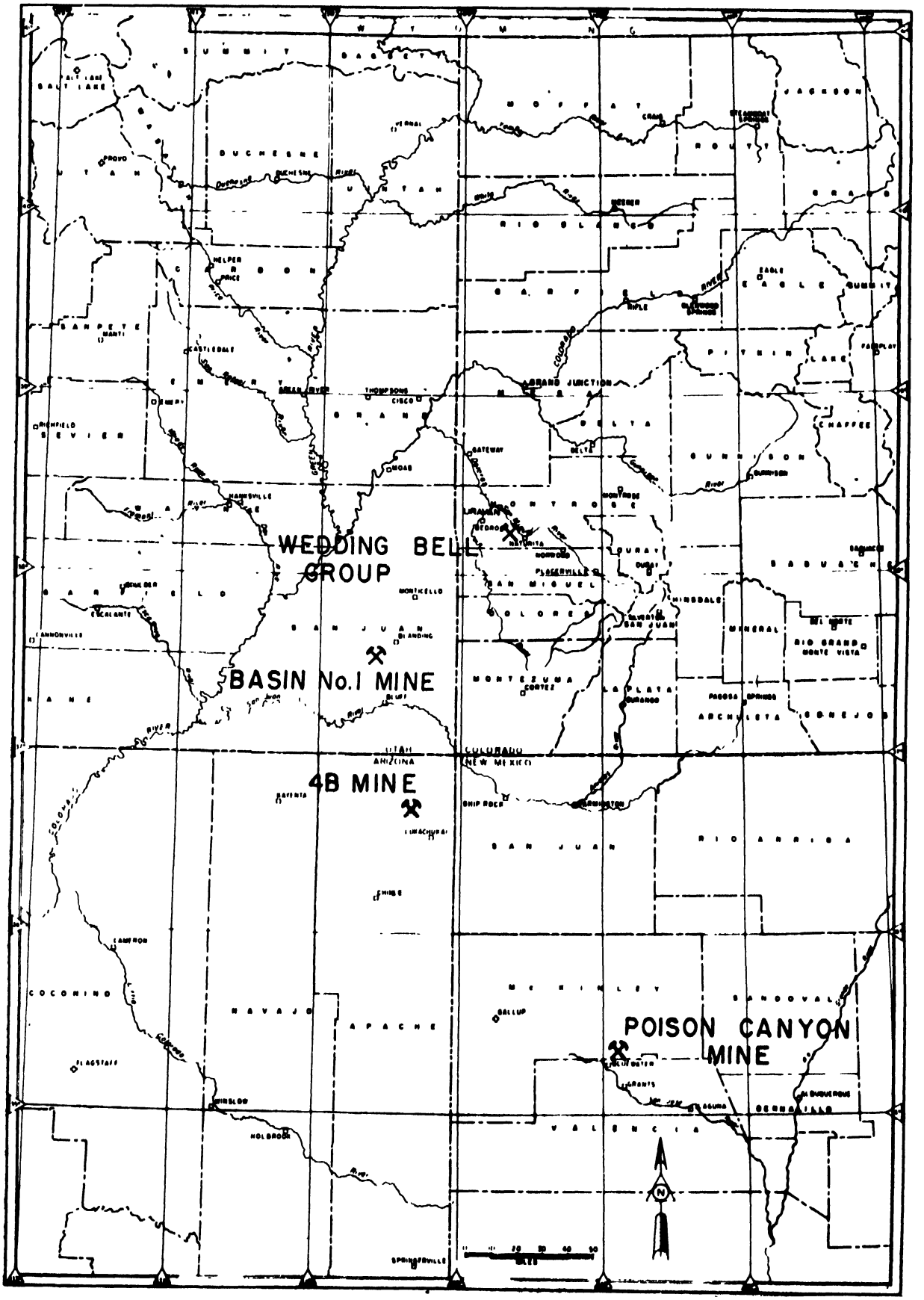


Figure 1. Location of example mines in the Morrison formation on the Colorado Plateau

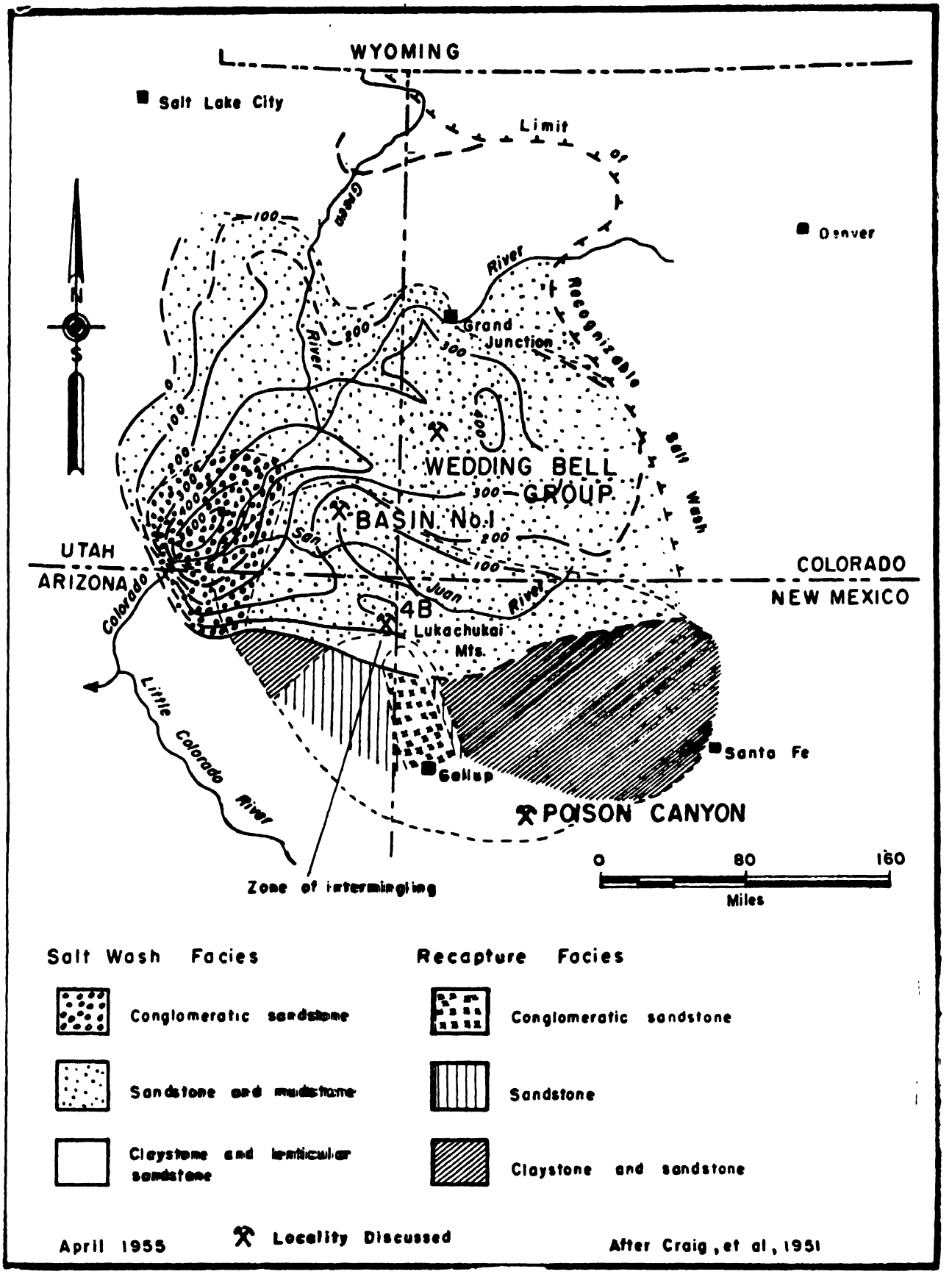


Figure 2. Isopach and facies map of Salt Wash sandstone and facies map of Recapture shale, Utah, Colorado, Arizona, New Mexico

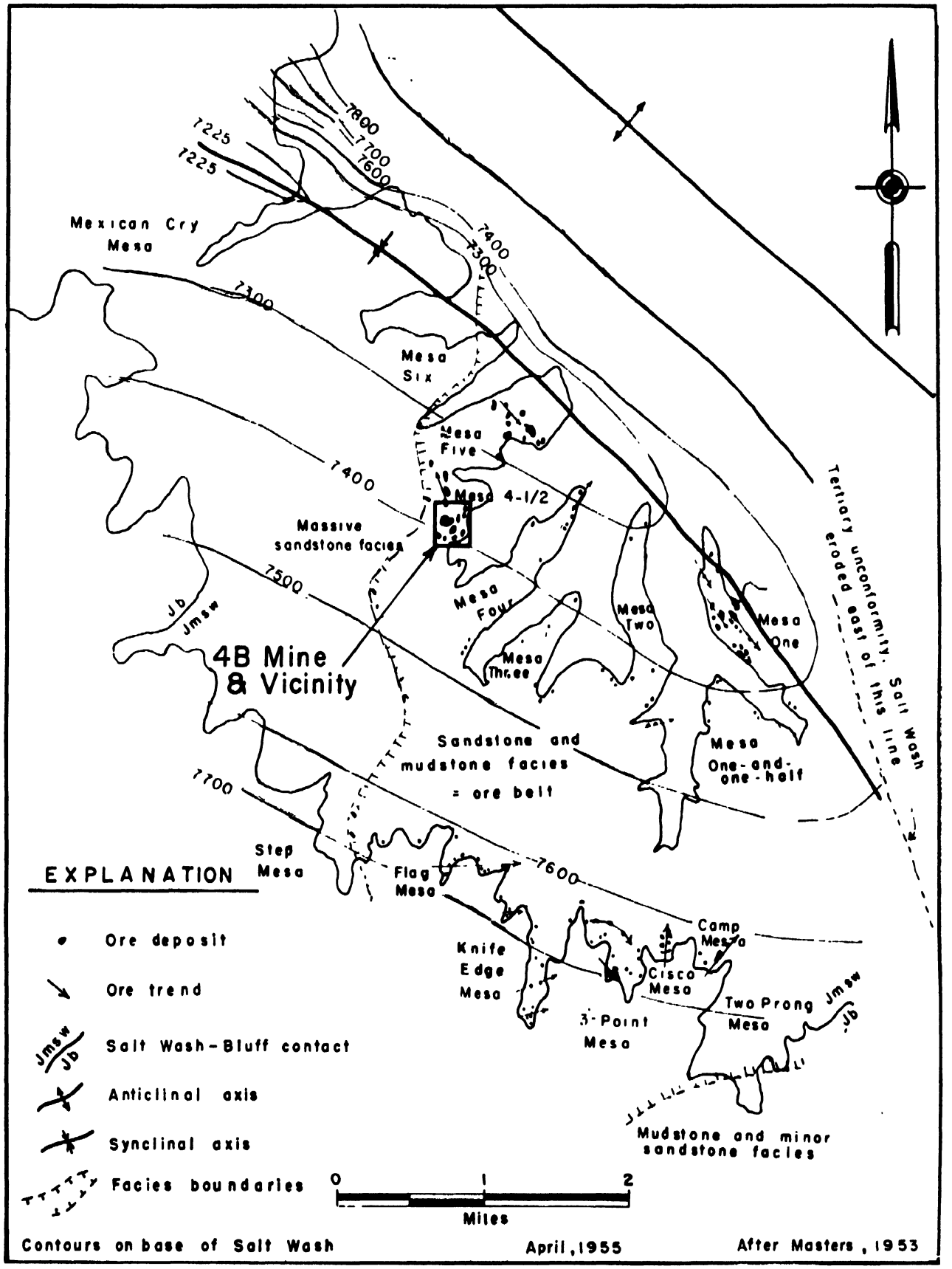


Figure 3. Ore deposits, ore trends, and sedimentary facies, Lukachukai Mtns., Apache County, Arizona

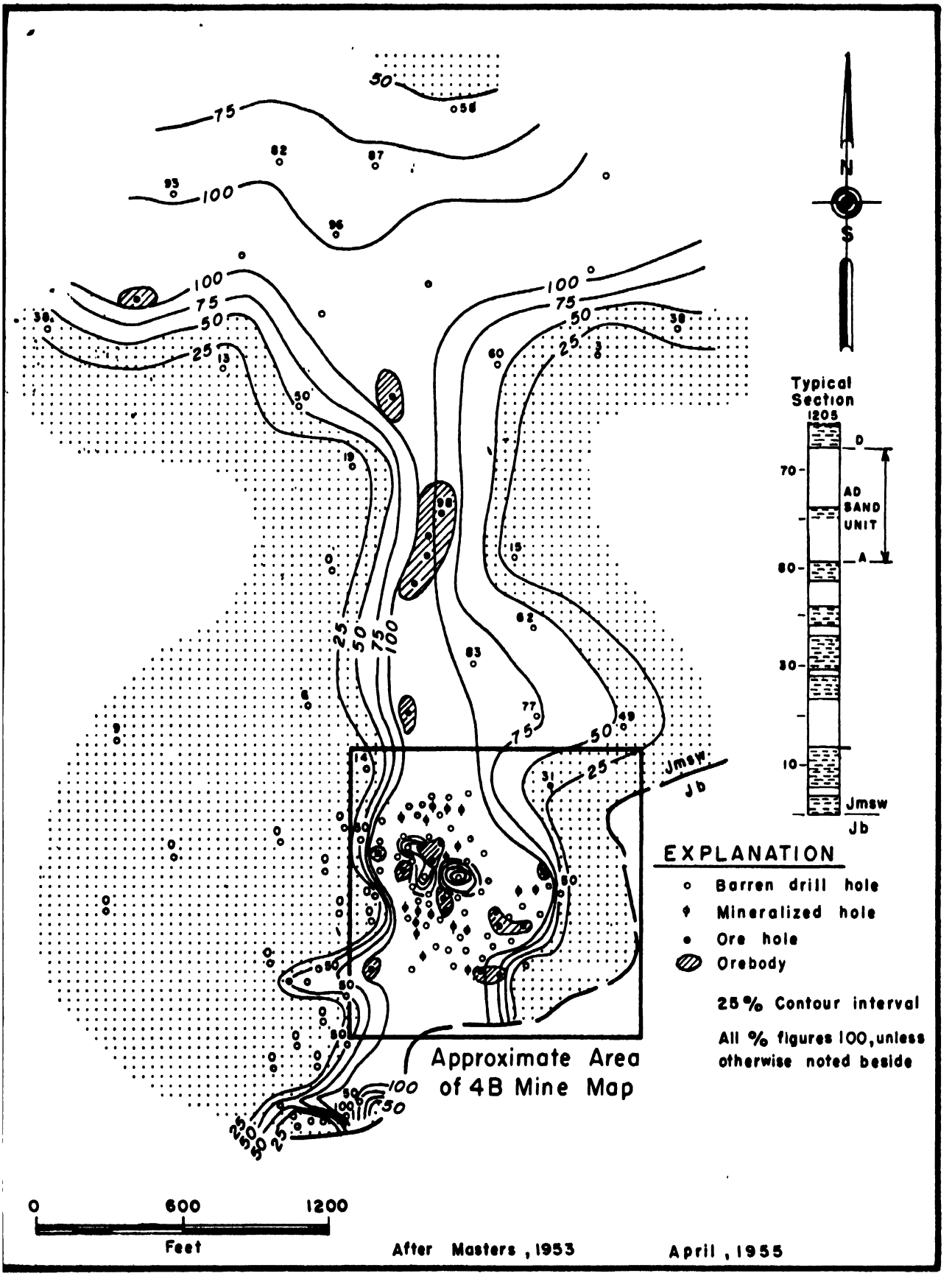
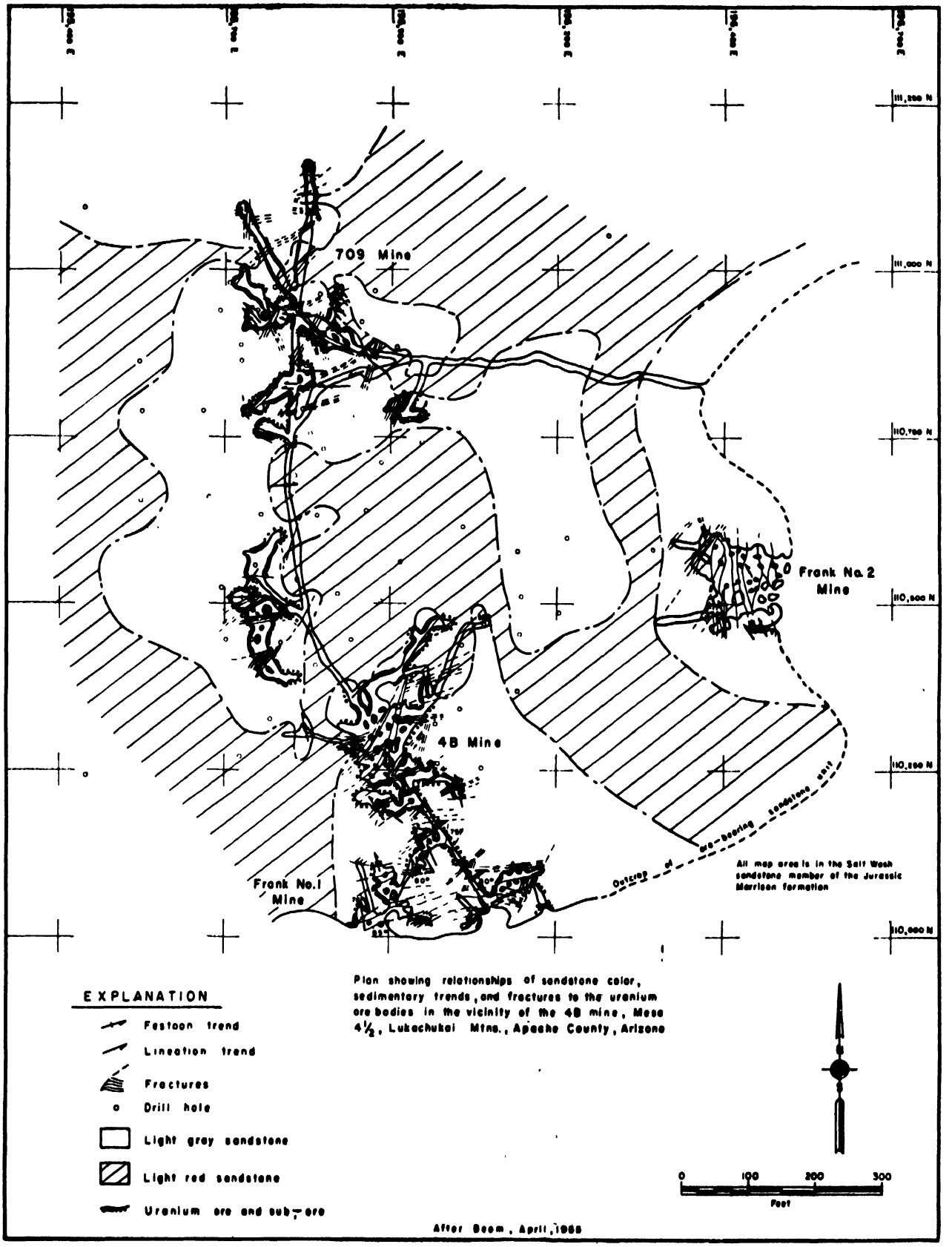


Figure 4. Isopercentage of favorable-color sand AD sand unit, Mesa 4½, Lukachukai Mtns., Apache County, Arizona



Plan showing relationships of sandstone color, sedimentary trends, and fractures to the uranium ore bodies in the vicinity of the 4B mine, Mesa 4½, Lukachukai Mtns., Apache County, Arizona

Figure 5. Geology of the 4 B Mine and vicinity Mesa 4½, Lukachukai Mtns., Apache County, Arizona

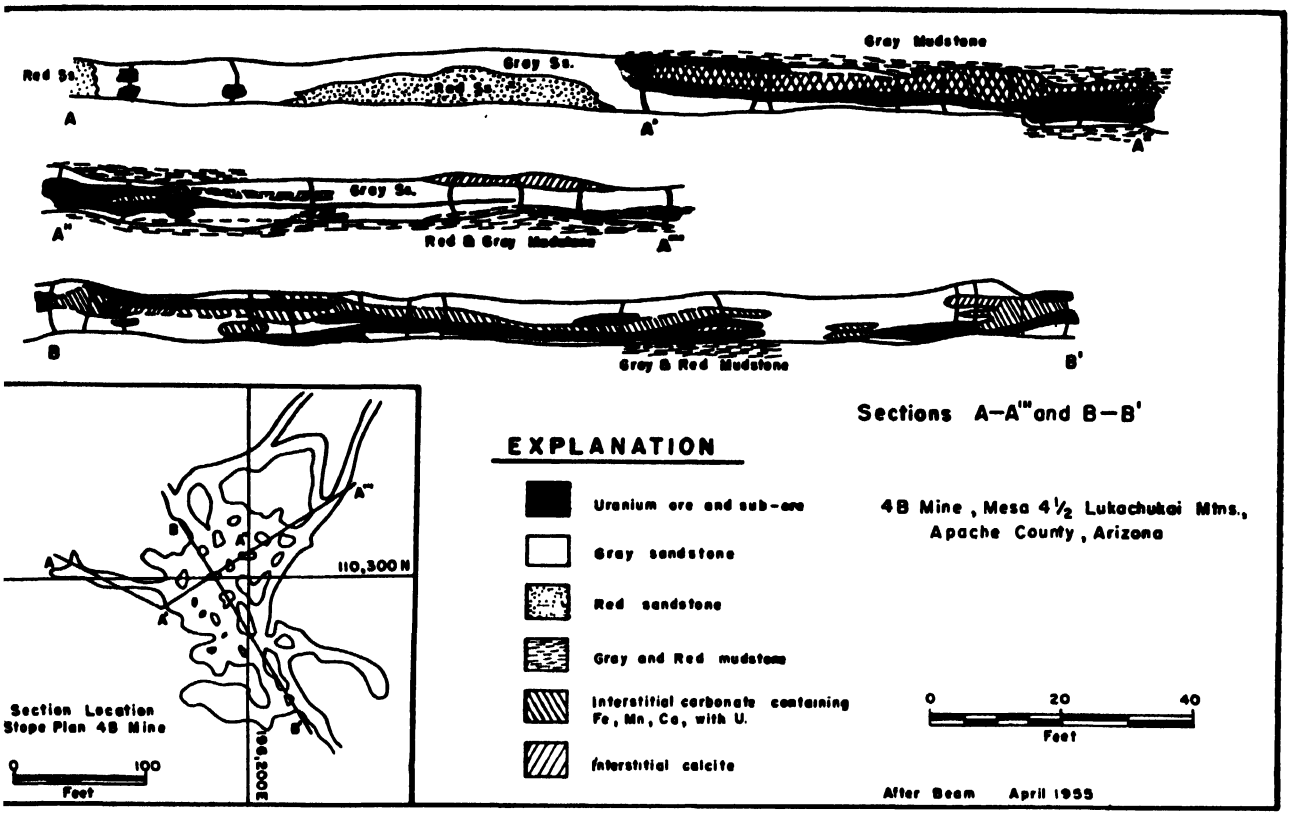


Figure 6. Sections showing uranium distribution and associated carbonate

nd the major sets parallel fault directions. Gilkey[8] ncluded the fracture pattern of the Zuni uplift ould develop from uplift rather than by lateral mpression. The major tectonic activity is post-akota and pre-Miocene.

tratigraphy and Petrology

The Poison Canyon deposit is in a thick sand-one unit near the base of the Brushy Basin shale ember. It is separated from the underlying West-ater by about 20 feet of pale blue-green mudstone. he sandstone unit appears to represent a localiza-on of continued deposition by an aggrading stream hich built up multiple lenses of coarse clastics inter-edded with minor seams of mudstone, conglomerate, nd zones of mudstone galls. This sandstone unit is 5 feet thick near the mine, but thins eastward nd to the west grades into a thinner silty unit Fig. 9). Near the mine about 60% of the sandstone medium- to coarse-grained and becomes increas-igly finer-grained to the east and west. The sand rains at the mine range from 4 mm to $\frac{1}{16}$ mm i diameter and are mostly subround. Average mposition of the sandstone is 48% quartz, 39% icrocline, 7% plagioclase, while limonite cement, re minerals and others total 6%. Cross-bedding nd lineations indicate deposition in east-northeast owing streams. Coalified fossil plant and fossil bone ragments are common in the ore-bearing sand-one. Figure 8 shows that the Mesa Top mine is so located in the thicker portion of the eastward ctension along the sedimentary trend of the sand-one unit containing the Poison Canyon mine.

Structure

The dip adjacent to the Poison Canyon mine is 2 degrees north. No major fault intersects the mine but a series of minor faults with displacements of 2 to 12 feet strike west of north and dip from 65 to 75 degrees either east or west. Fracture zones appear to be related to the faults and have a similar strike and dip.

Ore Controls

The orebody is elongate along the trend of sedimentary structures and is localized in the central, thick, coarse-grained portion of the sandstone unit. The orebody is cut by faults and fractures intersecting it at nearly 90 degrees to the long axis, and is slightly off-set vertically across the faults (Fig. 10). This might suggest the faults were post-mineralization and had no influence on localization. However, Konigsmark[7] has shown that grade and thickness of ore increases adjacent to the faults, indicating an influence on localization. Only secondary minerals are found on fault and fracture surfaces.

Some coalified plant fragments and some fossil bones in otherwise barren sandstone above the ore are uranium-bearing. Most ore-impregnated sandstone is usually within a few feet above the mudstone below the Poison Canyon sandstone.

Mineralogy

Ore in the Poison Canyon mine is classed as uranium-low vanadium; the V:U ratio averages 0.5:1. The primary vanadium mineral has not been identi-

fied. Except for secondary minerals on fracture surfaces the ore is unoxidized.

The primary uranium mineral coffinite[6] is intimately associated with a black carbonaceous material, tentatively called asphaltite, which impregnates the sandstone of the orebody.

Metatyuyamunite, believed to be secondary, is found as yellow halos in the sandstone around coffinite and along fractures cutting or adjacent to the orebody. Meta-autunite occurs as fine plates on fracture surfaces. Pyrite is fine-grained but abundant in the black ore. Traces of galena have been noted.

BASIN NUMBER ONE MINE

(Prepared by R. K. Pitman)

The Basin No. 1 Mine is in the Cottonwood Wash mining district approximately 13 miles west of Blanding, San Juan County, Utah. Vanadium-uranium deposits were discovered in the area in 1930.

Geology

Stratigraphy

Formations exposed in the district range from the lower Jurassic Navajo sandstone to the upper Cretaceous Mancos shale. The Jurassic Morrison formation, which contains most of the uranium deposits, is sub-divided into: the Salt Wash sandstone member (210 feet thick); the Westwater sandstone member (150 feet thick); and the Brushy Basin shale member (400 feet thick). All major ore deposits are in the upper portion of the Salt Wash member.

Only upper beds of the Salt Wash member are exposed in the mining area. Here the Salt Wash consists of fluviatile channel sandstone facies interbedded with marginal mudstone floodplain type facies. These have a general eastward trend which agrees with the regional depositional pattern for Salt Wash streams.[1]

The Salt Wash sandstone is normally fine- to medium-grained, and is mostly well sorted. The color is commonly light gray to buff, but may be a very light red. Sub-angular quartz grains are the major constituent with minor amounts of salmon colored chert, feldspar, and traces of heavy minerals. Calcite is a common cementing material in the sandstone. The mudstone and siltstone colors range from dark red and brown to greenish gray, and in many places the light colored mudstones appear to have been altered from originally darker colored rocks.

Coalified plant remains are commonly found along the marginal zones of the Salt Wash paleostream channels. Remains of large trees are common in some of the mines of the area, but in the Basin No. 1 Mine these have been so flattened that they appear as carbonaceous layers.

Structure

The Cottonwood area is on the east flank of the Comb Monocline where the eastward dip of the sedimentary rocks changes from six degrees two miles west of the Basin Number One Mine to approximately one degree near the mine.

The dip, based on a structure contour map of the top of Bluff sandstone, is estimated to be one degree near the Basin Mine. The true dip of the Salt Wash is obscured by initial sedimentary dips.

Joints in the mine are vertical and strike northwest but are not as prominent as the jointing in the overlying Westwater member. There is no local faulting.

Economic Geology

Subsurface mapping from drill cores adjacent to the Basin No. 1 Mine shows that the orebody is in an area of rapid change from a channel to a floodplain lithofacies.[9] Structure contours on the base of the ore-bearing sandstone indicate that a very shallow paleoscour is in close alignment with the thickest part of the orebody (Fig. 11). This is supported by an isopach map which shows that the thickest part of the ore-bearing unit aligns very well with the paleoscour low (Fig. 12). The orebodies do not always occur at the base of the sandstone, but are found as lenses irregularly distributed within the unit. These mineralized lenses within the mine are usually adjacent to thin mudstone beds or layers of clay galls.

Alteration of the red or brown mudstones and siltstones to gray-green in the vicinity of uranium deposits is a common phenomenon on the Colorado Plateau.[10] However, in this deposit the distribution of alteration does not consistently correspond with the thickest part of the orebody. Figure 13 was constructed by contouring the thickness of altered mudstone below the ore sandstone; on this was superimposed the outline of mine workings. An area with no alteration was found directly below the central portion of the deposit. Thus, there is a general correlation between altered mudstone and the vicinity of ore but no direct correlation between amount of alteration and ore grade or thickness.

The ratio V:U in the northern ore lens is approximately 5:1 in the center and increases outward to over 20:1 near the perimeter (Fig. 14). In contrast, the ratio is low on the perimeter of the southern and central ore lenses, but increases near the center of the deposits.

Underground mapping of the orebody indicates that greatest thickness coincides with the paleostream channel-fill. The few lineation and intrachannel scour directions noted underground in the ore sandstone substantiate the trend of the paleochannel determined by drilling (Fig. 15). Jointing is not prominent underground and does not appear to have been a factor in the concentration of uranium. Carbonaceous materials within the orebody are the locus of high-grade uranium-vanadium concentration, and are presumed to have been a factor in ore concentration, but most of the coaly material adjacent to the ore bodies does not contain uranium.

Many ore lenses were found to terminate in the vicinity of mudstone seams and clay galls. Individual

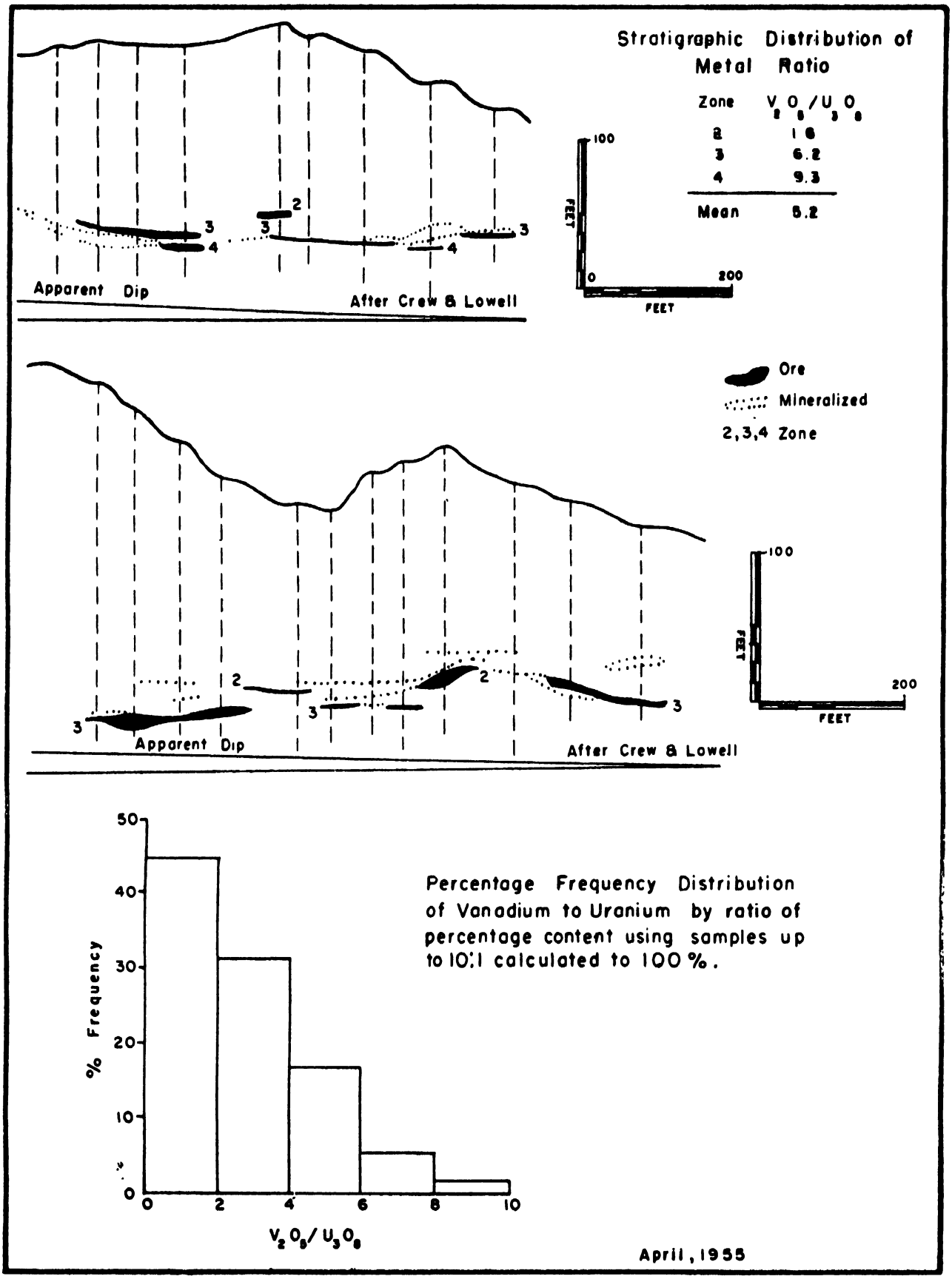


Figure 7. Vanadium-uranium ratio distribution, 4 B Mine locality Mesa 4½, Lukachukai Mtns., Apache County, Arizona

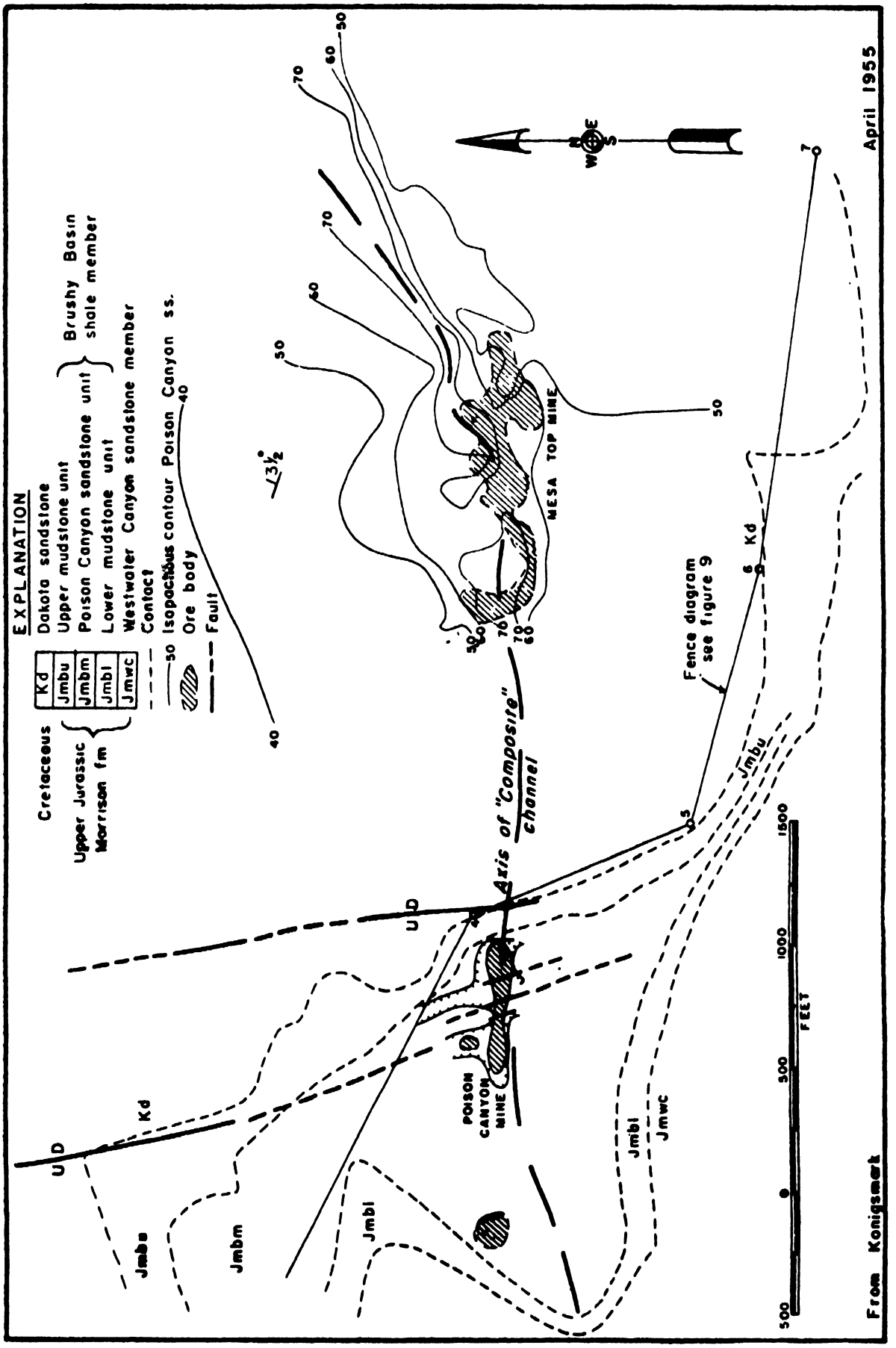


Figure 8. Areal geology showing relation of ore bodies to Poison Canyon sandstone thickness and to faults, Poison Canyon and Mesa Top Mines, McKinley County, New Mexico

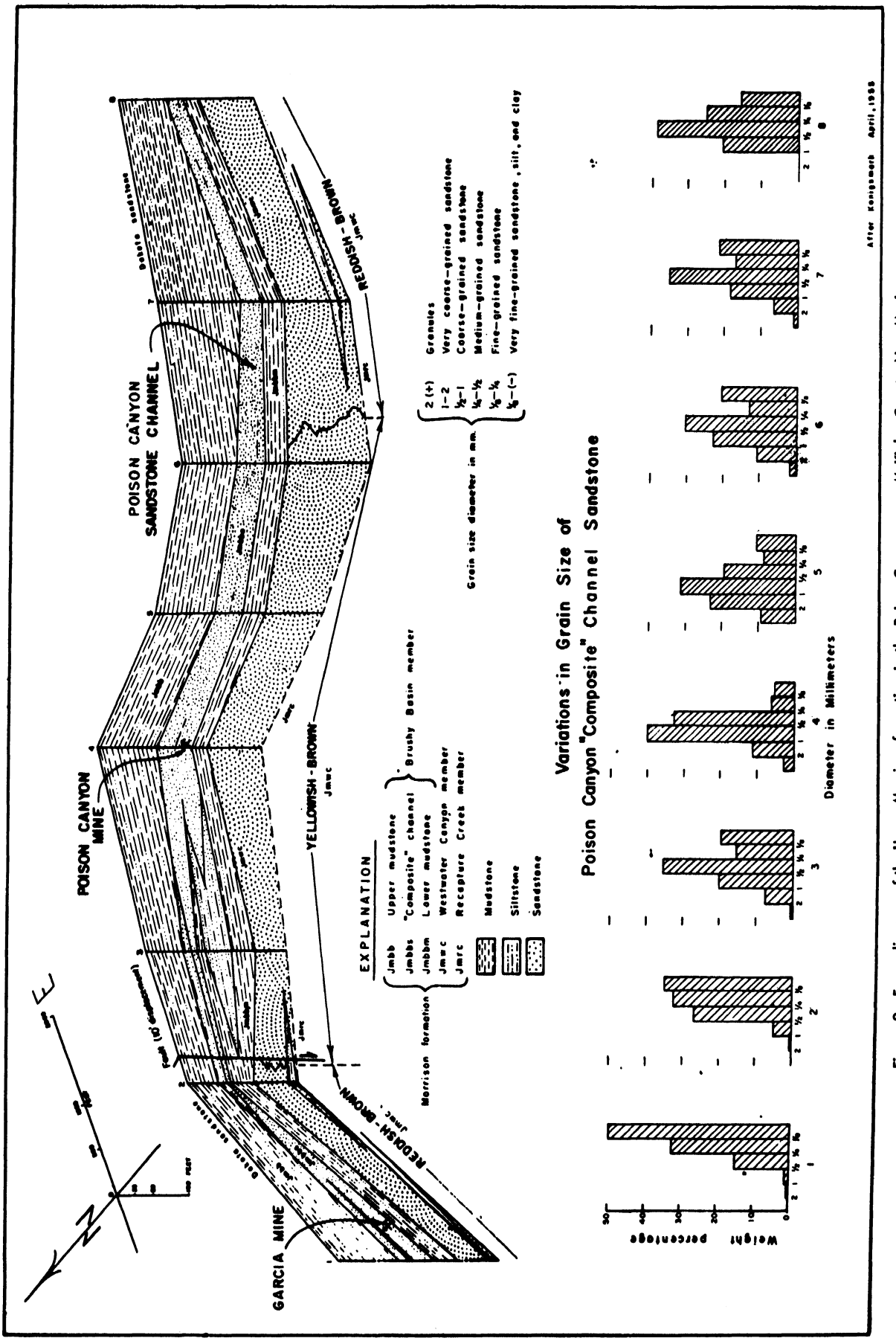


Figure 9. Fence diagram of the Upper Morrison formation in the Poison Canyon area, McKinley County, New Mexico

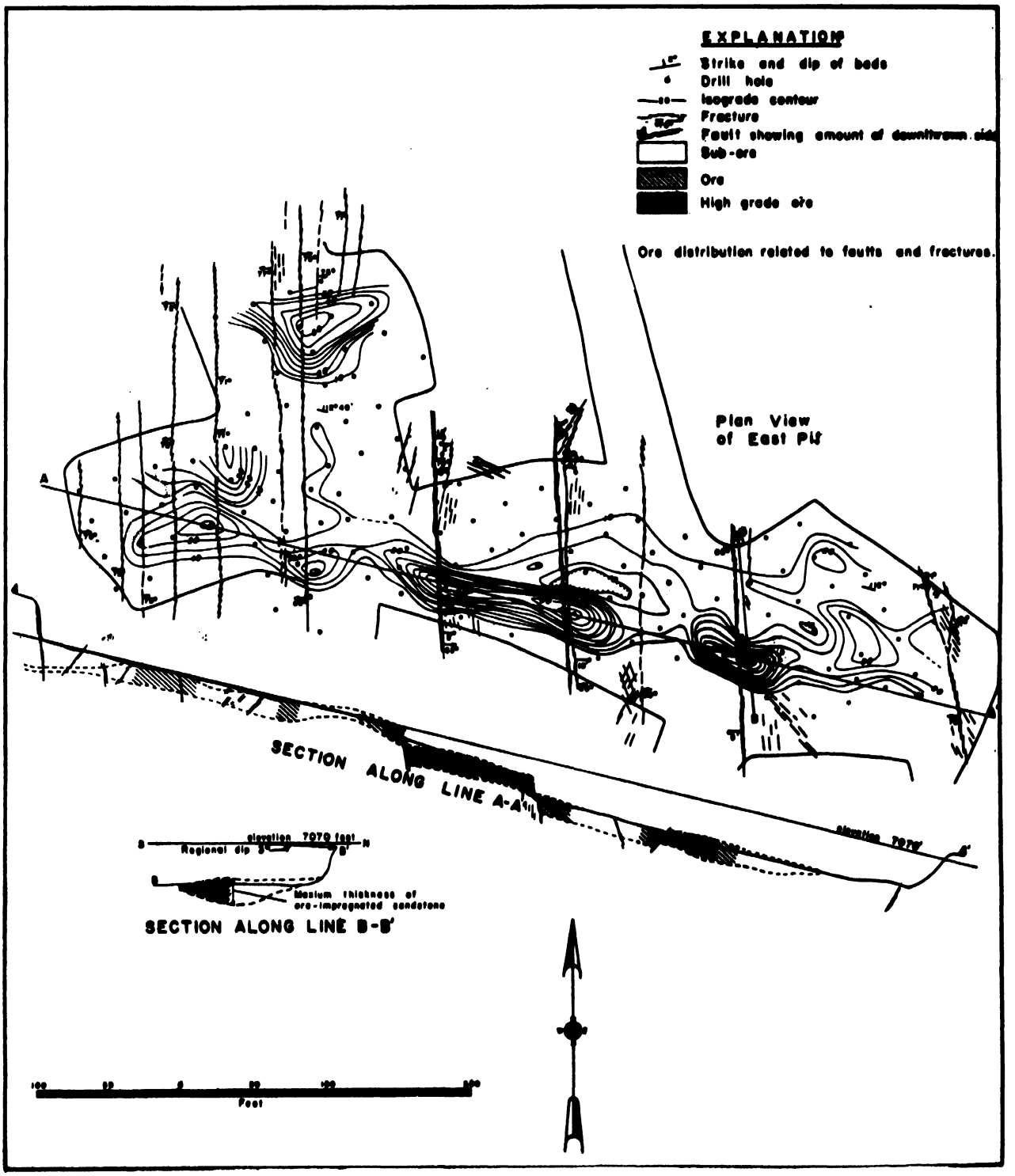


Figure 10. Poison Canyon east pit, McKinley County, New Mexico

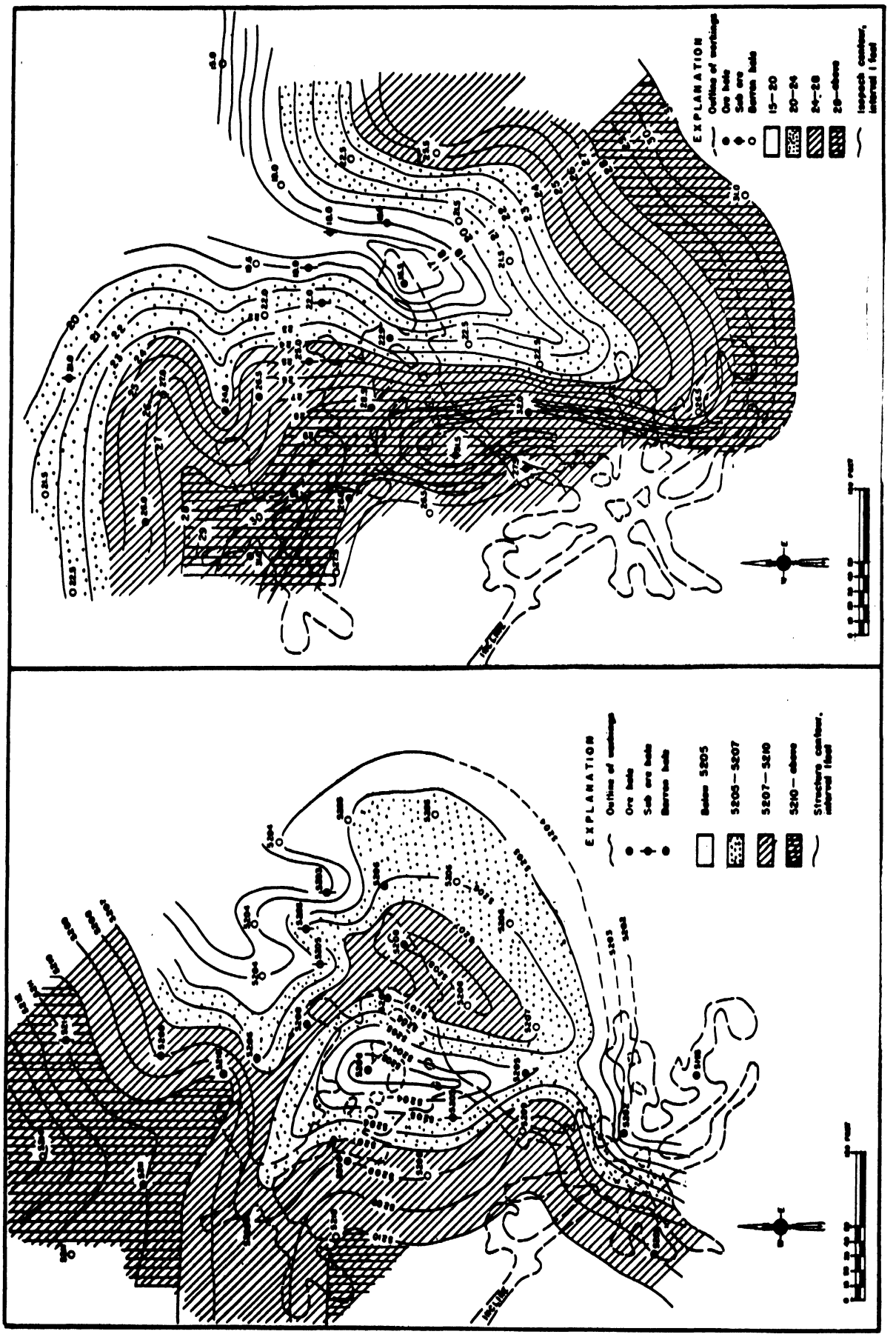


Figure 11. Structure contour map on base of ore unit, Basin No. 1 Mine, San Juan County, Utah

Figure 12. Isopach of ore unit, Basin No. 1 Mine, San Juan County, Utah

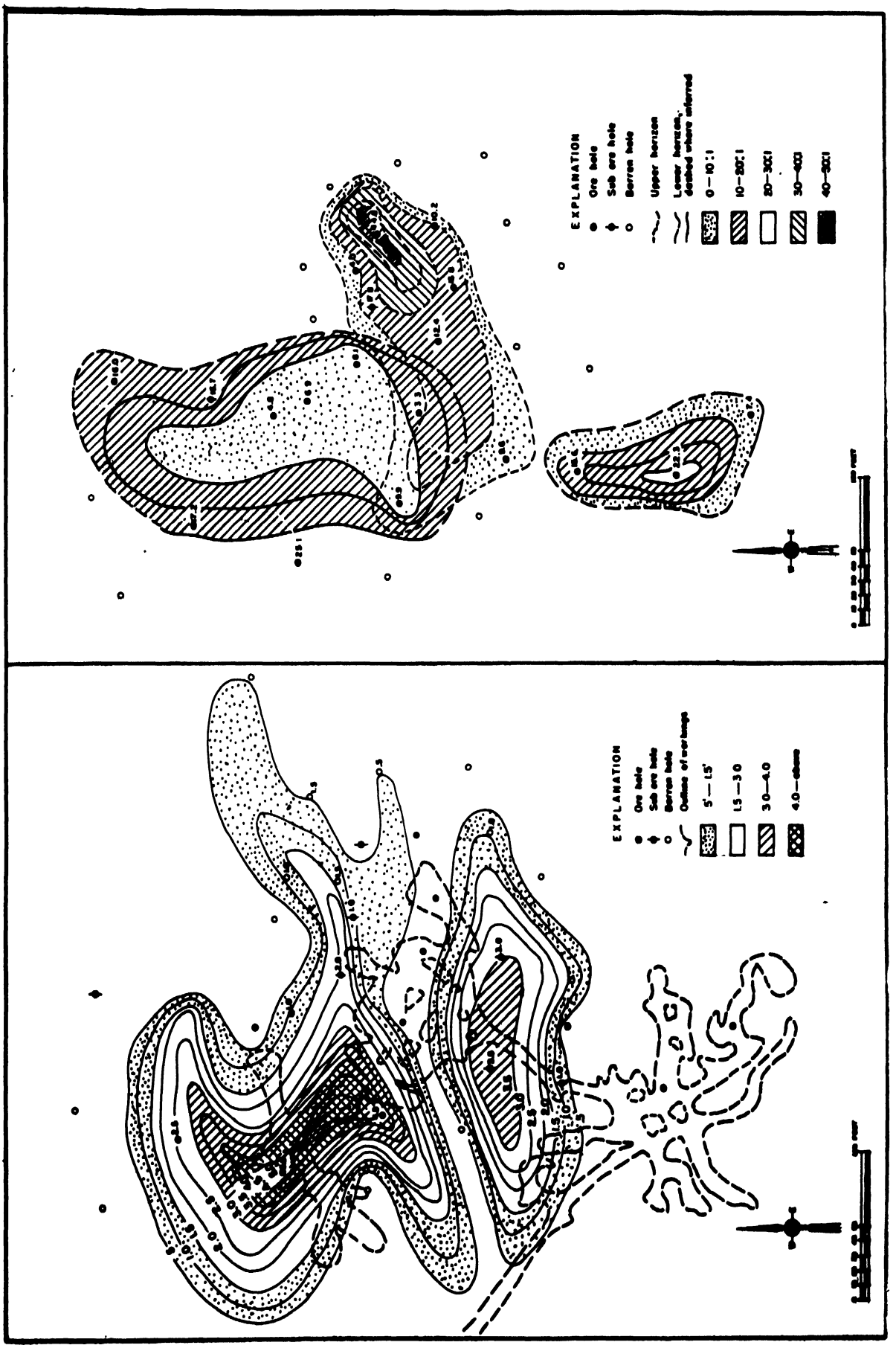


Figure 13. Isolith of mudstone color alteration below ore sand, Basin No. 1 Mine, San Juan County, Utah

Figure 14. Vanadium-uranium ratio map Basin No. 1 Mine, San Juan County, Utah

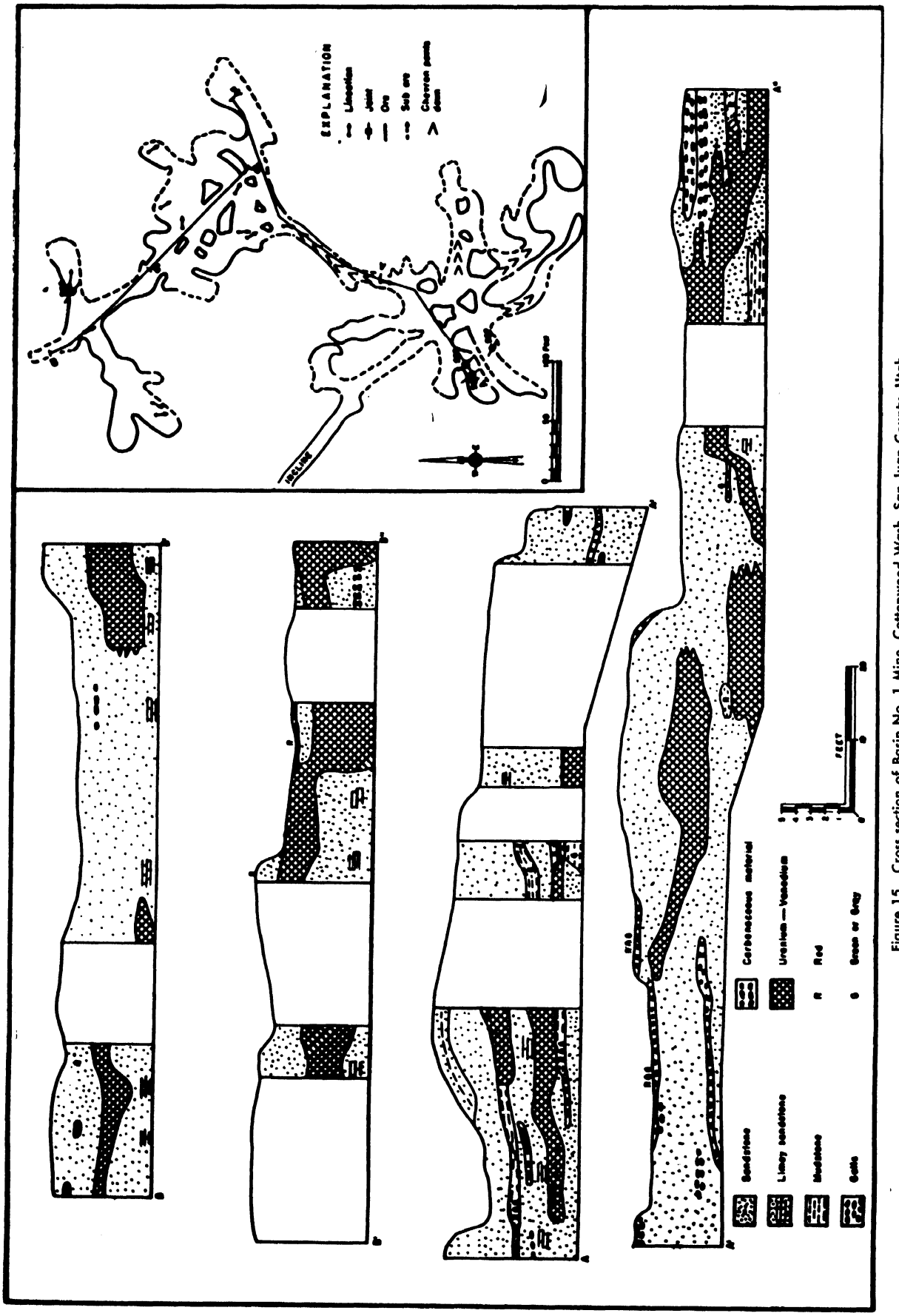


Figure 15. Cross section of Basin No. 1 Mine, Cottonwood Wash, San Juan County, Utah

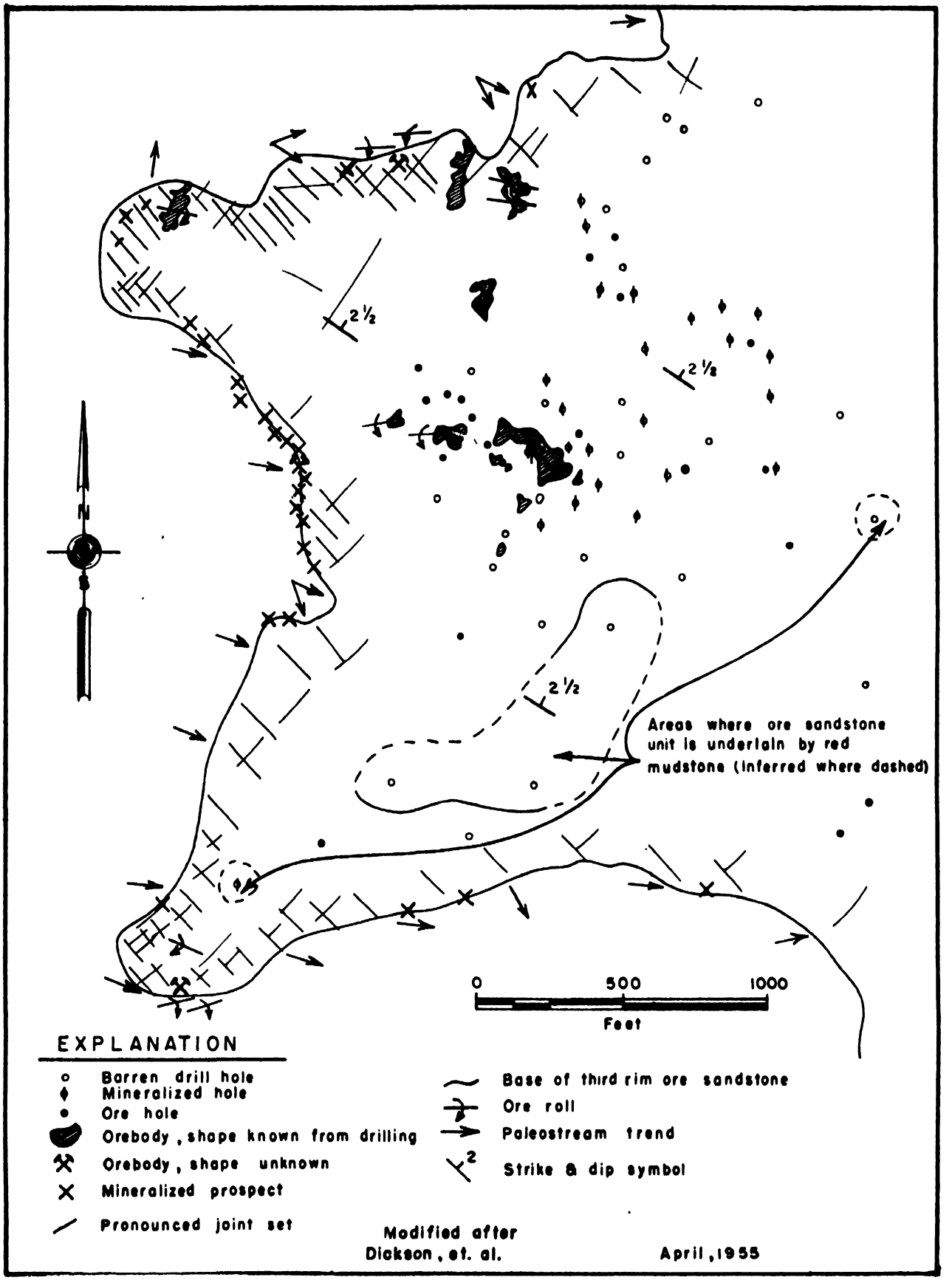


Figure 16. Geologic map showing uranium mineralization, Wedding Bell group, Bull Canyon, Montrose and San Miguel Counties, Colorado

lenses terminate abruptly and although the ore is mostly concordant with bedding it may become sharply discordant over limited areas (Fig. 15). Interstitial calcite cementation of the sandstone often occurs directly below the ore and occasionally above it.

Mineralogy

The Basin No. 1 deposit is below the water table and contains uranium and vanadium minerals of low oxidation state which are considered to be primary.[11] This is in contrast to the other mines in the Cottonwood district which, with one exception, are above the water table and contain only secondary uranium and vanadium minerals.

Uraninite has been identified replacing the cell walls in coalified plant remains. In polished section such a specimen was shown to consist of alternating, irregular streaks of shiny and dull black material. The shiny streaks, probably asphaltite, contained no uranium. In contrast the dull black streaks, with the deformed wood structure still apparent, contain uraninite as thin veinlets replacing cell walls. Metatyuyamunite has been identified as wall coatings of the mine workings. Vanadium occurs as a very fine granular black mineral tentatively identified as montrosite. In adjacent mines corvusite, pascoite, and metarossite are recognized. The ore deposits of the district are classed as high vanadium having a vanadium-uranium ratio of 10:1. The ratio in the Basin No. 1 mine ranges from 5:1 to 40:1. Traces of galena have been identified in the ore.

WEDDING BELL GROUP

The Wedding Bell group mines are in Bull Canyon, Montrose and San Miguel counties, Colorado. Production of vanadium from the Bull Canyon area began during World War I. The present phase of uranium mining began in 1948.

Details of geology of the Wedding Bell group are taken largely from Dickson *et al.*[12]

Geology

Structures

The Wedding Bell group is on the northern flank of the northwest trending Gypsum Valley anticline (a salt structure). Twenty-five miles to the northwest are the La Sal Mountain laccoliths.

Sedimentary rocks in the Wedding Bell group strike north 55 degrees west and dip 2½ degrees northeast. Fracturing is restricted to vertical longitudinal and transverse tension joints (Fig. 16) related to the northwesterly-trending salt anticlines, and to less common easterly-trending curved shear joints.

Stratigraphy and Sedimentation

Sedimentary rocks ranging in age from the Triassic Chinle formation to the Cretaceous Dakota formation are exposed in the area. Uranium-vanadium mineralization in the Wedding Bell group is restricted to the Salt Wash sandstone member of the Morrison formation which is 405 feet thick and consists of lenticular pink, or gray to tan very fine- to fine-grained sandstone with intercalated red and grayish-green mudstone and siltstone. Humic hydrocarbons derived from vegetal material are abundant. Rapid lateral and vertical facies changes characteristic of fluvial sediments are commonplace.

Paleostream flow (Fig. 16) is shown by orientation of cross bedding to have been easterly.

Economic Geology

Most uranium-vanadium ore in the Wedding Bell group is in the "Third Rim," the third prominent sandstone unit 300 feet above the base of the Salt Wash. The Third Rim ranges from 25 to 43 feet in thickness and generally exceeds 30 feet in the vicinity of ore, where it is gray to tan. Twenty feet above the Third Rim is a pink to gray sandstone ranging in thickness from a few to 25 feet, named the "Jacknife Horizon" after the Jacknife mine in the southwestern tip of the area (Fig. 16). No other ore deposits have been found in this unit, possibly due to low transmissivity.

All ore deposits in the Wedding Bell group are above the water table and contain high-valent uranium and vanadium minerals. Ore minerals identified include tyuyamunite and vanadium hydromica.

Alteration

It has long been recognized that in Salt Wash deposits red or pink sandstones are unfavorable hosts and become favorable only where altered to gray or tan.[10] In the Wedding Bell group, much of the Jacknife horizon is unfavorably colored.

Green mudstones underlie the Wedding Bell group except in areas known to be barren, where mudstones are red (Fig. 16). A very faint limonite staining in the form of small specks appears to coincide with broad belts of favorable ground, and individual orebodies are bounded by a crude halo of somewhat more intense limonitic coloration.

Orebodies are of two types: bedded and "roll". Ore rolls have variously curved sharp boundaries which transect bedding indiscriminately. Elongate orebodies (rolls), which in cross section are C-shaped and S-shaped, are the most common configurations. Most rolls in this area strike easterly (Fig. 16).

Rolls are bounded by curved fractures which have been variously explained. By one interpretation, they are post-ore fractures along a hypothetical diffusion front, the farthest advance of which is marked by diffusion rings along which the sandstone has been strengthened by cementation. Later curved fractures would presumably form along this surface of differential cementation. The presence of similar curved shear joints in barren sandstone, however, supports the interpretation that the curved fractures are pre-ore.

Ore Controls

In general, ore deposits in the Wedding Bell group are restricted to gray and tan sandstones having a thickness between 30 and 40 feet, to areas of high humic hydrocarbon content, to areas having

green rather than red mudstones at the base of the ore sandstone, and to areas of thickest and most intense limonite coloration. Within such favorable sandstones, ore may occur as either tabular bodies or rolls.

HYPOTHESIS OF ORE CONTROLS

Whatever the source of the ore-solutions and their manner of access of host sandstone, it is quite possible that eH and *p*H changes were responsible for actual precipitation of ore. It is suggested that interfaces between the fast and slack water stream deposits represented by the sandstone and mudstone would afford sufficient physical and chemical change to localize deposition. At this interface is found the rapid change in mineralogical and chemical composition of enclosing rocks.

Fossil carbonized plant material has been postulated as a precipitating agent. Isolated fragments may be replaced by ore minerals but unreplaced fossil plant material within the ore is also known. The "trash pocket" accumulations of fossil plant remains contain orebodies but usually not of major proportions.

It is postulated therefore that the ore deposits are localized in channel sandstones adjacent to lenses of mudstone or on the channel margins. Points of rapid facies change represent rapid change in physical and chemical environment and consequently are the most probable places for the effective but unknown reactions which result in uranium-vanadium deposition.

SUMMARY

All example deposits are in the proximity of a major regional structure such as the Lukachukai monocline on a flank of the Defiance uplift, the Zuni uplift, the flank of Comb monocline and the area between the Paradox Valley and Gypsum Valley salt anticlines. The beds in the vicinity of all mines dip from 1 to 2½ degrees. Although fracture concentrations generally coincide with orebodies in the 4 B mine there is no evidence for vertical control; a correlation of ore grade and thickness with small faults and fractures which displace the Poison Canyon ore is overshadowed by elongation of the deposit at nearly 90 degrees; ore rolls of the Wedding Bell are bounded by curved fractures variously interpreted as pre- and post-ore; and in the Basin Number One mine few joints were mapped and these had no relation to the ore.

Ore minerals of all example mines are impregnated fluviatile sandstones believed to have been deposited in the channel environment. All host rocks are interbedded with mudstone and contain coalified plant fragments which, when within the orebody, may be selectively replaced by ore minerals.

Individual orebodies are elongate and groups of deposits trend parallel to sedimentary structures of the host rock but in detail may be discordant and occur as overlapping shingles within a limited zone.

The vanadium content of example deposits ranges from 10:1 to 0.5:1 and, where studied, a zonal arrangement of the metal ratios was found.

No alteration of the type commonly associated with hydrothermal activity was noted. However, all host sandstones are light gray or tan and appear to have been altered from light red. Mudstone may also have been altered from red to gray-green adjacent to ore.

REFERENCES

1. Craig, L. C., *et al., A preliminary report on the Stratigraphy of the Morrison and related formations of the Colorado Plateau region,* US Geol. Survey TEI-180 (1951).
2. Stieff, L. R. and Stern, T. W., *The lead-uranium ages of some uraninite specimens from Triassic and Jurassic sedimentary rocks of the Colorado Plateau,* US Geol. Survey TEI-322 (1953).
3. Isachsen, Y. W., Mitcham, T. W. and Wood, H. B., *Age and sedimentary environments of uranium host rocks, Colorado Plateau,* Econ. Geol., 50 (1955).
4. Beam, T. E., *Ore Occurrence Study, Mesa 4½ mines, Lukachukai Mountains, Apache County, Arizona,* US Atomic Energy Comm. report in progress.
5. Masters, J. A., *Geology of the uranium deposits of the Lukachukai Mountains area, northeastern Arizona,* US Atomic Energy Comm. RME-27 (1953).
6. Gruner, J. W., Gardiner, L. and Smith, D. K., Jr., *Mineral association in the uranium deposits of the Colorado Plateau and adjacent regions,* US Atomic Energy Comm., RME-3092 (1954).
7. Konigsmark, T. A., written communication.
8. Gilkey, A. K., *Fracture pattern of the Zuni uplift,* US Atomic Energy Comm. RME-3050 (1953).
9. Pitman, R. K., Dodd, P. H. and Tom, C. W., P/516, *Subsurface techniques for outlining favorable zones using widely spaced core drilling,* Vol. 6, Session 7B, these Proceedings.
10. Weir, D. B., *Geologic Guides to prospecting for carnotite deposits on Colorado Plateau,* US Geol. Survey Bull. 988-B (1952).
11. Garrels, R. M., *Some thermodynamic relations among the uranium oxides, and their relation to oxidation states of the Colorado Plateau,* US Geol. Survey TEIR-455 (1954).
12. Dickson, R. E., *et al., Results of Drilling in Bull Canyon, Montrose and San Miguel Counties, Colorado,* US Atomic Energy Comm. RME-42 (in process).

Uranium and Thorium Deposits in Yugoslavia

By Milan Ristic,* Yugoslavia

Approximately 200 locations with occurrences of radioactive minerals have been discovered in the territory of Yugoslavia, which by its geological and tectonic structure is very favourable for the formation of radioactive deposits. So far, only those geological and mining occurrences have been investigated, which are believed to be of economic interest.

As in other countries radioactive minerals have first been discovered and explored in pegmatites. The main objects of exploration were the veins exploited for mica, feldspar and beryl.

Until the first discoveries of autunite and uranocircite in pegmatites in the central part of Serbia (author 1947), the majority of geologists considered that no conditions for discovery of deposits of radioactive minerals existed in Yugoslavia. Since then a systematic exploration has been undertaken with G.M. counters and the panelling of the placers of the whole territory. At first explorations were conducted mainly in the regions where pegmatites were found. However, very soon it became apparent that they were of a small economic value and, therefore, the systematic exploration of granite, crystalline and sedimentary fields was undertaken. In addition, all the mines were explored. In this way pegmatite deposits, as well as hydrothermal, regenerated and sedimentary deposits were discovered.

Today exploration is undertaken with the most modern methods, through the use of gamma and beta-gamma G.M. counters, scintillation counters, geophysical and mining prospections.

PEGMATITE DEPOSITS WITH URANIUM MINERALS

Numerous occurrences of pegmatite veins and lenses with radioactive minerals have been discovered. Only two regions have been explored and studied, but even they are not in exploitation.

Radioactive minerals are most frequently represented in pegmatite veins by monazite, theorite and uranium niobotantalites and much more rarely by uraninite and epidote.

These pegmatites are especially numerous in Macedonia, Serbia, Bosnia, Croatia and Slovenia. Most of the pegmatites are found in crystalline schists and are interbedded in them, forming lenses.

Pegmatite Deposits with Radioactive Epidote in Macedonia

In Macedonia, pegmatite veins with radioactive epidote have been discovered. In the formation of the neighbouring terrain mainly biotite and double mica gneisses, belonging chiefly to orthogneisses, have taken part. Muscovite gneisses, mica schists, amphibolic schists, eclogites, quartzites, phyllitic schists and argilloschists are represented to a smaller extent. Biotite and double mica gneisses, most frequently of "Augengneiss" structure and partially intensively feldspatized, are broken into by numerous pegmatite veins and lenses of various dimensions. Pegmatite veins and lenses have intruded themselves along the longitudinal joints, parallel to the schistosity of gneisses and other schists, but there exists also an insignificant number of veins which have intruded themselves under a certain angle in the direction of schistosity.

Approximately 50 pegmatite veins have been discovered in the explored areas. Out of this, 20 veins contained radioactive epidote, but only 8 veins represent more interesting objects at the present time. The pegmatites are on the whole coarse-grained and composed of albite, albite-oligoclase, microcline, quartz, muscovite and epidote. The epidote has striking dimensions. In various veins its crystals attain the length of one metre. It appears that the occurrence of epidote constitutes a regional characteristic of this area, in view of the fact that all the gneisses of the pegmatite region contain larger quantities of epidote. The manner of appearance and the form of the epidote crystals in thin sections of these rocks prove that it is not of a secondary origin, while its quantities most frequently exceed the limits of accessory minerals.

The quantity of uranium which, according to autoradiographic studies is to be found most finely disseminated in the crystalline lattice of the epidote, varies from vein to vein. The lack of thorium and rare earths that one should rather expect to find in the epidote, as well as the extremely irregular distribution of pegmatite with radioactive epidote, point to a certain extent to origin of uranium. Pegmatite fluids penetrating into the upper parts have met larger or smaller concentrations of uranium minerals, dissolving them and taking the uranium along, probably in the form of alkaline uranate. During crystallization the uranium entered into a solid solution, replacing calcium in the crystalline lattice of the epidote.

The uranium contents in the epidote vary from 110 to 3250 ppm.

* Institute for Geological, Mining and Technological Research, Beograd. In cooperation with D. Radusinovic, S. Divljan and G. Deleon.

Pegmatite Deposits with Uraninite and Beryl in Central Serbia

In Central Serbia numerous lenses and masses of pegmatite have been discovered in a terrain formed of crystalline schists and gneisses, including several smaller lenses in its neighbourhood which contain radioactive minerals and beryl.

The ground mass is formed of micaschists and mica gneisses of para series, which contain numerous pegmatite bodies, often of considerable size. Micaschists and gneisses alternate locally with entire zones or elongated lenses of amphibolic schists and gneisses. In the northern region of the terrain the upper parts of crystalline series, represented by marbles, cipolines and fine-grained micaceous quartzites, have been preserved from the effect of erosion.

It is considered that the main role in the forming of present tectonic structures has been played by tectonic movements of alpine orogenesis, which have conditioned the general trend NNW–SSE. The formation of overturned folds, imbrications and numerous faults has caused the forming of abnormal contacts between individual members of the para series.

The occurrence of numerous pegmatite bodies of a predominantly parallel trend of schists may be taken as the consequence of the undiscovered granite pluton in the depths, whose magma has provided, in the final stage, mobile fluids for the forming of pegmatite in the schist cover.

Pegmatite bodies are of an irregular form, coarse-grained textures with an irregular distribution of components in the various parts. In the core they are formed of very large crystals of quartz and feldspar, while the marginal fine-grained parts are of quartz, feldspar and tourmaline. Muscovite is scattered throughout the mass of pegmatite. Feldspars are represented by microcline-microperhite and albite. In the core large crystals of beryls (up to 30 cm in length), garnets and muscovites, are found. In addition, apatite, vivianite, sulphide-pyrrhotite, pyrite and melnicovite pyrite, with the radioactive minerals of uraninite, monazite, autunite and uranocircite, have also been found.

HYDROTHERMAL DEPOSITS

Typical vein deposits of pitchblende have not been found, but several hydrothermal deposits with pitchblende of a special type were discovered. Up to now only three of them have been explored and studied, namely, the lead-zinc deposits and a chromite mine of Macedonia and a deposit of uraninite and uranothorianite in the granites of Serbia.

Numerous radioactive anomalies on the regenerated ores, occurrences of radioactive limonite and secondary uranium minerals in old crystalline areas indicate that vein deposits of pitchblende of economic value may be discovered.

Occurrences of Pitchblende in the Lead-Zinc Mines of Macedonia

The region with radioactive anomalies is to be found in the northeast part of Macedonia. The average height being approximately 600 to 1000 metres above sea level. It covers approximately 1000 square km. It is without vegetation and lacks water.

This region is composed of a number of summits and volcanic cones. The trend of these cones and summits reveals two series of craters, showing cracks through which the lava used to erupt.

Tuffs and prophyllites, containing ore veins, are largely distributed in this region. As these rocks are extremely weathered, the erosion is very intense and the rivers and streams have cut themselves deep beds. Owing to intensive erosion, the largest part of the oxidized parts of ore veins has been taken away.

Geological and Petrological Data

In the northern part of this region volcanic rocks lie directly above the crystalline schists. The oldest rocks of this region are the crystalline schists.

The eruptive rocks are the product of granite, diorite and gabbros magma and appear in the form of veins and dykes. Granites and younger eruptive rocks, rhyolites, are to be found. Finally, there are also pegmatite and aplite veins.

Crystalline schists are represented by gneisses with micaschists and greenstones with phyllites and amphibolites. They are widely distributed and intruded by granites, pegmatites, aplites and quartz veins. Greenstones are represented by chlorite and amphibole, and more rarely by epidote and phyllite, types. The amphibolites have the character of intercallations in the gneisses and, more often, in the greenstones. In the phyllites, graphite schists are to be found locally and may be radioactive to a small degree.

These rocks, as well as the rocks in the Rhodope mass of which they form part, belong to pre-Paleozoic formations. Metamorphism was regional with a stronger eruption of magma. These rocks are of sedimentary origin, with injections of primary eruptive rocks. Phyllites would belong to the Paleozoic. The various parts of these rocks have been metamorphosed to a larger extent by later tectonic movements of variscian-hertzinian folding. The gneisses, amphibolites and mica-schists would belong to the mezo-zone, while phyllites and chlorite schists would belong to the epizone.

The effusive rocks are grey or green and are of porphyritic texture. Chemical analyses and microscopic studies have ascertained that they belong to andesites and dacites, which are different products of one and the same grano-dioritic magma, as well as to their tuffs and propylites. Thus, the following kinds of andesites and dacites have been determined: biotite-amphibole-andesite, sanidine-biotite-dacite and labradorite-augite andesite. The first of these is most widely spread and includes numerous xenolites of crystalline rocks, granites, pegmatites, as well as many small volcanic rocks and tuffs.

In the vicinity of ore occurrences rocks and tuffs have been altered in a large area. The main propylitization took place before and after the mineralization

in insignificant proportions. In the subvolcanic part of andesite and dacite sericitization, kaolinization and propylitization took place nearer to the surface with many xenolites alongside with the change of the chemical and mineralogical composition of xenolites and depositing of sulphide lead-zinc ore.

The basic structure of the tectonic form of this region is formed in the Laramian-Pyrrenean phase. That structure was deformed by later movements, which took place in the Oligomiocene, and a system of joints with a trend NW–SE was formed. Later movements in the Pliocene-Diluvium are characterized by extension and the positive and negative movement of blocks. During this phase joints and faults, without plicative forms, with a trend NW–SE were also formed.

The extension itself could also be caused by the central position occupied by the Rhodope mass in this area, where it constitutes the centre of the axis around which the Balkan peninsula is balanced.

Mineralogical Composition of Ore

In this region several occurrences of sulphide ore were found, but only the lead-zinc ore mineralization is exploited.

The study of the lead-zinc ore carried out so far has led to the discovery of the following minerals: galena, sphalerite, pyrite, arseno-pyrite, chalco-pyrite, melnicovite-pyrite, tenanite, enargite, luzonite, bournite, boulangerite, marcassite, chalcocite, covellite, bornite, alabandine, graphite, pyrargirite, polybasite, cerussite, melanterite, manganese, iron and copper hydroxides, limonite, gypsum and gangue minerals: siderite, barite, quartz, calcite, rhodocrosite and chalcedony.

Pitchblende was discovered in the parts of ore veins which showed increased radioactivity.

In this region several sulphide veins were discovered. All the veins show the trend NW–SE, with a fall to NE, and they are almost all fastly disappearing. Radioactivity is sporadic, but is concentrated in the SE part, and is related to the grey-black chalcedony in whose small channels, filled with druses of sulphide minerals, pitchblende was found.

The chalcedony in which pitchblende is found is composed of crypto-crystalline aggregates, which are made of numerous particles of submicroscopic size. The pitchblende is usually grey-black, and less often yellow-red. It contains numerous inclusions, often of submicroscopic size, of pyrite, galena and sphalerite.

The occurrence of pitchblende in the ore veins is of a great mineralogical and genetical importance. The occurrence is even more significant because pitchblende is genetically related to the sulphide minerals of the ore and forms a separate phase in the formation of this very complicated deposit.

The pitchblende shows a clear structure of gels in microscopic globular aggregates, intersected with irregularly distributed fissures. Their size amounts usually to 30–80 microns, and very seldom exceeds 100–150 microns.

Pitchblende can be seen by the naked eye in the little channels. It is black and earthlike. Less often it builds thin crusta and films over crystalline druses.

In the paragenesis with sulphide minerals the pitchblende appears most frequently on the margin of the fissures of crystals. Thus with galena it appears between the crystals, or on their margin. However, direct contact is very rare.

One seldom sees pitchblende replacing spalerite, which is then cracked.

The paragenetic place of pitchblende in the ore has been completely determined. It appears clear that it was deposited after the forming of the main sulphide ore body from secondary hydrothermal solutions, in which the radioactive substance was in a colloidal state, and that it coagulated under favourable conditions along the fissures not only of ore veins, but also of surrounding rocks. This was a slow process of coagulation, with a small inflow of electrolyte, which was of opposite charge and caused the sedimentation of pitchblende. For the coagulation of pitchblende from such solutions no high temperatures were needed, as in the case of hydrothermal solutions. Because of this origin pitchblende occurs scattered, without larger concentrations, in the various cavities, fissures, where colloidal solutions have penetrated.

Genesis

The discovery of pitchblende in the Pb-Zn occurrences, as well as of a number of radioactive occurrences related to the grey-black chalcedony in the Macedonian volcanic region, which are usually not found in this type of rock, can be best explained by the assumption that pitchblende deposits exist in the crystalline ground mass of volcanic rocks and tuffs of this region. This is a complex type of deposit, which is composed of sub-volcanic Pb-Zn and regenerated parts with pitchblende and chalcedony with uranium. The process of the formation of pitchblende might have occurred in the following manner:

During the Variscinian orogenesis, or even earlier, ore deposits were formed, and among them also deposits of pitchblende in the crystalline rock foundation composed of granite, gneisses, micaschists, amphibolites, chlorite and amphibole schists, phyllites, marble, serpentine and diabase, pegmatites and aplites. It is obvious that such a petrological composition is very favourable for the forming of pitchblende deposits.

During younger orogenic movements, which probably started towards the end of Upper Cretaceous and continued during Tertiary with the Sava phase, the ore deposits were subjected to considerable tectonic deformations. This tectonic phase caused a volcanic and sub-volcanic activity, which led to the eruption of large volcanic masses of andesite dacite rocks and to the deposition of their tuffs. It lasted from the Middle Oligocene to the end of Pliocene. At the end of these actions, in the post-

hume phase, mineral solutions were formed from which the Pb-Zn ore was deposited.

We can distinguish on the whole three fundamental paragenetic phases in the forming of the Pb-Zn mineralization of this region: (1) The forming of thinner veins with the development of gels-siderite and sulphide, formed by the impregnation and replacement of surrounding eruptive rocks; (2) the forming of economically important sulphide veins with siderite and quartz; and (3) the forming of thinner veins with barite, calcite, quartz and sulphides, as the final phase of sulphide mineralization of the deposit from the same source.

In the surrounding eruptive rock itself one notices a local silification with pyritization, which probably constitutes the oldest mineralization.

At the end of the Pb-Zn mineralization a new tectonic phase occurred, probably in the Pliocene-Dilluvium, which caused a reopening of ore fissures and the creation of new ones, cutting through the fold fissures. The trend of these fissures probably coincides with the trend of the fissures of the Variscinian-Hertzinian orogenic phase. This new tectonic phase was caused by extension and, therefore, the fissures thus formed might be very deep. These fissures were filled by secondary hydrothermal solutions, in which pitchblende was dispersed, and from which it was deposited in the form of gels along the fissures of ore veins and surrounding rocks. The fissures were probably reopened, reaching considerable depths, but they were again closed at the end of the tectonic movements. Hydrothermal solutions made use of empty fissures and channels, depositing pitchblende and chalcedony in them. Chalcedony contains fragments of sulphide or gangue minerals which were crushed and detached by tectonic movements and were involved in the silicate solution.

Finally, through the action of surface waters melnicovite-pyrite was formed in the fissures and channels of radioactive chalcedony. Thus were probably formed also the submicroscopic secondary products of pitchblende, perhaps torbernite and gummite, which may be found both in chalcedony and pitchblende.

Ore Occurrences of Antimonite and Realgar with Radioactive Impregnations in Macedonian Mines

In Macedonia there exist, as an integral part of the important chromite region, small occurrences of radioactive minerals as part of the As-Sb mineralization of subvolcanic type. This radioactive mineralization constitutes, owing to a simple but interesting paragenetic association, a rare phenomenon.

General Geological and Petrological Data

This region represents, from the geological tectonic point of view, only one part of the so-called Vardar Zone, which is composed of peridotites and sepentines, gabbros, diabases, sandstones and hornstones, Triassic and Upper-Jurassic limestones, dacite-rhyolites and granites. All these components form more or less regular belts with a trend NW–SE, which are overthrust imbricatedly.

The petrological composition of this region proper is rather varied. In addition to serpentinized peridotites, forming the ground mass of the whole region, there is a large number of magmatic intrusive and effusive rocks of the sub-volcanic region. Of the latter, the most important is a smaller mass of dacite-rhyolite on the western margin of the explored region, as well as a number of smaller granite apophyses never exceeds a few dozen metres in netically to the larger mass of biotite-granite in the NE part of this mining region. The size of these apophyses never exceeds a few dozen metres in diameter, and usually amounts to 10 metres. In some places these are granites of the moconitic type which gravitate either towards the syenites or towards the granodiorites. The best interpretation of this phenomenon is the following: the granite magma was subjected to a partial endomorphic metamorphism owing to the assimilation of a certain quantity of carbonate rocks, or perhaps serpentines. Actually these variations constitute only facial changes within the same apophyse or small mass which are often present in the whole peridotite mass.

It is characteristic that the granitoid rocks have not caused any contact changes during the intrusion. They are not to be observed either in the surrounding peridotite, or on the granite itself, or even at a very short distance from the contact itself.

The appearance of subvolcanic effusive rocks is significant in all respects. According to all investigations rhyolite dominates here, but dacite types are also noticed. We have here a mass of smaller dimensions which has on the surface the form of a lens with a trend NW–SE, whose maximum length is 450 metres. Another larger mass, also of an elongated type, runs parallel with the aforementioned lens. It is situated 100 metres more to the west, but it is a sterile mass.

The mentioned dacite-rhyolite mass, to whose post-hume activity are related the As-Sb ore occurrences, has left a considerable trace of hydrothermal alteration in the surrounding serpentine. The effusive rock itself has undergone hydrothermal changes along the mineralized parts on the contact.

The hydrothermal changes of the surrounding rocks are expressed in the destruction and transformation of serpentine into carbonate, limonitic and silicious masses along the cracks and at the contact with effusive rock where the circulation of hot solutions was the most intense. Phenomena of silicification and kaolinization have also been observed in the mineralized parts of dacite-rhyolite rocks. It has been established that these latter parts constitute a mixture of montmorillonite-nontronite clays with a large quantity of carbonate.

It is believed that these effusive rocks of the subvolcanic region are of the Miocene Age, and that they are older than the granite.

Mineralogical Composition of Ore

The As-Sb mineralization, to which uranium is exclusively related, appears in the marginal part

of the chromite zone at the contact of dacite-rhyolite and serpentinized peridotite. Although its composition is relatively simple, the ore contains an appreciable quantity of nickel, which is an exception for Yugoslavia, and is also rare in the world.

The mineralogical composition is the following: antimonite, realgar, a small quantity of orpiment, bravoite, pyrite and marcassite. In some places there is also chromite as a relict of earlier mineralization in the serpentinized peridotites into which mineral hydrothermal solutions penetrated.

The basic problem of this deposit is constituted by the following two fundamental matters: (1) a considerable presence of nickel in the ore; and (2) the increased radioactivity of the deposit, particularly in the places where richer Sb veins are to be found.

Spectrometrical and X-ray studies have established that the presence of nickel is probably due to submicroscopic grains of bravoite. The nickel contents vary from 0.13 to 1.59%.

As regards the increased radioactivity of the deposit it represents a rarity from the genetical point of view. As a matter of fact this increased radioactivity has not found a clear mineralogical confirmation. Nowhere in the studied material could be found traces of a primary radioactive mineral. In this respect several attempts have been made to examine the material by the autoradiographic method, but they have all shown, however, clearly diffuse photoprints. This confirms the conclusion that the source of radioactivity cannot be sought in definite centres-minerals, but that it is a question of a considerably dispersed radioactive substance.

The textural relations are sufficiently clear owing to the relatively small number of minerals in the ore. The following mineral sequence may be supposed: (1) chromite; (2) spherolitic antimonite; (3) zonal spherolitics of bravoite I; (4) coarse-grained, needle-like and fine-grained antimonite; (5) fibrous antimonite; (6) non-zonal bravoite II; (7) realgar and orpiment; (8) needle-like antimonite of II generation in the cavities of realgar; and (9) radioactive impregnations.

Genesis

This deposit belongs to a typical low temperature type related to post-hume hydrothermal solutions of dacite-rhyolite of the subvolcanic region, associated with the regeneration of radioactive mineralization. The latter is probably the result of the leaching of hydrothermal solutions of dacite-rhyolite and not granite origin, of the already existing concentration of uranium mineral in the crystalline substratum.

Hydrothermal Deposits of Uraninite and Uranothorianite in Eastern Serbia

The region where radioactive occurrences are to be found covers a considerable area.

With regard to its genesis, mineral species and extensiveness, the uraninite and uranothorianite deposit represents a rare phenomenon of this sort in the world.

Geological and Petrological Data

The investigated area, taken as a whole, represents a large anticline with a trend NW–SE. Its basis is formed by double mica gneisses and their Paleozoic cover. It consists of amphibolite, chlorite schists and other phyllitic schists with insignificant occurrences of quartzite and marble. These rocks were intruded by normal and olivine gabbros and diabases. There exist also several gabbros masses enclosed in the granite mass. After the intrusion of gabbros there was a new sedimentary cycle, when the sedimentation occurred. The lower part consists of contact and regionally metamorphosed conglomeratic and gneiss-like sandstones, while the upper part consists of phyllite sandstones and graphite schists.

At the end of the Carboniferous and at the beginning of the Permian an intrusion of granite occurred, represented mainly by normal calc-alkaline biotite granite, composed of ortoclase, microcline, microperthite and albite-oligoclase, quartz, biotite, apatite, sphene, magnetite, allanite and in some places also monazite. In the border zone, where the surrounding schists were assimilated, hybrid rocks were formed. They are represented by amphibole granite, amphibole syenite and diorite. Contact-metamorphic phenomena of a larger extent and intensity do not exist, partly because the largest part of the roof of the granite mass was destroyed by erosion, and partly because observation is rendered difficult owing to strong ulterior tectonic movements.

Jurassic conglomerates, composed of pebbles of all the mentioned rocks, lie transgressively over these formations. The sedimentary series ends with baremian limestones.

The old orogeneses, which have the old structures, ended with Hertzinian orogenesis, when the regional metamorphism of the Paleozoic cover was also finished. The trends of the old structure are E–N. Beginning with the Permian and up to the upper Cretaceous a new sedimentary cycle took place and the sea retreated after the Upper Cretaceous.

The Magmatic cycle took place at the time of the Hertzinian orogenesis. It began with diabases at the time of the sedimentation and continued through gabbros to granite with a weakly expressed aplite phase at the end. The Alphine orogenesis, ending with the Sava phase, formed the final tectonic structure. The main trend of the pressure was NW–SE.

The major part of rocks in the explored area is represented by calc-alkaline biotite granite, which shows all stages of mechanical deformations, from the weakly cataclized granite to real mylonites. Besides the strong serecitization of feldspars, the biotite is also completely transformed into chlorite. In various particularly crushed and moved parts, and along the cracks, the granite has been transformed into a clay substance and shows stronger radioactivity. The alteration of granite itself is typical for the hydrolitic effect of water.

The chemical analysis of granite has shown the following composition: SiO_2 65.68%; Al_2O_3 15.97%; Fe_2O_3 0.61%; FeO 2.38%; CaO 4.00%; MgO 1.33%; K_2O 2.38%; Na_2O 5.44%; TiO_2 0.15%; P_2O_5 —; MnO 0.03%; S 0.13%; CO_2 1.20%; H_2O^- 0.29%; H_2O^+ 0.21%; total 99.80%.

The recalculation of the chemical analysis of the rock according to the Lacroix (CIPW) method gives the mollowing magmatic parametres: I (II), 4′ 2.4′.

According to the Lacroix classification the rock belongs to the calc-alkaline granite of akeritic type.

The other granites of this region, with insignificant exceptions, show an identical chemical and mineralogical composition. It is characteristic that the isolated granite mass in the neighbourhood has the same composition as the mineralized granite, but without traces of intensive mechanical crushing and clay veins, and without showing any increased radioactivity above the normal.

Mineralogical Composition of Ore

The productive part of uranium in the granite, whose mineralogical composition has already been given, is to be found as uraninite and uranothorianite. They are rather equally distributed in the mass of granite. However, their concentrations have been noticed along larger cracks or heavily crushed parts. Uraninite considerably exceeds uranothorianite. Their size varies from 10 microns to 2.3 millimetres.

Their identification has been effected through X-ray and spectro-chemical analysis. On the basis of the powder diagramme it was ascertained that according to the value and cell dimensions the uraninite contained a smaller quantity of thorium. Uraninite is usually found in the form of grains, although sometimes idiomorphically developed cubic crystals are also found.

The above mentioned hybrid rocks at the contact of granite and surrounding schists, as well as around the enclosed larger blocks of schists and gabbros, which correspond to amphibole granites, syenites and also to a smaller extent diorites, also show only normal radioactivity.

Genesis

It has already been pointed out that the granite in the explored area shows all the stages of crushing, from the weakly cataclized to real mylonites and clay parts. The strongly crushed and cracked state of the granite has rendered possible an intensive penetration of magmatic fluids, particularly along larger and longer cracks, which has conditioned the kaolinization and the increase of uranium content precisely in these clay parts. It is supposed that these fluids of magmatic origin were represented in hydrothermal solutions and perhaps also in smaller quantities in the gases and vapors, which owing to pressure might have acted similarly to the solution.

The hydrothermal solutions contained uranium, perhaps as alkaline uranate. They could contain thorium to a lesser extent.

The alkaline solutions of uranate while penetrating the mechanically deformed granite had the possibility of the alternate solving and re-precipitation of uranium, which in the final analysis lead to their leaching. The most stable oxides of uranium may be preserved in places where there are no conditions for the existence of acid and alkaline solutions. Those are clay parts and veins in the granite, which actually possess the greatest radioactivity. According to incomplete results of studies this clay material is a product of hydrothermal alterations of granite.

The lack of greisen and of pneumatolitic minerals shows that there was no such activity.

Field and laboratory studies have established that the neighbouring granite massif undoubtedly originates from the same magmatic source, but that it has not suffered from tectonic disturbances, crushing and cracking, and so there are no conditions for the intense circulation of the waters of hydrothermal fluids. Consequently, it shows no increased radioactivity.

Therefore, all present investigations show that the occurrences of uraninite and uranothorianite have had a hydrothermal origin.

SEDIMENTARY DEPOSITS

Numerous sedimentary deposits of radioactive minerals have been discovered throughout the country. Of particular economic importance are the occurrences of radioactive coals in some mines of hard and brown coal and lignite. In Slovenia the layers of radioactive coal are sometimes 7 metres thick. Besides numerous occurrences of detrital deposits with thorium minerals, occurrences of bituminous schists with uranium and bauxites have been found. The latter will apparently also become a source for the obtaining of uranium, because in the processing of aluminum, the uranium concentrates itself in the so-called red mud. Of all these numerous occurrences of sedimentary deposits, only a small part of occurrences of radioactive coals and bituminous schists with uranium have been partially studied so far. For this reason, only these occurrences will be described here.

Radioactive Bituminous Schists in Slovenia

Geological and Petrological Data

The geological structure of the terrain in the neighbourhood of the mine is constituted of sedimentary formations of the Carboniferous, the Permian, the Triassic and the Eocene, which are developed in facies of limestones, dolomites, marls and schists. Bituminous schists which enter the composition of the vengen subdivision, are of particular interest with regard to the occurrence of radioactive materials.

The tectonic of the surrounding terrain and of the deposit itself is very complicated and is characterized by clearly expressed tectonic lines along which the overthrusting of older layers over younger ones took place. In the field of the mine itself, regarding the intensity of tectonic disturbances, one may dis-

tinguish the upper tectonically quieter part of the mine with the characteristic tectonics, without marked faults, where all formations spread continually with local decreases and increases of thicknesses, and the lower tectonically very complicated part of the mine, where, in addition to tangential stresses, lateral and vertical compressions played an important role in the forming of tectonic structures.

The relationship between this series and the other vengen formations is markedly irregular in the major part of the mine.

Radioactive materials are found in these bituminous schists, composed of minute grains of quartz cemented by bituminous and clay materials. Uranium is concentrated in the lower part of the schists in a layer whose thickness does not exceed 2 metres.

Autoradiographic studies have established that uranium is evenly distributed in the mass of schists. Therefore, no uranium mineral has been discovered by mineralogical studies. According to incomplete data it seems that uranium is predominantly related to the organic part of schists, and considerably less to the clay part.

Genesis

The origin of uranium in bituminous schists is primary and singenetic and is not connected with the formation of mercury ore. It has been established that the uranium content increased with the quantity of bitumen regardless of whether the schist is mineralized or not. Organic substance has played a similar role with regard to mercury, because it has conditioned its precipitation from solutions, so that the more bituminous parts contain a much larger quantity of mercury.

Deposits of Radioactive Coals in Yugoslavia

Radioactive coals have been discovered in Slovenia, Croatia and Bosnia. They belong to lignites, brown and hard coals. As studies have not yet been completed, only general data will be given here.

Geological and Petrological Data

Before the formation of coal series the old basis was transformed into karst. This foundation is formed of cretaceous limestones so that the existence of the morphological form of funnel-shaped fields has conditioned the forming of coal basins. Transgressive productive sedimentary series of various Tertiary age have been discordantly sedimented everywhere over the Cretaceous sediments.

The coal basins have not been, on the whole, involved in strong tectonic movements. The major part of observed movements within the coal series has been caused by the settling of masses which is expressed by a number of smaller faults which cut through the coal series alone.

The coal basins belong for the most part to fresh water and brackish types. The coal series form one or several seams whose thickness is from 0.5 to 8 metres. In all the discovered occurrences only the lower seams of coal, which either lie directly over the limestone or are separated from it by a thin layer of unproductive rock, are radioactive. Microscopic studies have led to the conclusion that the coal is composed of several components appearing in interbeds of various thickness, lenses and fragments. The following components have been found: duren, klaren, fusen, vitrain and xilen. Duren and klaren alternate in the layers and interbeds, while fusen, vitrain and xilen occur very rarely, most frequently in lenses and fragments. The dominant component in the majority of cases is duren.

The microcomponents are extremely varied. Duren possesses a particularly large quantity of microcomponents. Resins, in the form of resinous bodies with a regular orientation in xilen and vitrain, are the best represented, while in duren and klaren they occur without orientation, often isolated and sometimes concentrated in smaller groups. Particular mention should be made here of sclerotiae, which in certain occurrences are not found at all, while in others they are concentrated on the basic mass of duren. Microspores are a very frequent component of coal, while macrospores occur less frequently. Cuticules are also present in coals, mostly in fragments.

The interbeds which separate various coal layers consist of marls, marly sandstones and sandstones. In most cases they contain very fine grained carbonaceous materials, then orthoclase, plagioclase, amphibole, garnet, epidote, quartz and muscovite. Of the metallic minerals very fine grained pyrite and marcassite are to be found.

Mineralogical Composition of Coal

The coal is separated by heavy liquids, specific gravity 1.7, and the mineral material obtained has the following composition: gypsum, calcite, quartz, biotite, garnet, epidote, pyroxenes, amphiboles, muscovite, chlorite, feldspars, tourmaline and zircone.

The thermal and X-ray study of the lenses of the clay materials from these coals has established the presence of kaoline substance, quartz and a very small quantity of calcite.

Genesis

The present studies have not definitively established the origin of these mineralizations of uranium in coals. However, it may be asserted that at least one part of uranium in the coal is of biogenic origin. One cannot exclude the possibility that one part of radioactive materials was brought by underground waters and that it originates from limestone.

The amount of uranium in Yugoslav coals varies from 20 to 450 ppm.

Record of Proceedings of Session 6B

WEDNESDAY AFTERNOON, 10 AUGUST 1955

***Chairman:* Mr. J. da Costa Ribeiro (Brazil)**
***Vice-Chairman:* Mr. W. M. Hamilton (New Zealand)**
***Scientific Secretaries:* Messrs. R. Hara and B. Prakash**

PROGRAMME

P/1114 The natural occurrence of uranium and thorium.....United Nations

P/470 Nuclear fuel for the world power program.....J. C. Johnson

DISCUSSION

Panel Discussion on Uranium and Thorium Occurrences

***Moderator:* Mr. P. F. Kerr (United Nations)**

***Members:* Messrs. V. Angelelli (Argentina); J. P. Baxter (Australia); J. van der Spek (Belgium); E. Tavora (Brazil); A. H. Lang (Canada); M. Roubault (France); D. N. Wadia (India); F. Ippolito (Italy); K. Aki (Japan); C. P. Lobato (Portugal); S. H. U. Bowie (United Kingdom); and L. R. Page (United States of America)**

GENERAL DISCUSSION

Mr. P. F. KERR (UN) prefaced his presentation of paper P/1114 with the following remarks: This paper is designed to provide a review of the natural occurrences of uranium and thorium primarily for the nongeological members of the Conference. Twenty-three nations have submitted a total of ninety-five papers on this subject. Also, many comprehensive publications have been received. The total of all the information available provides a wealth of data available to the general public. It also furnishes us with great assurance of the adequacy of uranium and thorium resources for the peaceful uses of atomic energy.

Mr. KERR remarked in conclusion: It should be noted that the conference papers as well as the literature indicate important progress toward a better understanding of the natural occurrence of uranium and thorium. No other such short period in history has witnessed an equal accumulation of knowledge about two naturally occurring elements. The results of these studies have established geological patterns of occurrence which are fundamental to the maintenance of a continued supply of raw material. A great mass of information is now available to aid the search for supplies for the peaceful uses of atomic energy. At the same time, these studies contribute to a better understanding of the occurrence of other metals which are useful in peaceful applications.

Mr. J. C. JOHNSON (USA) presented paper P/470.

DISCUSSION OF P/1114 AND P/470

Mr. M. ROUBAULT (France): A little while ago, Mr. Kerr showed a slide of a fragment of fossil wood on which he said there was uraninite. I should like to know whether it was really uraninite or pitchblende. I would stress that this is not a question of detail. Mr. Kerr will agree with me that it has a general bearing on the description of deposits.

In asking this question, I wish to draw attention to the importance of distinguishing between uraninite and pitchblende. Is it uraninite or pitchblende which is involved here?

Mr. KERR (UN): The question of pitchblende or uraninite is an old problem. Whether one calls uranium oxide, pitchblende or uraninite depends upon several circumstances which are not always entirely geological. In terms of geology and mineralogy, however, uraninite is a definite mineral as shown in Dana's 7th edition, and pitchblende is a variety of uraninite. This is probably the most official definition that stands in the field of mineralogy. The piece of fossil wood which Mr. Roubault mentioned is one that is now in the American Museum of Natural History. It was collected in the Vernon Pick Delta Mine at the San Rafael Swell in Utah and is one of a considerable number of replacements of fossil wood. Some have been found that were practically solid uraninite or pitchblende—whichever term one prefers to use.

Mr. M. ROUBAULT (France): I thank Mr. Kerr for his reply, and would like to mention an important French work by Mr. Geoffroy and Mrs. Ceociat, published a few months ago, in which the authors discuss the distinction between pitchblende and uraninite, a question which has a very important bearing on the description of deposits and the measurement of the age of rocks and deposits.

The CHAIRMAN: To the recent discoveries of

uranium deposits, presented in Table I of P/1114, I am glad to add that some new discoveries have been made in Brazil, but, as a matter of fact, have not yet been discussed in the literature. One is the discovery made in 1952 of uranium and two zirconium ores in the State of Sao Paulo, and the other is a very recent observation of uranium associated with gold-bearing conglomerate at Sao Jacobina in the State of Bahia, Brazil. Perhaps Mr. Kerr could give us some information.

Mr. KERR (UN): The reports to the Conference have not as yet covered these occurrences. However, in 1941 I had the pleasure of visiting Pocos de Caldas, and it is most interesting indeed to observe that in such remarkable alkaline rocks, deposits of a concentration of the type described are being discovered. It is a region in which, I think, we can look forward to more mineral discoveries. I think that in the panel to follow Mr. Tavora may have something to say about this occurrence.

The CHAIRMAN: We shall now proceed to the second part of the meeting, which is devoted to a panel discussion on uranium and thorium reserves. Representatives of a number of countries will take part in this discussion, for which Mr. Kerr will be the moderator.

PANEL DISCUSSION

Mr. V. ANGELELLI (Argentina) reported on the occurrence of uranium and thorium in Argentina as follows: I am going to describe the general characteristics of the uranium deposits in the Argentine Republic. Prospecting for uranium and thorium ores in Argentina over the last three years or so has clearly shown that they are widely distributed throughout that extensive territory and that some economically workable deposits exist.

The areas surveyed cover only a small proportion of the total area which geological considerations indicate should still be investigated. Consequently, much ground will have to be surveyed before we can obtain a general idea of the full prospects of the country's radioactive mineral resources.

From the geological point of view, the deposits in question are distributed among the country's various structural units as follows: in the crystalline rock of what are called the Sierras Pampeanas; in the Paleozoic and Tertiary complexes of the Precordillera; in the Mesozoic and Tertiary areas of the Sub-Andine Sierras; in the various elements which compose the Puna; and in the Mesozoic complexes of non-Andean Patagonia, etc.

The ores which are now being processed in Argentina include primary species, such as uraninite, thucholite and pitchblende, and secondary species, among which uranophane and carnotite are the most important. These ores are associated with oxidized and sulphurized copper, compounds which generally contain a certain amount of vanadium and also, in some cases, of nickel.

There are at present two principal uranium-bearing regions, one in the south of the province of Mendoza and the other in central La Rioja. These regions are quite extensive, and they have deposits which in some cases show similar features. There is also a third region, recently discovered in the province of Salta, in which several quartz veins containing thorium ores in granite and pre-Cambrian crystalline schists have been found.

The pegmatites containing uraninite, autunite and other secondary uranium ores and occurring chiefly in the Sierras of Cordoba and San Luis are of no economic importance and are worked only in connection with the extraction of beryllium, feldspar, columbite-tantalite, etc.

Prominent among Argentina's uranium-bearing resources are the hydothermal concentrations, the age of which has not been established in every case in the absence of satisfactory evidence, though many of them are linked with the Tertiary eruptive cycle and contain Mesosiliceous rocks.

They occur as the fillings of cracks and faults in various thicknesses and stages of development and occasionally show signs of metamorphic displacement. Their host rocks are quartzites, shales, argillaceous and sandy sediments or volcanic rocks.

For the most part, the gangue consists variously of quartz, carbonates and fluorite.

In the weathered zone, which ranges from 15 to upwards of 20 meters in depth, the ore deposits consist of uranophane, schroeckingerite, carnotite and small quantities of autunite, associated with copper carbonates and iron oxides, and of pitchblende with sulphides of copper, zinc-blende, pyrite, etc., and sometimes, in the primary zone, niccolite.

The pitchblende sometimes occurs as rich thin lenticular concentrations, usually of small extent.

Except in one case, this ore is found in an advanced state of alteration, varying according to the depth of the working.

Among the deposits of this type may be mentioned the "Presidente Peron" and "Soberania" deposits in Mendoza, which are partly brecciated, calcite-bearing quartz veins; the deep-violet-colored, foul-smelling fluorite deposits of the "La Marquesa" mine in San Luis; the cupro-uraniferous veins of the "San Victorio" and "Santa Brigida" mines in La Rioja; the "La Niquelina" mine in Salta, etc.

Besides the group of hydrothermal deposits already mentioned, reference should be made, in view of their present importance, to those in the south of the province of Mendoza. They have not been studied sufficiently for us to be sure of their origin.

Certain features of these deposits indicate that they were formed by solutions descending through permeable cretaceous strata and, although the host rock shows no signs of hydrothermal effects, this theory of their origin cannot be altogether discarded. In some parts of the deposits, veins of Tertiary andesites cut through or into the ore-bearing beds.

These deposits, of which the main examples are at Cerro Huemul, Cerro Mirano and Pampa Amarilla, lie somewhat similarly to those occurring in the Colorado Plateau, and they sometimes form bodies of considerable size made up of conglomerates and sandstones containing some bituminous material. In the weathered zone, their mineralization consists of carnotite, copper carbonates, iron oxides, uraninite, thucholite, chalcopyrite, bornite, pyrite, zinc blende, galena, etc., distributed in depth.

Although little research has been done on deposits of sedimentary origin, it is known that the Triassic bituminous shales in Mendoza and also the heavy ores of certain gold and tin-bearing alluvia at Jujuy have a very low uranium content.

Lastly, without going too deeply into other uranium discoveries, I may mention that uranium has been found in the asphaltite ash of Mendoza and Neuquen and also in the bituminous sandstones of Comodoro Rivadavia, though the quantity and uranium content of these substances have not yet been thoroughly investigated.

Mr. J. P. BAXTER (Australia) reported on Australian occurrences of radioactive minerals as follows: I wish to present a paper (P/1071) which has been written by geologists of the Australian Bureau of Mineral Resources. Unfortunately, none of the authors could be present at the Conference, so I, not a geologist, am presenting the paper. It summarizes the present position with regard to the occurrences of uranium and thorium in Australia, and I do not propose to read any of it in detail.

The search for uranium and thorium in Australia has been conducted on an intensive scale for less than five years, and owing to the fact that the continent is a very large one and contains large areas which are believed geologically to be favourable for the occurrence of uranium, there is still an immense amount of exploration to be accomplished. The results presented here must be regarded as being of a preliminary character only, except in one or two areas which have been intensively studied.

The search has been carried out first by the Australian Atomic Energy Commission working in conjunction with the Commonwealth Bureau of Mineral Resources; they have covered considerable areas of the Commonwealth. In South Australia, the work has been carried out by the State Department of Mines of the Government of South Australia. In addition to this a large amount of private prospecting is now proceeding, but this has really only been under way for a comparatively short time. The results so far indicate that there are clearly four important areas for uranium production. The first of these to be discovered historically, is that at Radium Hill in the State of South Australia. The first to come into production and the one I will refer to first here is that at Rum Jungle in the Northern Territory, where uranium was discovered a few years ago. Geological and other forms of exploration established the existence of a commercial ore body and a considerable mining and treatment plant has now been established and is in production at this time. The ore in this case is obtained from open-cut workings. It had originally been intended to use underground mining, but the nature of the ground is such that underground mining was finally found to be impracticable, and a very large open-cut undertaking is now going ahead. The ore contains uranium and copper and small amounts of cobalt and is associated in the immediate vicinity with very considerable deposits of lead, although this does not occur to any extent in the ore which is being mined for uranium production.

Several other interesting and promising deposits of probably similar character have been met in the vicinity of Rum Jungle, but exploration of none of these so far has reached the stage where any final conclusions may be drawn as to their commercial value. Such work is proceeding at the present time.

In another area of the Northern Territory to the east, known as South Alligator River Area, quite considerable and promising deposits have been found. They seem to be generally of a similar character to those in the Rum Jungle area, and a very extensive programme of exploration is being carried out by a number of private enterprise companies, and there is every reason to hope that when this exploration is completed in the comparatively near future it will be possible to go ahead with commercial production.

There are in the north and northwest of Australia many other reports of radioactive minerals. I should perhaps say that this area, which is a very large one, is very poorly equipped with means of transport, and the time taken to make a thorough on-the-ground and underground exploration of reported radioactive discoveries may be considerable owing to the large distances and poor means of transport which are involved.

In South Australia at Radium Hill, where the occurrence of radium has been known for many years, there is now established a mine operated by the Government of South Australia. It is an underground mining operation. This material is then shipped, after concentration on the mine site, to Port Pirie, where it is treated for final preparation of uranium concentrates.

In the State of South Australia, other promising deposits have been discovered. There are quantities of low grade ore at Mount Painter. At Crocker's Well there are also extensive deposits of radioactive minerals, mostly uranium in granite rocks. These are thought to be capable of being worked commercially, though no actual mining has been undertaken as yet.

There are a number of other smaller deposits. There is an interesting one at Myponga, which is a deposit of pitchblende.

Leaving those two established areas, there is another one which is of considerable interest at the present time in the Mt. Isa-Cloncurry region in the State of Queensland, which is already well

known for its deposits of other minerals. Large numbers of occurrences of radioactive minerals have been reported there. At least some of these appear to be of commercial significance. One, known as the "Mary Kathleen" discovery, is now being intensively explored. Here again we expect within a few months to know whether this area is of commercial importance. The indications at the moment are that it will be. Geologically, it is interesting to note that a new mineral, a barosilicate of cerium, was discovered in this particular mine.

There is in the Mt. Isa area a number of other deposits, but it is too early yet to say whether they are of commercial significance.

Radioactive minerals have been reported from a number of other States and parts of the Commonwealth. Some of these are still being examined. In New South Wales there is an area not far from Broken Hill in which one might geologically expect a repetition of the Radium Hill type of occurrence. There is some evidence that this might be so.

Turning now from uranium to thorium, there are deposits of monazite in Australia which are recoverable from the extensive beach sand workings. Up the whole of the Eastern seaboard of Australia, the monazite content is low, but the total quantity, if it were recovered—it is not recovered at the moment—should provide very adequate supplies of thorium for any Australian requirements for atomic power production.

There are also several other thorium-containing deposits which have been reported in the general search for radioactive minerals. One deposit in particular in the Northern Territory, which is not a deposit of monazite and appears to contain thorium but no rare earths, is of some interest.

Mr. J. VAN DER SPEK (Belgium) discussed uranium occurrences in the Belgian Congo as follows: Like Mr. Baxter, the speaker who preceded me, I am not a geologist. Consequently, I shall merely comment very briefly on the paper (P/1105) prepared by Mr. Derriks and Mr. Vaes, the geologists of the Union Minière. Much to their regret, of course, these two gentlemen were unable to leave Africa to attend the Conference. Among the geologists who have been concerned with the Shinkolobwé mine and the geology of the Katanga as a whole, Mr. Schniling, Mr. Renard and Mr. du Trieu should also be mentioned.

I do not intend to go through the paper by Mr. Derriks and Mr. Vaes again here as it is extremely detailed and difficult to summarize. I shall merely attempt to answer the questions on it which have been passed on to me.

I think, however, that your attention may well be drawn to the main features of the Shinkolobwé mine. They are, firstly, the extreme variety of the ores and mineralogical specimens which have been found there; secondly, the high concentrations of uranium which occur in places, and lastly, the fact that the distribution of the Shinkolobwé ores is different from that of the Katanga copper, being mainly determined by geological characteristics, i.e., the various faults at Shinkolobwé and the presence there of a very special geological phenomenon called a sink, a kind of natural well.

The following questions have been put to me:

I have been asked whether the silicified and ferruginous dolomites in other parts of the Katanga are different in kind from those found at the Shinkolobwé mine. The situation is the same as for most of the deposits in what we call the group of mines: these dolomites have more or less similar characteristics throughout this area.

I have also been asked whether metallic ores have been found in what is called the Kundelungu, at Shinkolobwé and elsewhere in the Katanga. The Kundelungu is a geological formation in which there are no metallic deposits and which surrounds the mineralized horizons of the group of mines.

I have also been asked to what extent the oxidation of the uraniferous ores at Shinkolobwé is affected by the water table. The water table is the boundary between the unaltered and the oxidized ores.

The next question concerns the selenium found in the Shinkolobwé mines. I was asked whether any attempt had been made to establish the existence of selenium in the vegetation surrounding the mine. No such attempt has been made, and we do not think it would be worth while to make one at present. Perhaps this question can be studied later.

I have also been asked for an explanation of the mineraliferous concentration in the strata. The most probable explanation of the mineraliferous concentration at Shinkolobwé is that the uranium salts were introduced and precipitated by hydrothermal solutions.

On the question of the occurrence of magnesite, it seems that the type found at Shinkolobwé is not common to all Katanga.

Chlorite does not form haloes about the mineralization.

The last question relates to the large crystals of uraninite. I have been asked whether these large crystals are found at Shinkolobwé only in the vugs. The answer is "yes;" they are chiefly found in the vugs.

Mr. E. TAVORA (Brazil) discussed the occurrence of uranium and thorium in Brazil as follows: Although the existence of uranium and thorium in Brazil has been known for many years, it was only recently that the Brazilian Government put into operation a systematic plan of exploration to determine the available reserves in our country.

I shall speak first about uranium and deposits whose origin is related to molten magmas. We noted that many granitic rocks in Brazil are radioactive to a certain degree. However, we have found no indications so far that any of them can be considered an economical source of uranium.

As regards pegmatites, several radioactive min-

erals such as uraninite, euxenite, microlite, betafite and fergusonite have been found in these rocks. However, in spite of the presence of some unusual samples of uraninite weighing some kilograms, no proof has been produced that they may eventually constitute economically exploitable deposits. Such pegmatites have been found in certain states of Northeastern Brazil, such as Paraiba, Rio Grande do Norte and so forth, and also in the State of Minas Gerais. In both regions the pegmatites are already being exploited for tin, tantalum, columbium and so forth, since they contain cassiterite, tantalite, and columbite.

The exploration of certain pegmatites of the S. Joâo del Rei region, State of Minas Gerais, revealed a considerable amount of a uraniferous variety of microlite, which is called *djalmaite* and which occurs together with tantalite and cassiterite.

With regard to deposits whose origin seems to be related to thermal solution action, the presence of uranium in veins of the zirconium ore of the Pocos de Caldas plateau was discovered in 1952. Uranium is found there in the so-called Caldasite, which consists mainly of a mixture of zircon and baddeleyite. Uranium must be located, at least to a certain extent, in atom sites of zircon. However, the rather high percentage of U_3O_8 in the ore in some places seems to indicate that a large amount of this element should be ascribed to secondary minerals whose presence seems to be confirmed by unpublished results of photographic tests.

About two years ago, uranium was discovered in gold-bearing conglomerates of the Serra de Jacobina, State of Bahia. According to the results of preliminary studies, a conclusion was reached which established the similarity between these Brazilian conglomerates and those of Witwatersrand, Africa.

As regards uranium in phosphate deposits, results of qualitative tests carried out with the aid of radiation counters and quantitative chemical tests indicate that the phosphate deposits of Olinda, State of Pernambuco, bear a radioactive element which seems to be uranium. At the present time, this deposit is being exploited in order to supply raw material for the fertilizer industry.

As regards thorium, owing to the accessibility of the coastal alluvial deposits of monazite, the Brazilian reserves of thorium are better known than those of uranium. With the realization of the present program of prospecting and exploration sponsored by the Brazilian Government, it is difficult to say whether this disproportion will be maintained after the uncovering of vast territories in the backwoods of Brazil. New occurrences of both uranium and thorium are frequently reported.

I would now like to say something about deposits whose origin is related to molten magma. Monazite has been found in granitic rocks in some parts of Brazil and especially in the mineralized region of the northeast. Since in some of these places residual and alluvial deposits of this mineral are reported, there may exist a relationship between these and the rocks mentioned. It is only right to say, however, that none of these granitic rocks has so far proved to be economically interesting as regards extraction of thorium.

From pegmatites found in different parts of Brazil —the States of Paraiba, Rio Grande do Norte, Bahia, Minas Gerais, etc.—large samples of monazite weighing over a kilogram have been collected, but no conclusion has ever been reached that such deposits could be worked economically. The alluvial deposits of monazite of the coast of Brazil are traditionally known to be among the largest in the world. The proximity of these deposits to the tertiary "Barreiras" sandstone seems to indicate that the mechanical destruction of the latter gave rise to the formation of the former. Quite recently residual and other alluvial deposits of monazites were discovered at San Rafael and Florania in the State of Rio Grande do Norte, in which the monazite fragments are much larger than those of the beach deposits. Although much is hoped from the successful exploitation of these deposits, no final results of the exploratory work have as yet been disclosed which might enable one to judge the importance of the findings.

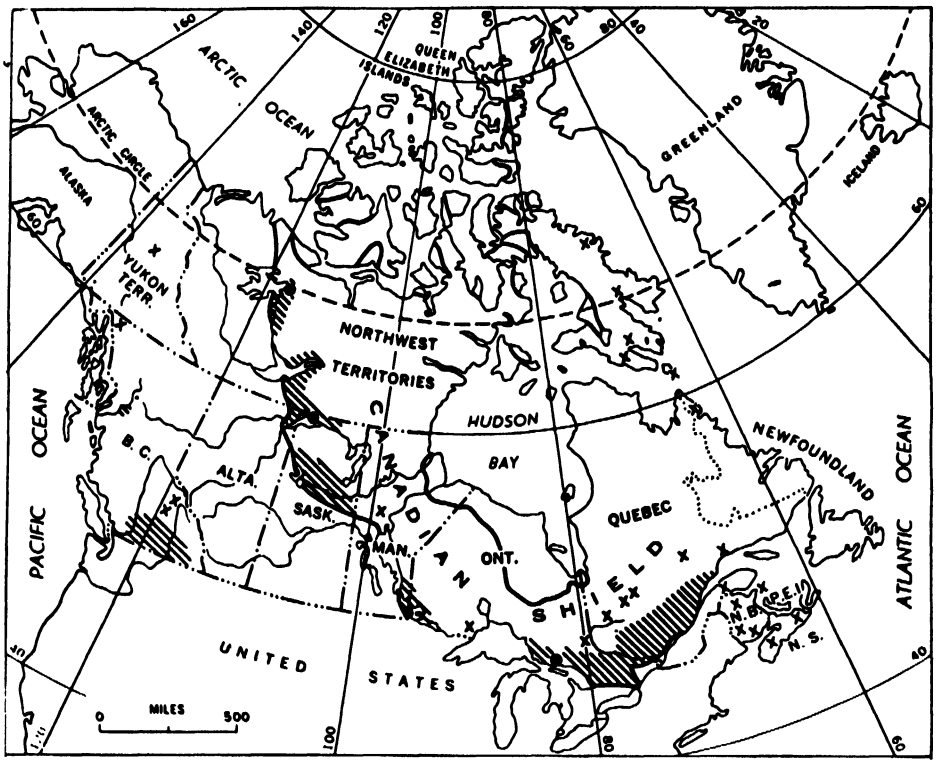
Not long ago, the presence of appreciable amounts of thorium in Morro do Ferro, Pocos de Caldas Plateau, State of Minas Gerais, was proved for the first time. In this deposit the thorium-bearing mineral has not yet been identified since the mineralogical and crystallographic studies are still in process. Thorium there occurs together with a rare-earth-bearing mineral which seems to be bastnaesite. At the present time exploration work is being carried out to determine the available reserves, whose eventual exploitation may be considerably facilitated by the deep weathering of the local rock and of the dyke in which the strongest radiation is concentrated.

Another recent finding in Araxa, State of Minas Gerais, which depended largely on a preliminary airborne scintillometric survey carried out by one of the private companies operating in Brazil, consists of a deposit in which pyrochlore is the main thorium-bearing mineral. At the present moment a detailed exploration of this deposit is being carried out.

Mr. A. H. LANG (Canada) summarized Canadian occurrences as follows: Mr. Kerr has outlined admirably the main features of the principal known deposits of uranium in Canada. I would like to enlarge briefly on a few of these features, but shall not attempt to go into details because most of these are available in various publications.

Slide 1 shows the present pattern of distribution of uranium deposits in Canada. To save time I shall mention only those in the Canadian pre-Cambrian Shield, although there are several promising occurrences in the younger mountainous areas in the western and eastern parts of Canada.

Ore production is now coming from Great Bear Lake and Beaverlodge, and next month it is sched-



LEGEND

Area containing one or more producing uranium mines . . . .

Area containing several or many radioactive occurrences . .

Isolated radioactive occurrences x

Boundary of Canadian Shield . . . . . .

Slide 1

uled to begin in the Blind River area. It is estimated that by the end of 1957 the gross value of uranium production in Canada will be about $100 million and that it will then rank in fourth or fifth place among the metals produced in Canada. The general pattern of uranium occurrence around the edge of the Shield has often been described. It still holds true, and the principal deposits are in parts of this zone where late pre-Cambrian strata were subjected to mountain building in late pre-Cambrian times. However, discoveries are also near large lakes and other facilities for travel, so I believe that the distribution is partly at least due to accessibility rather than to detailed geological features within the Shield. To save time, I shall not mention Great Bear Lake further because it is no longer our principal interest.

Slide 2 shows the generalized geology of the Beaverlodge district. Areas marked (7) represent the older pre-Cambrian strata, those marked (2) the granitic complex, and the black areas represent the younger pre-Cambrian strata. Pitchblende occurs in rocks of all these types and, if we count small occurrences probably of no economic value, there are more than one thousand individual pitchblende occurrences known in the area shown on this map. Time permits mentioning only the principal ones of the Eldorado Company and the Gunnar deposit. Production at present comes mainly from Eldorado properties along the St. Louis fault, and I have just been authorized to state that Eldorado is now undertaking an expansion of this plant from a capacity of 700 tons a day to 2000 tons a day. That production, with that of the Gunnar mine which is due to commence next month, makes this area one of the leading uranium areas of the world.

There is no time to enter into details but I would like to point out that we believe that structural features are much more important for the emplacement of the deposits than the ages or the types of the rocks. The Eldorado deposits are in the footwall of the St. Louis fault, and their precise location seems to be determined by zones of shattering that accompanied the faulting. The Gunnar deposit is shown in more detail on Slide 3.

The Gunnar deposit is a very large body of medium uranium content between two large strata of sedimentary gneiss. The deposit itself is in blocks of granitic composition that have been shattered to permit emplacement of disseminations of pitchblende, now largely altered to uranophane. This important secondary mineralization is so far unique in Canada. The deposit is about two miles from a very prominent fault—the Black Bay fault—and close to the intersection of two transverse faults whose existence

is presumed because, so far as I know, only a little shearing has so far been found by diamond drilling.

The rock in which the Gunnar deposit occurs is deeply eroded, partly because of its shattering and partly because it contains considerable carbonate. There was only one small outcrop of the ore body, which was found by a prospector who kept his Geiger counter turned on while he was crossing from one of the rocky ridges to the other.

The ore body lies here, represented by this large area of marshy ground (see Slide 4). After the discovery prospectors paid more attention to low-lying over-burdened areas, and other important discoveries have been made more recently as a result.

Slide 5 (which is from a diagram by F. Joubin) repeats the information which was shown by Mr. Kerr. I will just repeat the position of the principal deposits in the belt which extends for about 80 miles around here. The Pronto mine is due to commence production next month, and later still larger production is assured from the Nordic property and the Quirke.

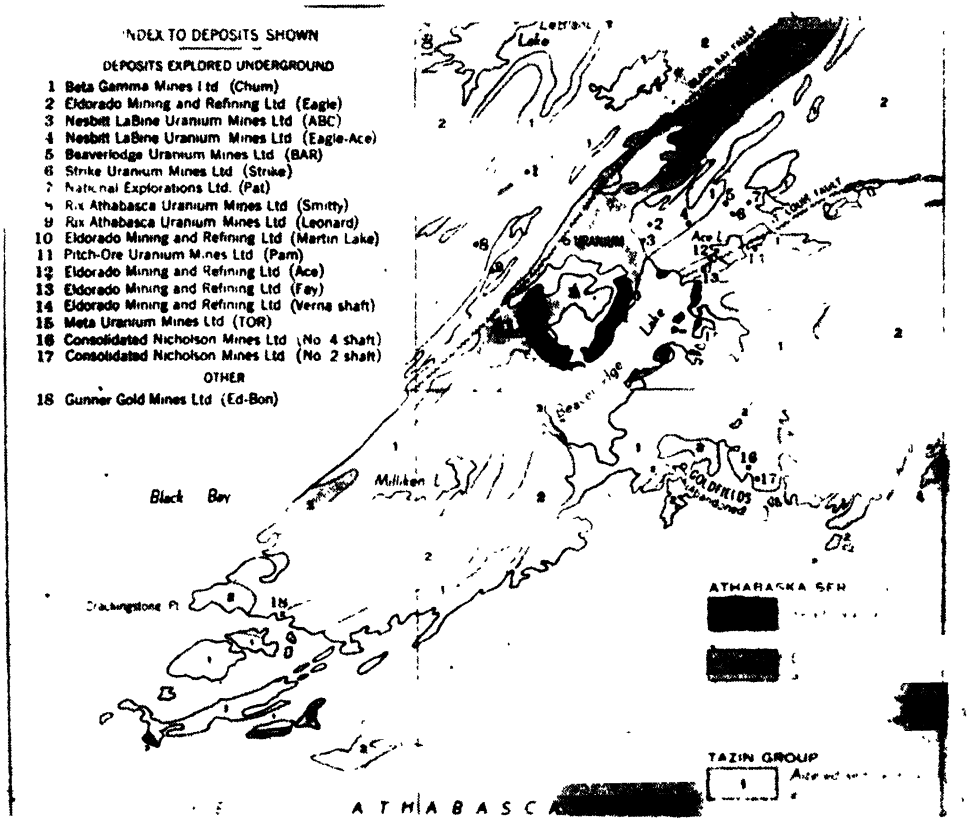
During the past year deep drilling on the Denison property has revealed a great tonnage, although the tonnage of the properties that I mentioned earlier is very great, and it is now apparent that the Blind River region will become one of the largest uranium producing areas of the world, if not the largest.

The cross-sections shown in Slide 6 (also after F. Joubin) illustrate the manner in which the conglomerate-bearing ore beds occur. At the Pronto the conglomerate is right on the granitic basement, or virtually so. There are a few places where small patches of argillite are beneath the conglomerate.

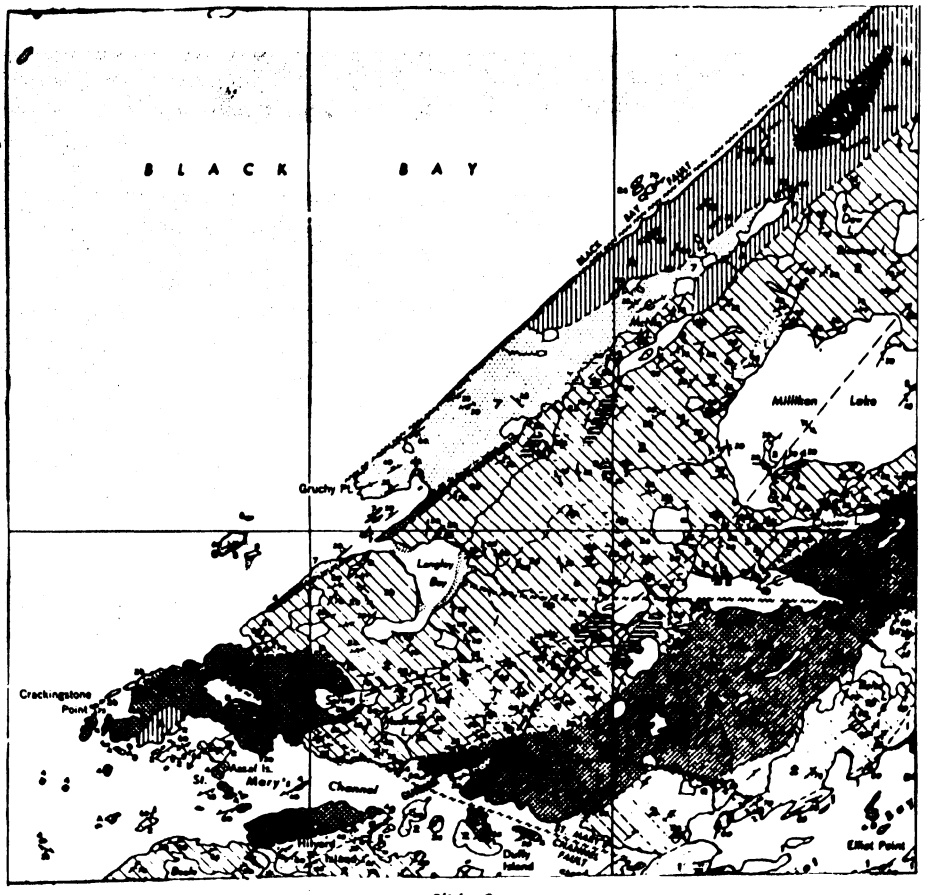
At Nordic Lake there is one bed at the basement and another important one about 40 feet above it. These beds average from 10 to 12 feet in thickness. At Quirke there is a whole series of beds and the principal one is near the centre.

Time does not permit my discussing the Blind River deposits in further detail. The origin is still a matter of great controversy. Geologists working in the district, as well as visitors, are strongly divided in their views. This is not surprising when we consider the many years during which such controversies have raged in other parts of the world. The Geological Survey is carrying out a detailed survey of this problem, but my colleagues are not yet prepared to commit themselves beyond saying that they do not see at present how either the bare placer theory of origin or the bare hydrothermal theory can explain all the evidence. They tend at present towards a combination of two processes.

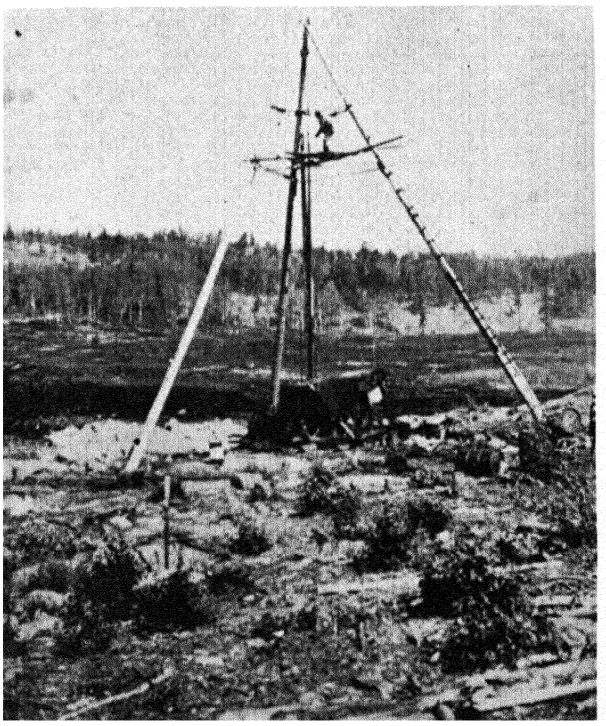
I would like to close by mentioning the Bancroft area which I pointed out on the map of Canada. What we call the Grenville Sub-Province along the southern part of the Canadian Shield in Ontario and the Province of Quebec is considerably different from other parts of the Shield, and one of these differences is that, although it contains a very large number of uranium occurrences, these are, mainly speaking, pegmatites. Pegmatites, of course, are also widespread in other parts of the Shield and pegmatitic occurrences constitute our most numerous type



Slide 2. Generalized geological map of Goldfields region



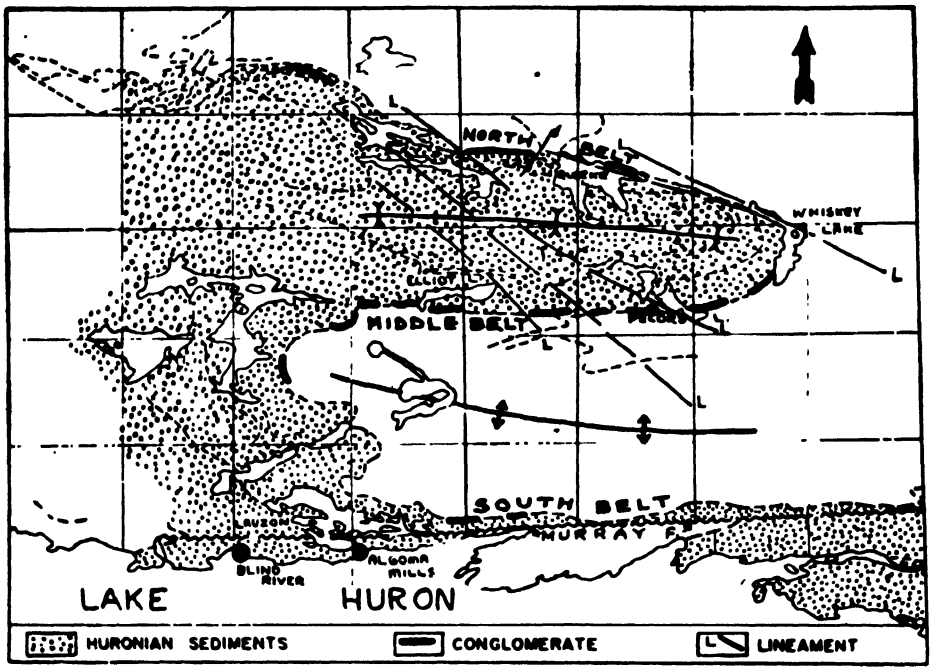
Slide 3



of occurrence. Most, however, are small or sparsely or erratically mineralized, but a few, particularly in the Bancroft area, have shown promise, and one of these, the Bi-croft, has just been assured by the Eldorado Company of a contract to enter into production. This will mark the first successful exploitation of a pegmatite deposit in Canada and one of the first, I believe, in the world. However, it does not alter our general conclusion that most pegmatitic occurrences are not favourable.

Mr. M. ROUBAULT (France) discussed uranium deposits of France and the French overseas territories as follows: The exploration of uranium-bearing ores in France began in the nineteenth century but, at the time that the Commissariat à l'énergie atomique (Atomic Energy Commission) started prospecting in 1946, it had scarcely advanced beyond the mere collection of mineralogical data.

After a preparatory period, lasting from 1946 to 1948, an accurate method of prospecting involving the systematic use of the Geiger counter and careful traversing of all possible uranium-bearing zones was perfected. This method, which is described in detail in P/338 (Session 7B, Volume 6, these Proceedings), soon proved successful. The first really significant event was the discovery of a seam of solid pitchblende at La Crouzille (Haute-Vienne) in December 1948, and this was soon followed by the discovery of other deposits.



Slide 5

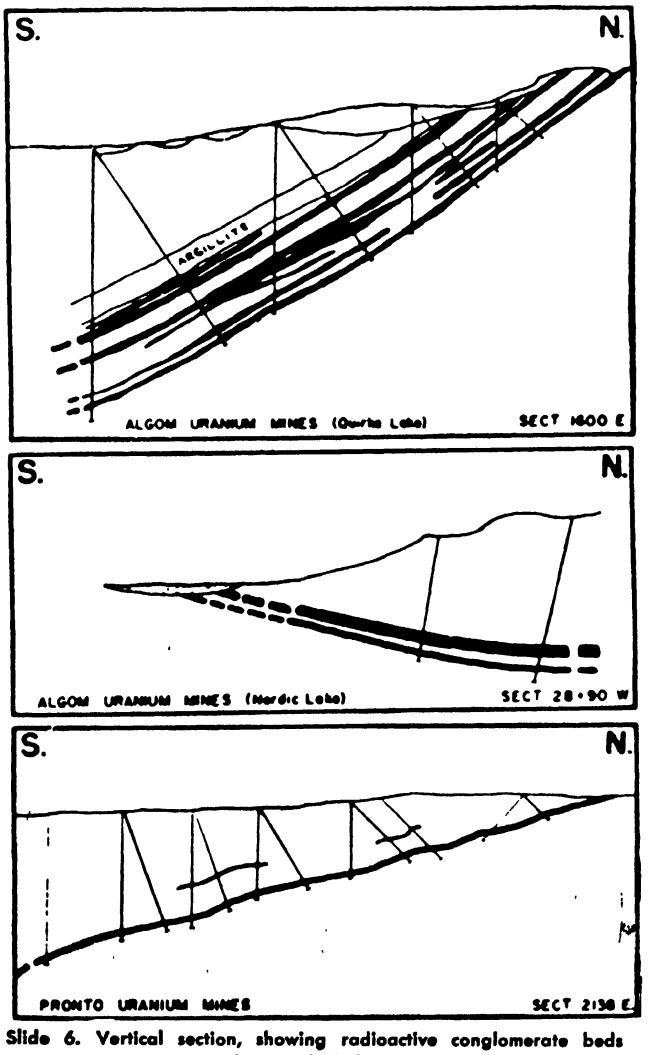
In metropolitan France, exploitable formations so far explored are situated in the crystalline zones of the Hercynian massifs—the Massif Central, the Vendée and the Vosges—except for a sedimentary deposit consisting of uraniferous bituminous schists, which is also situated on the eastern slopes of the Vosges.

Slide 7 (Fig. 1 of P/328) shows that the French Hercynian massif includes the districts of Mortagne, La Crouzille, Lachaux and Grury, which are the centres of the four main uranium-bearing areas in France. The main features of the ore-bearing zones are as follows:

In the Autunois and Morvan districts, activity mainly revolves round two centres, one of them being the La Faye centre, near Grury, which may be seen on the map. It has a branched vein with a siliceous gangue and dispersed uraniferous ores, containing pitchblende in the deeper parts and supergene ores nearer the surface. Work on a large scale has been done here in preparation for mining the deposits in the near future.

At Bauzot, near Issy L'Evêque (Slide 8), mining operations are in progress. The deposit is a fairly regular one of the vein type and contains fluorite, a little silica and a very fine pitchblende. It has been explored to a depth of less than 280 metres; its average content is low.

Slide 9 (Fig. 2 of P/328) shows a geological map of the northern section of the Morvan massif. Issy L'Evêque and Grury are clearly visible. The outline of the granitic massif which we generally refer to as the Luzy batholith has been marked heavily in black. As a matter of historical interest, I will point out for you Saint-Symphorien de Marmagre, very near the town of Autun, and will remind mineralogists that it was there that the mineral generally



Slide 6. Vertical section, showing radioactive conglomerate beds (heavy black lines)

known as autunite was discovered a century and a half ago.

In Auvergne, the first area with which I shall deal is the Lachaux area. Here, the siliceous fillings of fractures, finely impregnated with parsonsite of an exceptional mineralogical type, have been worked for several years [Slide 10 (Fig. 4 of P/328)]. This ore was very poor and of limited value. Some fifteen kilometres away, however, in the Bois Noirs area, a rich deposit consisting of a pitchblende breccia embedded in granite was discovered in the years 1951–1954. This breccia also has a very high silica content and corresponds to an important fracture zone.

Slide 11 (Fig. 5 of P/328) shows a geological map of the part of Auvergne in which the Lachaux and Bois Noirs deposits are situated. I draw your attention to the lines on the slide. The three parallel lines represent three large fractures, particularly the line on the left which marks what we call the "Limagne marginal fault."

Slide 12 shows you the operating plant, as it stands at present, at the mineshaft of the Bois Noirs mine. You will see that it looks much the same as all the other French uranium workings.

I will now go on to the third region. In the La Crouzille district of the Limousin, 20 kilometres north of Limoges, the structure of the deposit is exceptionally simple. The solid pitchblende occurs in association with some pyrite, in fractures at the intersections of a vein of green rock, which we call "minette," where it cuts across the granite.

Slide 13 (Fig. 7 of P/328) is a general view which shows the structure of the La Crouzille mine very clearly. The layer of pitchblende has a real "swordblade" conformation and has so far been explored down to the 200 metre level. It cuts perpendicularly through the dark veins of minette.

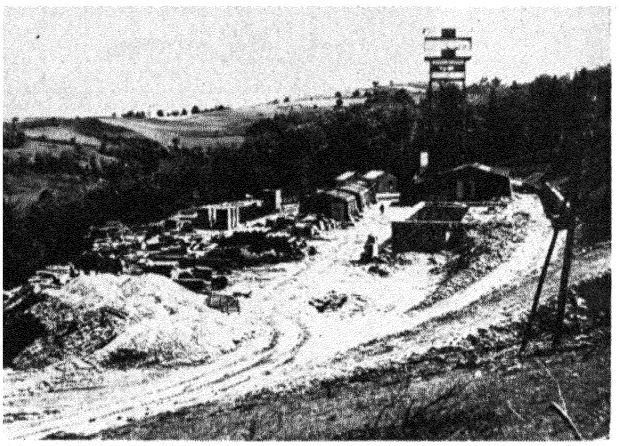
Slide 14 is a view of the La Crouzille mine which, as I have said, was the first French uranium mine.

In a fourth region, the Vendée, in the west of France, two workable deposits have so far been explored in the granitic massif of Mortagne and, at several points, near or next to crystallophylian formations. The first of these, at Chapelle Largeau, consists of pitchblende and yellow products in a fracture zone with quartz gangue; and the second, at Ecarpière en Gétigné, near Clisson, is made up of regular veins of fluorite and finely dispersed pitchblende. These veins have been explored to a depth of 200 metres.

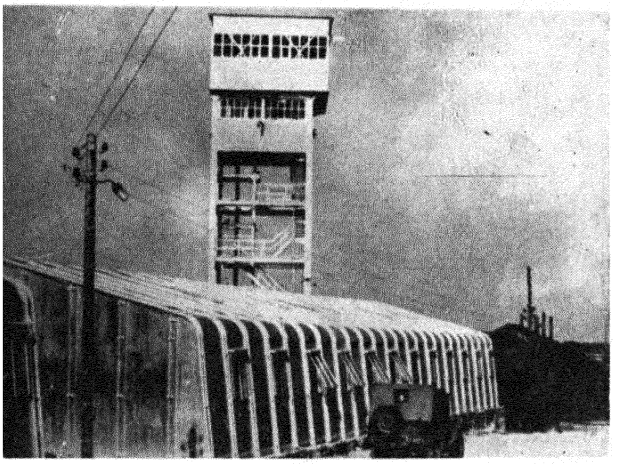
Slide 15 (Fig. 9 of P/328) is a geological map of the Mortagne region in the West of France, and you can see on it the great granitic massif of Mortagne. The various ores, numbered 1 to 6, give the exact situation of the different deposits listed in the paper.

Outside these four main areas, other deposits or traces of similar origin have been located in metropolitan France. In particular, we may mention the formations at La Creuse, near Boussac, the Beaujolais and Vosges formations and the formations in the southern part of the Massif Central (Aveyron and Lozère). Lastly, a deposit very different from those already mentioned has been located in the Schaentzel area in the Haut-Rhin. This deposit consists of carbonaceous uraniferous schists in a form not mineralogically defined.

In the French Overseas Territories, the prospecting done by the Commissariat à l'énergie atomique in the various French African territories has



Slide 8



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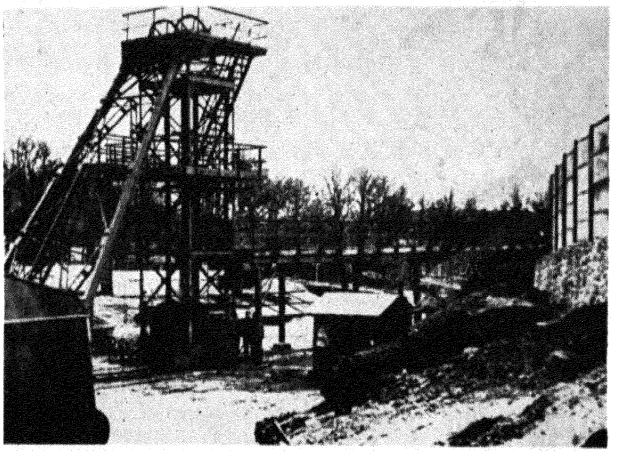

Slide 14

so far resulted in the discovery of workable deposits only in Madagascar. After first being directed towards the pegmatite ores (niobotantalates) and the lacustrine ores in the Antsirabé area, all known before 1945, our attention has latterly been concentrated on the uranothorianite discovered in alluvial and eluvial deposits in 1953. This uranothorianite is found in primary deposits in the pyroxenites of the crystallophylline base in the south of the island.

Slide 16 (Fig. 11 of P/328) is a map of Madagascar. The hatching in the eastern part of the island indicates the position of the crystalline and crystallophylline zone. The unshaded area represents the sedimentary surface covering which falls away to the Mozambique Channel. In the centre, you have the Bétafo area, rich in pegmatite veins, which is well known to mineralogists on account of betafite. It is in this area, then, that the pegmatites are found. At Vinaninkarena, near Antsirabé, small deposits of lacustrine ores are found. Lastly, in the southern part of the island, some curious and very interesting deposits of uranothorianite dispersed through pyroxenite accumulations have recently been discovered in the Tranomaro and Fort Dauphin area.

In conclusion, it may be said that after less than ten years of prospecting and exploration work, France is today in possession of a number of what may be described as substantial uranium deposits, and there are many indications of the existence of other workable formations. I should like to end by stressing the fact that these results are the outcome of sustained and methodical endeavour in which nothing has been left to chance.

We have thus established the existence of substantial French uranium deposits.

I will end by expressing the hope, which is shared by the French authorities, that so far as metallogeny is concerned this Geneva Conference will mark for all countries the beginning of a flood of scientific publications on the structure of deposits and their exploration.

Mr. D. N. WADIA (India) next reported as follows on the deposits of radioactive minerals in his country: I shall confine myself to giving a few facts about the geological environment, the structural features, grade and quantity of the uranium and thorium of India. The other material facts with regard to geological conditions, mineralogical features, etc. are given in the text of my paper (P/875).

Uranium in India is principally a product of igneous and metamorphic rocks. No uranium ores associated with sedimentary rocks have so far been known. India possesses a large number of units but, so far, we have not discovered any appreciable ore-bodies in the sediment. The uranium ores of India belong to these three categories:

1. Low-grade ores disseminated in Archaean metamorphic rocks, along the Singhbhum thrust zone, 65 miles long—the Bihar Copper Belt—associated with soda-granite intrusions in apatite-magnetite rocks, chlorite schists, quartzites, etc., paragenetic minerals being copper, molybdenum, pyrite and apatite and as segregations and disseminations in granitic gneiss in the Aravalli series in Rajputana. A zone occurs in one of the most ancient mountain systems of the world, along a belt which is, roughly, about 40 to 60 miles long.

2. Uranium ores of the second category are found in pegmatites: pitchblende and complex niobates, tantalates and titanates of uranium.

3. The third category of uranium ores is found in deposits of monazite in beach sands on the East and West coasts of the peninsula.

One notable fact to be mentioned here is that the uranium in India is associated with sulphidic copper and oxidized iron rather than with gold, lead, zinc, or vanadium. Workable uranium occurs in copper mine tailings.

The uranium content of category (1) ores is rather low, varying from 0.03 per cent to 0.46 per cent. A large tonnage of ore within this range of grade is available from the Singhbhum area and from the other areas mentioned above. The ore is probably a primary uranium compound capable of simple chemical leaching by carbonate methods. The estimated amount of economically extractable uranium from these two localities, so far discovered by us, is, roughly, several thousand (about 10,000 to 15,000) tons. The complex uranium minerals of category (2) have U_3O_8 contents ranging from 10 per cent to 39 per cent. These are minerals of pegmatite origin and their occurrence, as is the case of pegmatitic deposits, is highly erratic.

The third category of Indian ore is the monazite deposits of Travancore and Madras, which yield from 0.2 per cent to 0.4 per cent of U_3O_8. This is liberated when we extract the thorium and rare-earth compounds. Reserves of uranium locked up in this source are computed at between 3,000 and 4,000 tons, the bulk of which is easily and economically extractable. The newly discovered variant of monazite, the rare mineral cheralite, discovered in certain pegmatites in Travancore, contains from 4 per cent to 6 per cent uranium and from 25 per cent to 31 per cent thorium.

The few facts which I can give about thorium in the brief time allotted to me are the following. The chief ore is monazite, the monoclinic phosphate of some 14 rare-earth metals of the cerium group, in which thorium occurs as a constant ingredient—8 per cent to 10.5 per cent ThO_2. Monazite occurs in granites and gneisses of Nilgiri, Mewar, parts of Bihar and Madras. But the main source of Indian monazite is in the widespread beach sands of Malabar and the Coromandel coasts. Several new deposits have been discovered during the last two years on both coasts. These constitute a thorium asset of world importance. The monazite has accumulated through ages by the concentrating action of sea waves, along with ilmenite, rutile and zircon. Detailed quantitative survey is being conducted and a reserve of a little over a million tons of monazite is proved

on the Travancore-Cochin littoral. The total reserves of thorium contained in monazite in India are calculated at about 150,000 tons at a conservative estimate.

There are vast areas of the country, both in the peninsula and in the Himalayas, which are yet unsurveyed, and in my paper I have given a list of about 13 potential units of the country which may yield uranium of some commercial value.

Mr. F. IPPOLITO (Italy) reported on deposits in Italy as follows: I will give here the results obtained up to now in Italy in the field of uraniferous minerals, both by the National Committee for Nuclear Research and private companies acting in agreement with the Committee. The areas explored up to now are very limited in relation to those whose geological characteristics may be investigated in the future. It must be added that good mineralization has been discovered in areas where, previously, some experts had excluded this possibility.

The geological measurement and the geophysical prospecting carried out during the summer of 1953 and 1954 in the Maritime Alps have revealed that the more favourable grounds for uranium prospecting include the ancient quartziferous porphyries and their tuffs of Permian age, now transformed into porphyroid slates of Maritime Alps near Cuneo.

The Committee geologists paid particular attention to this formation. The mineralized areas of the northern branches of the Maritime Alps were divided into three zones, each of them corresponding to a different fundamental structure.

The first and largest one, located near the village of Peveragno (Cuneo) extends from Val Colla to Val Pesio and includes, from west to east, the explorations and the prospecting of Tetti Meni, Rio Freddo, Eretta, Ciarma, Valle dei Morti, Valle del Malinverno and Rio Argentina. The second and more limited area affects the light porphyry slates south of Lurisia. The third and last zone extends from Val Corsaglia to Val Casotto, around Pamparato, and includes the prospecting of Volpi, Bric Colmè, Case Furù, Assunta, Ravino and Val Limona. Just east of the last locality the mineralized formation disappears owing to the tectonic phenomenon in connexion with an intrusive body, successively transformed into gneiss.

The results obtained in the field of geophysical prospecting by the Soc. Montecatini and the Società Mineraria e Chimica per l'Uranio appear in the different observations published by technicians of the two companies.

It is useful to mention here how the mining works which have been carried out, though still of a research character, have allowed the extraction of a certain amount of rough mineral.

At Rio Freddo the pitchblende, whose presence is indicated on the surface by abundant secondary autunite, has been found at a depth of 10 to 15 metres. In excavation operations here, the Montecatini dug about 300 tons of rough material having a uranium content varying from 0.2 to 0.5 per cent.

The Società Mineraria e Chimica per l'Uranio dug the following amounts of material in the two localities of Bric Colmè and Fiolera: rough material with 0.3 to 0.6 per cent of uranium equal to some tens of tons; and rough material with a content of 0.1 to 0.3 per cent of uranium equal to more than 100 tons.

As a whole, the first prospecting stage carried out by the National Committee for Nuclear Research can be considered as positive, as the more important mineralized areas in the Maritime Alps have been covered by a preliminary investigation. We may therefore consider, on the basis of the results already obtained and also those which are being obtained by private companies, that the research and exploitation problem of uranium in Italy should be considered as justifying optimism. Also the laboratory research now being done contributes to this opinion and seems to increase our hopes.

Mr. K. AKI (Japan) then gave the following report on occurrences of uranium and thorium in Japan: The paper which I am presenting was written by my colleague, Mr. Sato, and his staff of the Geological Survey. To my sorrow, Mr. Sato cannot join in this discussion. I am not a geologist, but permit me to read his paper (P/1036).

Systematic field investigation for uranium- and thorium-bearing minerals in Japan was just started by the Geological Survey in autumn of 1954, and the work done so far is no more than a part of a preliminary survey for rare-element resources. Until last year it consisted only of random surveys.

Most of the radioactive minerals found in Japan are refractory uranium- and/or thorium-bearing minerals. They are associated with each other and have a close relationship to granitic pegmatites, occurring in the pegmatites and allied alluvial and diluvial deposits. They were seldom mined for production purposes. In most cases they were merely the object of scientific research or collection of minerals. A variety of secondary uranium mineral was found recently, as referred to later, in a metallic ore deposit.

Modes of occurrence of the uranium and thorium minerals related to pegmatites can be classified into the following three types:

1. Accessory Minerals in Granitic Rocks

Zircon, monazite, allanite and others are sometimes present as accessory minerals in granitic rocks. The quantity of such component minerals is very small, and, in most cases, the content of uranium is less than that of thorium.

This type of occurrence can be observed in granitic regions such as the Abukuma Mountainland, Naegi district in Gifu Prefecture, Kurashiki City in Okayama Prefecture, and others.

2. Minerals Present in Granitic Pegmatites

Monazite, euxenite, allanite, xenotime, fergusonite, samarskite, thorogummite, autunite and other radioactive minerals sometimes occur in druses, or as inclusion in micas, being associated with feldspars

and micas in part of graphic structure in pegmatites. Well-formed crystals of such minerals have been found so often that mineralogical and chemical studies have been made of them.

Outstanding examples of this type are found at Ishikawn-machi and vicinity, Fukushima Prefecture, in the southwestern part of the Abukuma Plateau; Suishôyama in the northwestern part of the same plateau; Naegi-machi, Gifu Prefecture, Kôbe area in Kyôto Prefecture; Hakata-mura, Ehime Prefecture; Bôfu City and Yanai-machi, Yamaguchi Prefecture; and Nagatare area, Fukuoka Prefecture.

3. Minerals Present in Residual or Placer Deposits Derived from the Above Two Types

In the regions of granitic rocks and pegmatites mentioned above, residual materials are produced on the land surface containing uranium and thorium minerals derived from the disintegration of the granitic and pegmatitic rocks due to weathering. These products are transported and sorted by running water and sometimes form placer deposits filling up the neighbouring river valleys.

The most remarkable locality of this type is the Naegi district in Gifu Prefecture.

Though the occurrence of uranium and thorium in Japan was previously confined to minerals originating in granitic rocks and pegmatites as mentioned above, a kind of uranium mineral contained in metallic ore deposit was found for the first time in 1954 in the Miyoshi mine in Kurashiki City, Okayama Prefecture.

In this area, quartz veins occur in biotite granite, having trends roughly parallel to each other. The ore deposit consists of quartz veins accompanying wolframite and cassiterite, 10 to 20 centimetres in width. The ore is of rather low grade, containing molybdenite, chalcopyrite and arsenopyrite as its minor constituents. Some 5 to 10 centimetres of both sides of the quartz veins are greisenized granite.

The uranium mineral is zeunerite, often found along the cracks in the vein and greisen. Primary uranium minerals have not yet been found.

The wall rock granite is estimated as a part of the Cretaceous intrusion mass of "Hiroshima Granite", which is distributed widely in the southwestern part of the mainland. Systematic field surveys, including airborne and car-mounted methods, have just now started on this favourable granite area around the Miyoshi mine.

Further investigations will be carried on regarding various metallic ore deposits in granitic rocks. The ages of granitic rocks in Japan are late-Paleozoic, Mesozoic, late-Mesozoic (Cretaceous) and Tertiary (Miocene). It is not yet known which granite in age is most favorable.

As I pointed out, our experience in this field is so short that it is difficult for us to give definite conclusions. But, generally speaking, the notes mainly relate to pegmatite in granitic rock of late-Paleozoic origin. We have discovered the existence of Mesozoic and late-Mesozoic deposits in the western part of Japan. We are now paying more attention in the surveying of these areas. We may send reports to the Conference on this matter in the future.

Uranium and thorium minerals that deserve special mention for the present in Japan are refractory minerals related to pegmatite. They consist of phosphates, tantalates, niobates, silicates, titanates, etc. Uraninite and other oxide minerals are rare. If such deposits are to be exploited, the complexity of their component minerals must be properly taken into account.

It must be emphasized, again, that the systematic prospecting for uranium and thorium has just been started, and the outcome depends entirely upon the progress of survey and research to be carried out hereafter.

Mr. C. P. Lobato (Portugal) discussed uranium occurrences in Portugal as follows: The existence of uraniferous ores has been established both in Portugal itself and in Angola and Mozambique.

The most important deposits in Portugal are concentrated in the granitic Hercynian massif of the Douro and Beiras, with different facies depending on whether the surrounding rock is granite, gramilite or greisen; and the ancient massif, the mudstone of the Beiras and the antracolitic formations are traversed by numerous doleritic and basaltic veins.

The uraniferous veins constitute a metallogenic province with three zones of mineralization, in which deposits of cassiterite, wolframite and sulphur ores are rare or non-existent.

Up to the present, no radioactive mineralization has been discovered in sedimentary formations. The main features of the three mineralized zones may be described as follows:

Zone A: This comprises the most important deposits in the Viseu-Nelas-Carregal do Sal area and consists of a series of regional shear zones caused by the alpine movements that created the Sierra da Estrala horst. Among the regional shear zones, there is a system of faults due to east-west and north-south tension.

In the recent stage of mineralization, horizontal movements have given rise to faults with adjacent tensions favourable to the deposit of layers of pitchblende in highly faulted areas, with breccias containing micro-botryoidal pitch of colloidal origin in a matrix of finely granulated quartz, pyrite, galena, sphalerite and chalcopyrite.

There is a direct relation between uranium mineralization and the alteration and metasomasis of the feldspars and alumino-silicates.

The host granites associated with the veins often show a dispersed uraniferous mineralization of the *stockwerk* type resulting from mylonitization.

Zone B: This comprises the Guarda-Belmonte-Sabugal area, which has very extensive fracture zones filled with mineralized veins and numerous diabasic dykes.

The tension faults gave rise to a quadrilateral formation of shear zones in which were deposited

veins of white quartz—jasperoid and breccia—pitchblende, pyrite and chalcopyrite, the last-named either dispersed through the quartz or converted by epigenesis into chalcocite and covellite.

A direct relation between the distribution of the uraniferous deposits and the amount of hematite and sericite in the host granites has been observed.

Zone C: This comprises the deposits in the Francoso-Aguiar da Beira-Moimenta region. They have two structures, one that of the shear zones running in a north-south direction and the other determined by tension faults along lines governed by the general direction of the basic shear zones. A special feature is the existence of rudimentary radial shear zones, which determined the last stage of the mineralization process.

The veins consist of white and black coarsely crystalline quartz, and occur in zones or brecciated, with successions of vugs. The pitchblende and secondary ores occur as fine veins, crystalline intrusions or pulverulent micro-botryoidal deposits on quartz crystals, as geodes or in vein fissures.

From the point of view of metallogenic classification, the Portuguese uraniferous deposits belong to the primary-vein, low-temperature type, characterized by a group consisting of quartz, jasper and chalcedony; the uranium occurs in the form of pitchblende and secondary ores associated with pyrite, marcassite, galena, sphalerite and chalcopyrite.

The veins are epithermal and there are no ores formed at the high temperatures associated with alpine orogeny.

The overseas ores are of the "refractory" type and of very complex composition. In Angola, Portugese West Africa, the pegmatite veins of the Dande, embedded in the gneisses of the basal complex, have been worked for muscovite and beryl. They are found together with garnet, pyrite, chalcopyrite, epidote, chlorite and torbernite.

In the Caala area there is a fault area close to the line where the vast granitic-dioritic massif of the Bengula Plateau meets a complex of quartzites, sandstone and mudstone belonging to the Oendolongo system. There is a thick vein of quartz containing pyrite, chalcopyrite, malachite, chrysocolla, native gold and some scattered flakes of torbernite.

Traces of radioactivity have also been found on the vast Bengula Plateau in formations of the basal complex. They occur either in dolomitic limestones, as at Longonjo, or in finely granulated and deeply altered rocks, as at Bailundo.

The gold-bearing alluvium concentrates occurring in the boundary zone between the great granitic batholith and the surrounding formations of the basal complex, which are derived from low-content veins of metamorphic formations, have also been studied.

The gold-bearing concentrates of the basal complex contain a large proportion of rare earths, thorite, columbo-tantalates and cassiterite.

The main components of the pegmatites in the Cazengo-Malange area are quartz and orthoclase and the subsidiary components are titano-magnetite and veins of vermiculite. Sometimes samarskite is found, always together with quartz.

In Mozambique, Portuguese East Africa, there are two uranium-bearing regions, north of Tete and in the departments of Zambesia and Niassa.

In this region, the following formations are very well represented: (1) a metamorphic complex of the ancient crystalline base, consisting of marly schists, amphibolitic schists and crystalline limestones, probably of Archean origin; (2) a gabbro-doleritic intrusion, which presumably partly absorbed the preceding complex, of pre-Karroo age; (3) the Karroo system, mainly composed of mudstones, sandstones and conglomerates, sometimes interbedded with coal; and (4) a more recent granitic-syenitic intrusion, probably of Tertiary age.

The uraniferous deposits, represented by pegmatite dykes and hydrothermal veins, are concentrated in haloes at the boundary of the gabbro-doleritic complex, which were exposed to powerful tectonic thrusts and in zones where there is much scapolite formation.

From the geological point of view, five types of primary uranium deposits may be distinguished: (1) scattered mineralization in fine-grained acid rocks, where the uraniferous ore content may be up to one per cent; (2) large continuous veins of pegmatite derived from granito-syenitic magmas; (3) veins of calcite of extended stringer formation and considerable size; (4) veins of gabbro pegmatites rich in pyrozene and resulting from metasomatic changes, the veins being invariably thin and short; and (5) impregnations of scapolitized strips of gabbros, generally irregular and small.

The uraniferous ores consist chiefly of davidite, and sometimes samarskite and stibium-tantalite. Small accumulations of solid pitchblende with yellow alteration products are also found occasionally.

These ores are generally associated in varying proportions with pyrite, pyrrhotite, chalcopyrite, molybdenite, rutile, ilmenite, magnetite, calcite, apatite, tourmaline, scapolite and vermiculite.

Mr. S. H. U. Bowie (UK) commented as follows on the occurrence of uranium and thorium in Great Britain and the British colonies: I have been asked to summarize three papers (P/759, P/760, P/761) submitted by Mr. Davidson of the Geological Survey. The first paper is on the mineral resources of Great Britain, the second is on the mineral resources in the British Colonies, and the third is on the occurrences in the Federation of Rhodesia and Nyasaland.

First, as regards Great Britain: Close to a hundred occurrences of uranium mineralizations have been found in Devon and Cornwall, but none is of significant economic potentiality under modern conditions. The principal lodes are of east/west or north-east/south-west trend and generally conform to a thermal zonal arrangement whereby tin occurs within the granite and copper where the lodes pass

into the metamorphic aureoles of shale or 'killas'. Pitchblende, altering to metatorbernite and other secondary minerals, is found in the copper zone, most frequently where the wall-rock is diabase; but this radioactive mineralization is always in pockets of no great extent.

Cross-course lodes of somewhat later formation and of north/south trend also carry uranium ores, usually associated with cobalt, nickel and bismuth minerals. The South Terras mine near St. Stephens, which during intermittent operations has produced between 75 and 80 tons of uranium oxide, is of this type and is the only property which has been worked solely for uranium. Past uranium production from other Cornish properties can be measured in hundredweights rather than in tons, and the aggregate output from all sources has not exceeded 100 tons of uranium oxide.

Uranium mineralization is not rare in the sedimentary rocks of Britain, but nowhere does it reach an over-all grade sufficient to meet commercial exploitation.

The likelihood of finding important new uranium and thorium deposits seems rather remote since Britain has been mapped in greater detail than any other country of comparable size in the world.

Next, the British Colonies: No uranium deposits of economic significance have as yet been found in any of the British Colonies, Protectorates, Protected States and Trust Territories. Occurrences of uranium minerals in pegmatites and migmatites are far from rare, and various attempts have been made to work such rocks for uraninite in the Uluguru Mountains of Tanganyika, and for euxenite or samarskite at Nanseke in Uganda, at Rupununi in British Guiana and near Mbabane in Swaziland. These efforts have supplied no more than a few hundredweights of concentrate at a prohibitive cost. The extensive deposits of albite- riebeckite-granite at Kaffo in Northern Nigeria, which carry 0.33 per cent Nb_2O_5, 0.012 per cent, U_3O_8 and 0.03 per cent ThO_2, may one day become of commercial value, but the output of radioactive elements will only be possible if the deposit can be worked for niobium.

As regards thorium, the known sources of thorium are more plentiful. The tin mining operations of Nigeria and Malaya, for example, are capable of yielding by-product thorium if the need arises. In Nigeria, the resources lie partly in monazite and partly in thorite. At present the throughput at the tin dressing sheds totals about 75 tons of thoria per annum, and the reserves that will be mined over the next 20 years amount to between 1000 and 2000 tons. The aggregate reserves of Malaya exceed those of Nigeria, but differ in character in that the thoria is present almost wholly as monazite.

As regards the Central African Federation, many occurrences of radioactive mineralization have been found in the Federation of Rhodesia and Nyasaland, although only one of these has been shown to be a deposit of workable extent. There are sound geological grounds for hopes of further discoveries and extensive prospecting is at present being undertaken.

The most promising discoveries of uranium are those in the copper mines of Northern Rhodesia but as yet only in the Nkana mines has the tonnage and grade of uranium mineralization been found to be sufficient to warrant the erection of a treatment plant. The payable ore at Nkana occurs as disseminated ore in a part of the mine where copper and cobalt values are below cut-off grade, thus permitting selective working. Similar copper ores with a little uranium occur in Lomagundi, Southern Rhodesia.

At numerous localities in all three countries of the federation, pegmatites and migmatites have been found to carry radioactive minerals—notably uranothorite, allanite, euxenite, samarskite, betafite, pyrochlore-microlite, monazite, zircon and tantalite. Some attempts have been made to work deposits of this kind but it is unlikely that they will prove remunerative. Extensive deposits of pyrochlore with 0.8 to 4.5 per cent ThO_2 are present in carbonatite vents at Chilwa Island in Nyasaland and at other localities, and these may furnish some by-product thorium provided the pyrochlore can be worked on a large scale as a source of niobium.

Mr. L. R. Page (USA) reported on occurrences of uranium and thorium in his country as follows: I would like to present this afternoon a summary of paper P/471. Uranium has been found in all major geologic environments in the United States, except those typified by ultramafic and plateau basalt igneous rocks and certain marine sediments.

Concentrations of uranium occur in igneous rocks, veins, terrestrial clastic rocks; precipitates and evaporites; lignite, coal, and asphaltic materials; marine black shales and phosphorites. Most of the uranium of ore grade is in the Orogenic belt between the 100th and 120th meridian of west longitude; a few deposits occur elsewhere.

Some igneous rocks contain much more uranium than do most granites. The uranium occurs as discrete uranium minerals, disposed in the structure of the rock-forming minerals, adsorbed on the surface of grains, and dissolved in fluid inclusions and intergranular fluids. The uraniferous intergranular fluids are leachable in dilute acid and may offer a very low-grade, exploitable source of uranium for the future.

Uraniferous vein deposits in western United States are mainly Tertiary in age and most of the exploitable deposits are in crystalline rocks of pre-Cambrian, Mesozoic, and Tertiary age. Occurrences in eastern United States, mostly undated, are mainly in rocks of Paleozoic or pre-Cambrian age. Pitchblende or uraninite, associated with base metal sulfides or with fluorite, is the principal uranium mineral in the vein deposits at depth. Supergene secondary minerals occur in some deposits, but are not abundant.

The vein minerals, for the most part, were de-

posited under near-surface conditions; a few may have been formed at intermediate depths. Hydrothermal alteration of the wall rocks includes silicification, sericitization, chloritization, argillization, and alunitization. Red hematite zones adjacent to veins are common.

The principal sources of uranium in the United States, however, are in the terrestrial sandstones, mudstones, and limestones in which the uranium minerals occur disseminated as pore fillings and impregnations. The largest and most numerous of these deposits are in rocks of Mesozoic age on the Colorado Plateau, but similar deposits also occur in Mesozoic and Tertiary rocks on the fringes of the Plateau; and in the Cordilleran Foreland east of the main folded and thrusted belts of the Rocky Mountains. Uranium also occurs in Paleozoic sandstones on the Colorado Plateau, and in Texas, New Mexico, Oklahoma and Pennsylvania. In all, 37 sedimentary units have yielded uranium; 18 have furnished at least 1000 tons of ore averaging more than 0.1 per cent U_3O_8.

These areas are characterized by simple folded mountains alternating with broad, asymmetric basins. In the Black Hills of South Dakota and Wyoming the uraniferous districts are above major structural terraces on the pre-Cambrian surface and the individual deposits are on similar minor structures in cretaceous sandstones. Similarly in the Colorado Plateau, regional structures such as uplifts, faults, joints and Tertiary igneous stocks and laccoliths appear. On the Colorado Plateau most of the significant production is obtained from formations containing varying proportions of fluvial conglomerates, sandstones, and mudstones in which plant debris is abundant. Copper, copper-uranium, and vanadium-uranium deposits, both oxidized and unoxidized, have been found; uraninite is the chief ore mineral in many deposits. Exploitable ores are in many cases restricted to the sides and bottoms of channel fillings in shallow depressions in the lower contact of the porous clastic rocks. In other places they are not restricted to channels or to any particular stratigraphic unit; most, however, are in sandstones or coarse clastics in the lower part of the formation.

They may be localized in the thicker parts of the sandstone lenses by sedimentary structures, such as channels, lenses, and intersections of crossbeds, and have their long axes parallel to current lineation, festoon bedding trends, and scours.

Widespread uraniferous marine sedimentary rocks include the phosphatic rocks of Permian age in Idaho, Montana, Wyoming, and Utah, and of Tertiary age in Florida; the Chattanooga black shale of Devonian and Mississippian age, and some black shales of Pennsylvanian age in the Central States. The uranium content generally is less than 0.01 per cent. Aluminum phosphate deposits of slightly higher grade have been derived from the weathering of marine phosphorites and of phosphatic nodules in some marine black shales. Marine sandstones, conglomerates, mudstones, and limestones rarely contain concentrations of uranium. Because the marine phosphorites are of wide extent, they contain large tonnages of uranium, some of which can be recovered, under favourable conditions, as a by-product of the manufacture of triple superphosphate.

In the United States, as in some other countries, many of the more important deposits are those in which uraninite is disseminated in sedimentary or metasedimentary rocks, and vein deposits are playing a less important role. This requires that we review the classical theories of origin of uranium deposits. Studies of absolute age of uranium minerals have been especially important in this connection and deposits such as the carnotite of the Plateau, formerly considered essentially syngenetic are now known to be clearly epigenetic. This fact, together with the spatial distribution of some deposits, implies that the uraniferous solutions travelled tens of miles along the porous clastic host rocks before deposition.

GENERAL DISCUSSION

The CHAIRMAN: I have two questions for Mr. Wadia (India). Have you observed occurrences of monazite in underwater deposits on the continental platform or only on the shores? Secondly, does any possibility exist of a regeneration of the deposits of monazite as a consequence of the movement of waves?

Mr. WADIA (India): The deposits of monazites have been found to extend below water level to a depth of a few fathoms. Then again, along the coasts there are a great many places on the beds of lakes where we have observed considerable amounts of monazite, but the continental shelf—the platform itself—probably has a fair amount because at the end of every monsoon, the period of the heavy rains when the sea is very rough, new deposits of monazites are washed onto the shore. It does not mean that the sea itself is contributing any material quantities of monazite but that it is the material that is accumulated on the continental shelf which is washed on to the shore.

Session 7B

PROSPECTING FOR URANIUM AND THORIUM

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Methods of Prospecting for Uranium and Thorium

By C. F. Davidson and S. H. U. Bowie,* UK

In no phase of mineral exploration is there a wider range of technical methods at the disposal of the prospector than in the search for radioactive ores. Indeed, so many are the techniques available, and so vociferous are their respective advocates, that it tends to be forgotten that successful prospecting is almost always based upon the application of fundamental geological knowledge. Nearly all important deposits of uranium and thorium have been found, not by chance, but by the systematic exploration of country which geological experience suggested was potentially hospitable to radioactive mineralization. It is true that, very exceptionally, wild-cat discoveries have been made by enthusiastic amateurs equipped with Geiger counters, and the operations of workers of this kind deserve every encouragement. But in any major programme of mineral exploration, useful discoveries are most likely to be made where the field work is founded on sound scientific knowledge. Geological control is a prerequisite to all intelligent prospecting operations, no matter what ancillary aids to exploration are employed.

The first essential step towards making a systematic exploration for radioactive mineralization in any circumscribed region is therefore a comprehensive study of the existing geological information on the area in question, by one or more geologists who are well acquainted with the now extensive literature describing the geological, geochemical and structural environments in which such mineralization is most likely to occur. From such preliminary research it may in many instances be possible to postulate what are potentially the most favourable localities demanding priority in field operations. All known occurrences of mineralization, particularly sulphide mineralization, should be systematically listed, for more uranium ore has been found in old prospects and in working or derelict mines than anywhere else; and attention should be specifically directed to formations which bear an apparent petrological similarity to known uranium provinces elsewhere. Contemporaneously with this work, the prospectors to be engaged in the field operations should receive training in the recognition of common radioactive minerals—not only of the fine specimens found in museums, but more particularly of the paint-like traces of secondary uranium minerals and of the iron-rich gossans without visible uranium which so often are all that is seen at the surface. The type of training given must differ greatly according to the terrain to be explored, that appropriate to the glaciated lands of Canada, for example, being entirely dissimilar to that necessary for successful work in the heavily-weathered and soil-masked rocks of Central Africa. In this preliminary phase also the mineral scout should be instructed in the use and maintenance of the instrumental aids with which he may be supplied, such as ratemeters for routine prospecting and for field assay work, and ultra-violet lamps for fluorescence tests. In circumstances where geological information is so inadequate that no guiding rules for exploration can be laid down, it is probably wiser not to undertake a specific search for uranium and thorium ores at all, but instead to initiate a programme of geological reconnaissance mapping coupled with a general prospecting campaign for economic minerals of any kind. Workable sources of radioactive minerals are of quite rare occurrence, and in completely unknown territory there is more hope of finding uranium as a by-product of a search for copper, cobalt, silver, and other metals than in explorations directed solely towards uranium ores. Similarly the discovery of workable thorium ore could well result from a search directed more to the alluvial tinstone, columbite and ilmenite that it so often accompanies.

ELECTRONIC AIDS TO PROSPECTING

In all radioactivity explorations the principal tool of the intelligent prospector, surpassed in importance only by his geological knowledge, is a field ratemeter —either a Geiger-Müller counter or a scintillometer. Both of these instruments measure the gamma radiation from near-surface occurrences of radioactive elements, but in somewhat different ways. In the former, the ionizing radiations produce secondary electrons which are amplified by gas multiplication within the envelope of a Geiger-Müller tube, whereas in the latter the radiations produce scintillations in a phosphor and these are amplified with the aid of a photomultiplier (or electron multiplier) tube. Less than one per cent of the gamma rays passing through the Geiger-Müller tube produce a secondary electron which will be counted, but nearly all the rays entering a large thallium-activated sodium iodide crystal will cause scintillations capable of being recorded. This difference in the response of the two types of detector is most pronounced for the softer terrestrial radiations but is scarcely perceptible for cosmic rays. An

* Geological Survey of Great Britain.

efficient scintillometer is about 50 times more sensitive to terrestrial gamma rays than a Geiger-Müller counter, and as the two instruments respond similarly to cosmic rays it might be expected that it is 50 times easier to detect an anomaly with a scintillometer than with a Geiger counter. This, unfortunately, is not so, since the background gamma count is also increased substantially with a scintillometer. Peirson and Franklin[1] have indicated that the performance factor, or the ability to detect a radioactivity anomaly, can be as much as seven times higher in a scintillometer than in a Geiger-Müller counter if the two detectors are of the same volume; but since it is very much easier to make large Geiger-Müller tubes than it is to make large efficient volumes of scintillation material, this factor is in practice reduced to about three.

Portable Field Instruments

The prerequisites of a good portable field ratemeter are compactness, lightness in weight, robustness, and hermetical sealing to permit its use in all climates. The batteries should be of a kind readily obtainable, and they should be few in number and easily replaced; whilst the meter should be calibrated in milliroentgens per hour so that a quantitative measurement of the radioactivity at the point of observation is available. Beyond this, the choice of instrument will depend largely upon the degree of reproducibility sought in the proposed investigation. The statistical accuracy of a ratemeter depends upon the count rate of the instrument and the time interval over which the pulses are integrated. A variation of about 10 per cent is normally satisfactory and most British ratemeters are designed to give this reproducibility of readings on a short pause at field stations. For routine prospecting, where no compensation is made for terrain factors such as local topography (solid-angle effects), absorption by soil cover, and disequilibrium due to weathering, a high statistical accuracy is quite unnecessary. The pulse rate for a good prospecting instrument may be as low as one or two counts per second over flat-lying, feebly radioactive, bedrock (e.g., limestone) with a grade equivalent to 0.001 per cent U_3O_8.

For more detailed studies, for example in contouring the distribution of radioactivity at an anomaly, a ratemeter should have a count rate of about five pulses per second over bedrock of low radioactivity. If the meter integration time on such an instrument is 10 seconds the statistical error will be 14 per cent, and if the integration time is increased to 20 seconds the reproducibility will increase to $\pm$ 10 per cent. An increase of from 20 to 30 per cent in the count rate, equivalent to an increase of about 0.001 per cent U_3O_8 in the bedrock, can be measured with certainty using an instrument of this sensitivity provided the operator stops for about a minute to take each reading.

For a given statistical accuracy the count rate must be raised if a quicker response is required; and to maintain a standard deviation of 10 per cent in surveys made *without stopping* at a walking pace of three miles per hour, the background count of the instrument must be increased considerably. In these circumstances, to measure the average radioactivity over traverse intervals of 10 feet the pulse rate would have to be about 40 counts per second, with an integration time of 2.5 seconds. It is not practicable for field geologists to carry Geiger-Müller instruments containing single or multiple tubes with large enough cathode areas to give this response; but the required count rate can be achieved by using a scintillometer with a thallium-activated sodium iodide crystal about an inch in volume, and effort is therefore being directed towards the production of British equipment of this kind.

Unfortunately the operating voltage of present-day scintillometers is about four times that of a halogen-quenched Geiger-Müller counter, and from the aspect of the prospector the increase in battery weight necessary to maintain the high-tension supply to the photomultiplier tube largely offsets the advantages gained by the scintillometer's higher sensitivity. Again, no scintillometer has yet been manufactured anywhere which is as stable and robust as a good Geiger-Müller counter under field conditions; and for many years to come the former type of instrument is likely to be the more costly. At present the scintillometer possesses practical advantages only where it is considered essential to detect an anomaly barely above background—a circumstance which rarely occurs in prospecting. Within a few years' time, however, small but thoroughly reliable scintillometers operating from ordinary torch cells through junction transistors should meet all the requirements of prospecting programmes, and if their cost can be reduced to a competitive level, they will probably replace Geiger-Müller counters in all operations save field assay work. For the execution of approximate radiometric assays in the field, a ratemeter with a thin-walled beta-sensitive Geiger-Müller tube, which can be surrounded by annular sample holders, has proved more satisfactory than any other type of portable equipment.

Car-borne Instruments

In countries where there is a good network of roads and motorable tracks, particularly if as in Africa these roads are not paved with introduced road metal, much useful prospecting can be carried out by the use of a sensitive radiation detector mounted on the roof of the prospector's vehicle, usually a Land Rover. During prospecting on foot a ratemeter is normally carried at about eighteen inches from the ground, and at this height most of the signal is received from rocks within a radius of 10 feet; but when the height of the detector is extended to 5½ feet the coverage is extended so that, in flat terrain, nine-tenths of the signal comes from within a radius of 50 feet. An even wider radius can be covered, under favourable circum-

stances, by mounting the detector high above the car. Surveying with car-borne equipment can conveniently be carried out at speeds of up to 30 miles per hour; and to obtain an accuracy of 10 per cent over 50-foot traverses at this speed, the count rate must be about 85 pulses per second over feebly radioactive bedrock with 0.001 per cent equivalent U_3O_8.

Surveying with car-borne equipment has been carried out by the Geological Survey of Great Britain, at home and overseas, at various periods since 1950, and it has resulted in numerous discoveries of radioactive mineralization. The instruments at present employed are both Geiger counter and scintillometer type. The latter has a background count of 40 pulses per second over feebly radioactive bedrock, with time constants of one second on the ratemeter and an automatic alarm circuit, and effectively six seconds on a recorder which provides a graphical representation of the radioactivity. To obtain the maximum signal, the Geiger-Müller tubes of appropriate sensitivity are arranged in a close-packed bundle with their long axes parallel to the path of the vehicle: and in the scintillometer equipment it is advantageous to use two crystals, one on each side of the vehicle. British car-borne scintillometer equipment now under development uses a single large crystal with a five-fold increase in count rate over the crystals previously employed; but this is intended for use in geological mapping rather than in explorations for ore.

Bore-Hole Logging Equipment

The radiometric logging of diamond and percussion drill holes, with or without continuous graphical recorders, is now a routine operation in many fields where such exploration for mineral deposits is in progress. For this work the choice between a Geiger-Müller counter and a scintillometer depends upon local circumstances. Scintillometers are capable of resolving much narrower and weaker zones of radioactivity than Geiger-Müller units by virtue of the high specific activity of the scintillation phosphor, and for this reason also the logging speed, for the same statistical accuracy, can be much faster with a scintillometer. They are, therefore, particularly suitable for logging feebly radioactive marker horizons for oil and coal, provided the bore-hole temperature is not unduly high. But the size of currently available photomultiplier tubes precludes the use of scintillometer probes in holes of less than two inches diameter—that is, in most holes drilled in search of uranium ore. Geiger-Müller probes, on the other hand, can be used for both AX(1⅞ in.) and EX(1½ in.) holes, and can also be made slim enough to be inserted without removing the rods. Since the intersections of ore and sub-ore being sought have a high radioactivity quickly detectable by Geiger-Müller counter, there would apparently be no useful purpose served by developing a small scintillometer for bore-hole work in uranium fields.

AERIAL RADIOACTIVITY SURVEYS

The use of sensitive scintillometers in aircraft has in recent years been widely advocated as a rapid means of prospecting for radioactive minerals, and it seems probable that more money has been expended on this technique than in any other form of primary exploration for uranium ores. Unfortunately the results of this work have been far from encouraging. Not a single important uranium deposit has been found by this method, and several cases are on record where aerial surveys failed to detect known deposits and where workable ores were later found in regions which by aerial survey had been reputedly shown to be barren. In Canada, where from four to five thousand occurrences of radioactive mineralization with over 0.05 per cent equivalent U_3O_8 have been located, less than a dozen of these were found by aerial prospecting—although here such exploration had till recently a temporary phase of popularity. Probably the reason for the lack of success in most of these aerial exploration programmes is that they were carried out as wild-cat enterprises, without any preconceived geological basis for the operations. If it is unremunerative to undertake wild-cat reconnaissance solely for uranium ores, neglecting other minerals, on the ground, it is much more so to do this from the air.

Even with the most sensitive scintillometers aerial surveys should be flown at a very low altitude, certainly under 200 and if possible at 100 feet, if an anomaly due to a virgin ore body is to be discovered. This low flying, undertaken necessarily by a small slow aircraft, unfortunately precludes the simultaneous operation of scintillometer and magnetometer surveys, but is necessary for two reasons. Firstly, the gamma radiation from ground level is less absorbed by the air and less dispersed from the point of origin than it would be at a higher altitude. Secondly, since the outcrop of a radioactive ore body is likely to form only a very small part of the area subtended by the scintillometer, it will give a proportionately greater part of the total signal if the plane is nearer the ground, and the ore body will thus be more readily perceptible. Such low flying, however, demands not only the co-operation of a sympathetic insurance company but also requires for complete coverage strip flying along lanes not more than 400 feet apart. The cost of an aerial operation examination of anomalies discovered, thus becomes almost as high as that of a fair geological reconnaissance during which minerals other than radioactive ores may well be found. Further, from empirical tests it seems apparent that even a highly sensitive scintillometer will not detect a well exposed small lode deposit, carrying say 0.15 per cent U_3O_8 over 3 feet width, if the line of flight at 200 feet is transverse to the strike of the lode.

The number of anomalies per unit area found in an aerial survey of this kind will depend upon the type of country traversed. For example, in granitic terrain with fairly rugged topography and a patchy

distribution of outcrops, "highs" will be found in great profusion, some due to small hills, some to bare rock exposures surrounded by overburden, some to sparse disseminations of monazite and other radioactive minerals dispersed through the granite or derived alluvials. The anomaly which indicates a potential ore deposit will occur but very rarely—and unless the flight is carried out very close to the ground it may well prove impossible to distinguish it from peaks attributable to many other causes.

Notwithstanding what has been said on the high odds against success when using aerial radioactivity surveys in the primary or reconnaissance phase of exploration, the technique has a use—perhaps eventually its only use—in secondary prospecting, as a tool to check quickly whether or not abnormal radioactivity is present in some stratigraphical or structural environment which from experience elsewhere the geologist considers to be favourable to mineralization. Where, for example, some stratigraphical horizon is known to be mineralized at one locality, and where geological maps or aerial photographs showing the disposition of the strata are available, check tests on the radioactivity can rapidly be made from the air at all other supposedly favourable exposures. Successful use of the aerial scintillometer in this way has been made in the uranium fields of the Colorado Plateau in America and Blind River in Canada. Other comparable studies are to be found in the aerial radiometric mapping of deposits of phosphorite and of monazite-bearing beach sands. In work of this kind it seems probable that the helicopter will soon replace slow-flying aircraft.

GEOCHEMICAL PROSPECTING

The search for uranium ore bodies by panning or loaming of alluvial concentrates is seldom undertaken, for uraninite (pitchblende) and its secondary alteration products are virtually unknown in modern sediments because of the ease with which they are pulverized and dissolved during transportation. Complex uranium minerals such as euxenite, betafite, brannerite and samarskite readily survive in placers, as do also monazite, thorite and thorianite; and although in almost every case these minerals derive from pegmatites and granites too low in grade to be payable, instances have been known where pebbles of monazite and grains of thorianite have been traced back to workable deposits. The study of the derivation of radioactive placer minerals should therefore not be neglected by the prospector.

The ready migration of uranium in solution on weathering of primary ore suggests that geochemical techniques, involving quantitative chemical analysis for the metal in soils, alluvium, vegetation and surface waters, may be of value in searching for new uranium ore bodies. In prospecting for uranium, however, quantitative chemical studies of soils and alluvium have seldom been undertaken due to the ease with which even a low tenor of the radioactive elements may be detected by radiometry. But where such analytical examination is being made for other metals, tests for uranium might usefully be incorporated. A rapid method for such work, utilizing paper chromatography, has recently been developed.[2] Chemicobotanical techniques involving the analysis of plant ash have also been studied, but seem likely to be useful only in the exploration for extensions of known ore bodies in sub-desert regions where there is a thick overburden and plants are deeply rooted. No direct ecological aids to uranium prospecting are known, but locally geobotanical studies can be of indirect assistance: in Colorado, for example, bushes of *Astragalus* are dwarfed where rooted in soils rich in the selenium that commonly accompanies the uranium ore; and in the Congo-Rhodesian Copperbelt certain plants which are commonly found in soils overlying copper-cobalt ores direct attention to mineralization in which uranium may be present.

In country which is difficult of access—for example, in heavily forested mountain terrain—quantitative determinations of the uranium content of the drainage waters may help to delineate first the river basin, and then the tributary valley, in which uranium mineralization is most likely to occur. Studies of this kind can materially reduce the size of the region which calls for detailed surface prospecting. A field analytical method for prospecting work of this kind utilizes anion exchange resins for the extraction of the uranium from water samples, the resin then being ashed and the content of uranium estimated fluorimetrically by comparison with specially prepared standard phosphors.[3]

In large copper, gold, and other mines the presence and approximate distribution of uranium mineralization underground can be detected by examining the various upcast ventilation fans for radioactivity with a field counter. Any high radioactivity present is due mainly to the daughter products of radon, which are deposited from the upcast air, together with mineral dust, on the grille protecting the rotating fan blades.

REFERENCES

1. Peirson, D. H. and Franklin, E., *Aerial prospecting for radioactive minerals,* Journ. Appl. Phys., *2,* 281–291 (1951).
2. Hunt, E. C., North, A. A. and Wells, R. A., *Application of paper-chromatographic methods of analysis to geochemical prospecting,* The Analyst, *80,* 172–203 (1955).
3. Ostle, D., *Geochemical prospecting for uranium,* Mining Magazine, *91,* 201–208 (1954).

Uranium Prospecting in Canada—Ground and Aerial Surveys*

By A. H. Lang,† Canada

Prospecting for uranium, carried on with growing intensity in Canada during the last twelve years, has resulted in some outstanding mines and several promising prospects. More persons are searching for uranium today than for any other metal, and uranium mining is assuming a major place in our mineral industry. The methods of prospecting are imperfect and are not exclusively Canadian, but they have produced results, therefore we are pleased to describe them, with the hope that some features may be useful to persons in other countries. We are grateful for this opportunity to learn of the experience of our colleagues abroad, and to discuss matters of mutual interest

The subject of prospecting for uranium in Canada cannot be more than outlined in a short paper, but other publications give more detailed information on many phases of the subject. This paper, therefore, is merely an up-to-date summary touching on the main features and providing references to further data. The survey paper includes information on Canadian uranium deposits and thus renders it unnecessary to make more than brief mention here of the types of deposits and their geological characteristics and distribution.

1. GEOGRAPHICAL AND GEOLOGICAL NOTES

Canada is a country of contrasts. Its population is concentrated in the southern parts, where cities and towns, industries and transportation facilities are highly advanced. Beyond are vast thinly populated areas where pioneering conditions prevail, and where the frontier is rapidly being extended northward, largely by mining activities. In most parts of the country the summers are temperate and pleasant and the winters fairly long and severe.

Physiographic and geological conditions vary greatly and divide the country into five main natural regions which have a great bearing on the possibilities and conditions of prospecting. The largest of these main regions is the Canadian Precambrian Shield which includes about half of the country; here the rocks and the terrain are considerably like those of Scandinavia. The Shield is flanked by lowlands, the largest of which form the great Interior Plains. To the west a wide belt of high mountain ranges forms the Canadian Cordillera, and at the opposite extremity of the country are the more ancient and more subdued mountains of the Appalachian region in southeastern Quebec and the Maritime Provinces. A large mountainous belt composed of folded rocks comprises the Innuitian region in the Arctic Islands.

Prospecting in and near settled areas can be done fairly conveniently, but in more remote regions prospectors must be able to live and work under rugged conditions, usually requiring a good deal of organization and expenditure as well as experience. Ordinary prospecting and geological studies are done only when snow is absent, this period varying from about seven months in southern Canada to about four months in the far northern mainland. Diamond drilling, underground work, and many kinds of geophysical prospecting are, however, carried on in winter as well as in summer. Ordinary prospecting is almost always done on foot. To reach the scene of the day's work a wide variety of transport is used, depending on local conditions. Automobiles, including trucks, and jeeps are used where roads are available. In most parts of the country local travel is by canoe or small boat, commonly powered by an outboard motor. Several years ago it was customary to make trips of several months' duration entirely by canoe, but the present custom is to use seaplanes to transport men and equipment to and from the desired locality. A canoe for local use is commonly carried by lashing it to the struts supporting the floats of a seaplane. A few prospectors who fly their own aircraft dispense with a canoe. In regions where canoes and seaplanes cannot be used, travel of more than a day's duration often requires back-packing, or, in the Cordilleran region, use of pack-horses. Limited use is now being made of helicopters, and of "para-dropping" supplies from aircraft, in connection with general prospecting, and these methods will probably be used in connection with uranium as occasion demands.

2. HISTORICAL SUMMARY

Since the discovery of important gold placers in the Cordilleran region in 1858, when what is now Canada was largely fur-trading territory, prospecting and mining have played an increasingly important part in the economy and the development of the country. After the first waves of placer activity, prospectors turned their attention to searching for lodes

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† Acting Chief, Mineral Deposits Division, Geological Survey of Canada, Ottawa.

and soon found deposits that, for many years, made British Columbia the leading mining province. Other mines were brought to production in the Appalachian region. Early in the present century the Canadian Shield began to unfold as the country's most important metal-bearing region. Thus has developed an admirable group of prospectors to whom Canada owes much. The qualifications of the earlier ones were mainly their resourcefulness and their ability to travel and live in remote places; they did not require much technical knowledge because they searched in virgin territory and found fairly obvious mineral showings. Today the leading Canadian prospectors are not only good woodsmen, but are well qualified technically, generally as a combined result of having worked under experienced men, of having attended short courses sponsored by mining organizations or government departments, and of having devoted considerable time to independent study. Most of these men make prospecting their full or main occupation, and are at least as well qualified as first-class tradesmen are in their respective callings. Along with the development of prospectors and mining there has been a growth of exploration departments in the larger mining companies, and of other companies devoted entirely to prospecting and the developing of prospects. Also, from very small beginnings, Federal and Provincial mining departments have played an important part by making geological investigations and providing other services. Thus, when uranium became important, Canada was not only fortunate in having regions suitable for its discovery, but also in having good prospectors who quickly adapted themselves.

Occurrences of uranium-bearing minerals were reported from time to time after 1847, from different parts of what is now Canada, but the early discoveries were small and only of academic interest. By 1914 the importance of radium was recognized to such an extent that in that year the Geological Survey of Canada published a booklet on prospecting for radium and assigned two field parties to investigate known occurrences of radioactive minerals and to search for additional ones. Bonuses were offered by the governments of British Columbia and Ontario for commercial discoveries of radium, but these were unpaid and were eventually withdrawn. Field and laboratory research on radioactive minerals was resumed by the Geological Survey in 1921 and has continued without interruption; the early work did not lead to commercial discoveries, but it laid the foundation for later work. Electroscopes, scintilloscopes, and photographic plates were used in connection with these early investigations. A portable Geiger counter was made and used in Canada in 1932 and improved models were built from time to time thereafter.

A most important event took place in 1930, when LaBine discovered pitchblende at Great Bear Lake. This deposit was brought to production as the Eldorado radium-silver-copper-cobalt mine in 1933. The manner of discovery is mentioned in a later section of this paper. From 1931 to 1934 interest in the Eldorado discovery caused the finding of several additional occurrences of pitchblende in the Northwest Territories and one in Saskatchewan. One of these was productive on a small scale from 1936 to 1939.

In 1942 demand for uranium caused the Federal Government to ask the Eldorado company, which had temporarily closed its mine, to reopen it, and soon afterwards the Government bought the company and has operated it ever since as a "Crown company". As a security measure, staking and mining for radioactive minerals by private interests were banned in 1943. In 1944 the private Eldorado company and later the Crown-company with the aid of the Geological Survey, began an intensive campaign of searching for additional ore at the Eldorado mine and investigating other known radioactive occurrences and prospecting for additional ones. In about four years this resulted in the discovery of more than 1000 occurrences, mainly of pitchblende, and exploration of the better ones was begun.

Late in 1947, as the need for greatest secrecy had passed, the bans on private staking and mining were removed and the Federal Government encouraged private prospecting and mining for uranium by guaranteeing a market for acceptable ores and concentrates; the guarantee has been extended to 1962. This opened the way for uranium to take its place in the broader field of prospecting and mining. Information on the occurrence of uranium and on techniques for prospecting and testing discoveries, gained during the period of strict secrecy, was made available by publications and services of government organizations. A minimum of control is exercised by the Atomic Energy Control Board, which was established in 1946. Regulations require only that discoveries be reported to the Geological Survey of Canada which acts as agent for the Board; that an Exploration Permit be obtained from the Board before advanced exploration such as diamond drilling, underground work, or removal of bulk samples is done; that the holder of a permit furnish the Geological Survey with full details of the work done every three months; that a mining permit be obtained before production is commenced, whereupon monthly reporting is required; that figures for ore reserves and production, other than dollar value, may not be published once production is assured; and that radioactive substances may be disposed of only to Eldorado Mining and Refining Limited. Private prospectors and companies began to search for uranium in 1948. Their numbers have increased yearly, as have the number of known occurrences, and the smaller number of promising prospects. At first the large established mining companies were slow to take an active interest in uranium, but the results obtained at the Gunnar discovery in Saskatchewan in 1952–53 and at the Pronto and Algom properties in Ontario in 1953–54 have caused many of them to participate in prospecting ventures and in the optioning and exploring of discoveries by others.

One of the main features in the development of uranium mining in Canada has been the increasing attention paid to lower-grade deposits. The Eldorado mine at Great Bear Lake is a relatively small, high-grade mine, and it was natural to suppose that others of this kind might be found and developed by intensive effort. However, although many small high-grade occurrences of pitchblende were found, none has yet become a major producer; the Ace and Gunnar deposits in Saskatchewan are of moderate grade. As early as 1948 authorities pointed out the likelihood that lower-grade deposits would become important. More and more attention has been paid to large deposits of medium and low grades, and to the development of processes for treating such ores. As a result, large deposits of material averaging about 0.1 per cent U_3O_8, if favourably situated, are now considered minable. Because of these changes in emphasis, the development of some deposits and districts has been slower than would otherwise have been the case.

The history of airborne methods of prospecting for uranium is outlined in the section 6 of this paper.

3. TYPES AND DISTRIBUTION OF KNOWN DEPOSITS

The types and modes of occurrence of known deposits both in our own and in other countries have an important bearing on the selection of areas for prospecting and on the geological formations, structures, and mineral associations that warrant attention. It is important to bear in mind, however, that other unsuspected areas and conditions may also be fruitful. The types and distribution of known Canadian occurrences are discussed in the survey paper,† but a few of the main points are repeated here. A wide variety of uranium deposits have been found in Canada, but those that are producing or for which production is assured at the time of writing are "hydrothermal" pitchblende deposits occurring both as veins and as disseminations, and uranium-bearing conglomerate whose origin is still open to more than one interpretation. The origin of the latter may have an important bearing on prospecting for other deposits of this kind. Pegmatites and related types of deposits containing uranium minerals, generally in minor amounts, are very common. Most appear to be unfavourable, but it has always been pointed out that there might be exceptions, and we now have a few that are showing promise. Special studies are being made to try to learn why these are exceptional and how the information can be applied to prospecting and to the judging of pegmatitic discoveries.

By far the majority of known occurrences, and all the present producers and assured future producers at the time of writing, are in the Canadian Shield. About 50 occurrences are known in the Cordilleran region, and some are promising. A few occurrences have been found in the Appalachian region, but so far they have warranted only limited exploration. Discoveries have not yet been made in the Plains or Innuitian regions; the possibilities that occurrences may be found in these regions are receiving limited attention, which cannot be increased at present by government agencies because of staff shortages. Most of the discoveries in the Shield are in a wide marginal belt, and the "hydrothermal" and "conglomerate" deposits show a tendency to occur in rocks at Late Precambrian age and in older rocks that have been subjected to folding and faulting in Late Precambrian time. I believe that there are some geological foundations for these generalizations, but also that the distribution of known occurrences is partly related to the accessibility of the marginal belt. Therefore, I believe that other parts of the Shield and regions outside the Shield have possibilities.

† Paper P/1114, Session 6B, Vol. VI, these Proceedings.

4. KINDS OF PROSPECTORS

Canadian prospectors are of many types but are divisible into three more or less distinct classes: (1) qualified prospectors who work with little or no supervision; (2) members of large organized prospecting teams; and (3) amateurs.

The qualified prospectors are persons who make prospecting their main or part-time calling. They usually work with one partner, or alone. Some finance themselves from having previously sold a mining property or by working during part of the year at some other occupation, but most are financed by small syndicates of business men or are employed by mining companies. In the latter case, the custom is to pay the prospector a salary, plus a bonus or share in the event of an important discovery. The only direct government financial assistance for prospecting consists of limited schemes provided by the governments of British Columbia and Saskatchewan for prospectors who can qualify. Independent prospectors and syndicates usually dispose of attractive discoveries to companies that undertake exploration; there has been no small-scale mining for uranium in Canada by prospectors or small syndicates.

Some companies conduct organized prospecting campaigns, either in remote unstaked areas or to investigate a mining property. The program is usually supervised by a geologist or mining engineer experienced in this kind of work, and in a large program he may have professional assistants. Qualified prospectors may be engaged to work under general supervision, and if so they are likely to be assigned to a small favourable area and permitted to work as they see fit. However, because it is difficult to obtain a number of well qualified prospectors, the more common practice is to employ local woodsmen, intelligent natives, and university students to work under close supervision. In general, it has been found that good woodsmen and natives are better for actual prospecting whereas students are better for assisting with the instrumental work of surveying and with geological mapping.

Many amateurs are attracted to the search for uranium, largely because of over-simplified and over-

glamorous publicity. It is true that the use of a counter affords an amateur more chance of finding an important deposit than he would have in prospecting for non-radioactive minerals, and perhaps even of finding an important discovery in an environment being ignored by more experienced workers. There are, however, so many occurrences of weakly radioactive rocks and of accessory radioactive minerals as to cause great confusion. Beginners lack the knowledge and experience to choose favourable areas for prospecting, to work to good advantage, and to judge what they find, and they usually become unduly excited about the first occurrence found. We do not discourage beginners, but try to point out that unless they are satisfied with the merest outside chance they must learn at least the fundamentals of prospecting. Too many fail to do so, and so far have demanded attention out of all proportion to the meagre occurrences usually found. They flood government agencies with worthless samples and elementary inquiries, instead of mastering a few fundamental principles that are explained in readily available literature. We have borne this as patiently as possible, to allow for the chance of an occasional important discovery.

5. GROUND METHODS OF PROSPECTING

The principles of choosing areas for prospecting, and the basic techniques of prospecting, are applicable to uranium and to other metals. They include paying attention to favourable rocks and geological structures, wall-rock alteration, mineral associations, and brightly coloured secondary minerals. They also include the tracing of mineralized fragments to their source, and the use of the prospector's pan. A highly specialized phase consists of diamond drilling along particularly favourable geological contacts or structures even when no indication of the mineral sought has been found at the surface.

Basically, there are two methods of covering terrain. The "roving" method consists of a day's travel more or less at random, usually on foot. The "systematic" method consists of fairly or completely systematic traverses, usually guided by plotting points on air photographs or by pace and compass traverses or picket lines, in much the same fashion as in the making of a geological map. The lines may be from ½ mile to 100 feet apart, depending on the size of the area to be covered and the detail required. Both methods are useful and depend much on conditions. The "roving" method is more usual for reconnaissance and the "systematic" for detailed work in smaller areas, but the "systematic" method is also used for preliminary work in large areas, particularly when a number of relatively unskilled men are employed under supervision.

Authorities are agreed that Geiger or scintillation counters are virtually indispensable for prospecting for uranium—although they should not be regarded as rendering ordinary techniques unnecessary—and that few of the occurrences found since about 1946 would have been discovered without use of counters. This is mainly because the uranium minerals in these deposits are usually dispersed rather than massive, and are therefore difficult to see, and because the secondary minerals, which aid in visual detection when exposed, are commonly washed or dissolved from the actual exposed rock surface, and are more likely to be found after breaking into the rock where a counter has registered a reaction.

For ordinary work it is generally considered that the smaller Geiger counters that are equipped only with earphones are satisfactory. They have the advantages of being smaller, lighter, and cheaper than the more elaborate models. In general, the cheapest ones seem to get out of order too frequently, but those costing from about $100 to $150 are fairly satisfactory, although it is advisable to have a spare in reserve. Misleading results are commonly obtained as a result of the "mass effect" of a body of slightly radioactive rock. Prospectors are advised to consider counts obtained from outcrops, drill core, and other fairly large amounts of rock only as an indication that it is worth while to take a few hand specimens or chip samples. These are then carried to a place where the background is normal, and held individually against the counter. If each fails to cause a count of two or three times background, the samples may be discarded and the occurrence ignored; but if the count is raised to this amount or more, the sample concerned, and perhaps additional ones found by further search, should be sent for assaying.

Geiger or scintillation counters equipped with meters are desirable for prospecting or studies in connection with low-grade deposits and rocks, for examinations of prospects by engineers or geologists, and for making special radioactivity surveys. The latter, which are usually plotted as contoured radioactivity plans, have proved very useful for detailed prospecting after a small favourable area has been outlined. Readings are taken along lines, to form a grid with intervals of 100 to 10 feet depending on the circumstances, and the counter is moved slowly from station to station in case a marked rise in count is obtained between the regular stations. For work of this kind scintillation counters seem preferable in most respects except price, but satisfactory results are obtained under most conditions by using good meter-equipped Geiger counters, which cost about half as much as scintillation counters.

Another method, that may be called the "routine method", is simply to test with a counter all outcrops, pits, dumps, etc. in an area, or specimens in a collection. Important discoveries have resulted from the detection of radioactivity in a specimen that did not appear to contain uranium and that had been in a collection for years. Minor discoveries have been made by testing old prospects opened up for gold or other metals. Several years ago the Geological Survey invited all mines producing other metals in Canada to send representative samples of their ores, in the hope that uranium might be found at some mines, at least in by-product quantities. Hundreds of such samples were tested by the Mines

Branch and the Geological Survey without significant results, but a little uranium has recently been found at a producing copper mine after the staff detected radioactivity there. The Geological Survey has also tested large numbers of bit cuttings from wells drilled for oil or gas, without significant results, and has asked its petroleum geologists to investigate strongly radioactive horizons found by the radioactive logging that is now commonly done in connection with drilling for oil or gas.

Geophysical methods other than those based on radioactivity have not yet been used appreciably for prospecting for uranium, but more use will probably be made of them in future, particularly for testing favourable zones at depth. Geochemical methods of prospecting for uranium have not been used extensively. Some preliminary studies of the possibilities of using analyses of water and vegetation as an aid in locating uranium deposits have been performed by government scientists, but these have indicated only that the methods held possibilities for further investigation. These and other methods would probably have received much more attention in Canada but for the success of radioactivity detectors, the abundance of untested outcrops in many areas, and the number of other problems requiring attention. We believe, however, that geochemical methods of prospecting for uranium hold possibilities and that further use of them should and will be made in future. Some mining and exploration companies have recently begun to investigate and use these techniques for uranium but they have not yet reported results.

6. AERIAL RADIOACTIVITY SURVEYS

Experiments in prospecting for uranium by means of airborne detectors have been conducted in Canada by organizations of the Federal Government since 1947 and are still being continued. More recently, since the advent of scintillation counters, private organizations have made many airborne surveys, including some for Provincial Government departments. Instruments and techniques that are useful under certain conditions have been developed and a few uranium deposits that have not yet been explored extensively have been found by these methods. Although it is true that by far the majority of known Canadian occurrences were found by ground methods, it must be borne in mind that these methods have been in use for a much longer time and that what are now considered to be favourable airborne methods have been in use only for about two years, therefore adequate comparisons with ground methods cannot yet be made. Airborne prospecting for uranium is believed to hold promise for certain kinds of deposits and under certain conditions, but it does not appear to be as simple or as universally applicable as is sometimes supposed. Much information has been published,[1-19] therefore the following notes merely summarize the results of Canadian experience.

In 1946 Eldorado Mining and Refining Limited obtained the assistance of the National Research Council in beginning a joint airborne research project. A few test flights were made by Eldorado personnel in 1947 and 1948, which indicated that Geiger counters were preferable to ionization chambers. In 1948 the development of an airborne scintillation counter was begun. In 1949 the two organizations mentioned above were joined by the Geological Survey of Canada and the Royal Canadian Air Force in an expanded project to try to develop airborne methods for both preliminary reconnaissance of large areas and detailed prospecting of small areas. Further tests of ionization chambers and multiple-tube Geiger assemblies were performed. These were unsatisfactory, so work was concentrated on the design of a more sensitive scintillation counter. In 1950 three shielded scintillation probes were mounted in the aircraft in an attempt to provide better discrimination between small and large sources of radioactivity, and extensive tests were made at a height of 500 feet above terrain, but all anomalies investigated proved to be large areas of weakly radioactive rock. The larger joint project was abandoned but the Eldorado company and the Geological Survey continued to experiment. Scintillation counters were built for use in a "bird" towed beneath a conventional aircraft, and in a helicopter, and were tested in 1953. It was hoped that discrimination between small and large sources might be obtained by comparing readings from a counter in a "bird" and one in the aircraft, but this gave no improvement over the former method. Experiments by Eldorado with a low-flying helicopter for prospecting a large group of claims were fairly successful, and this work was continued in 1954. The Geological Survey is continuing to use airborne scintillation counters in conventional aircraft in connection with its aeromagnetic surveys, and in helicopters in northern Canada.

Scintillation counters have been used by private Canadian organizations in conventional aircraft since 1949 and in helicopters since 1953. A few discoveries were reported to have been found in the earlier years by means of conventional aircraft flying virtually at tree-top level, but the extensive surveys made at a height of 500 feet at this time did not have the benefit of the more advanced scintillation counters now available commercially in Canada. Surveys made in 1953 with conventional aircraft at heights of 300 to 500 feet are reported to have been successful in locating fairly extensive deposits such as those of the Blind River region. Low-flying helicopters using commercially available scintillation counters have been used fairly extensively in Saskatchewan during the past two seasons for prospecting blocks of claims, and a few pegmatitic occurrences are reported to have been found in this way. In both the work done by private organizations and by Eldorado with helicopters it has been concluded that best results are obtained by flying irregularly from outcrop to outcrop, and keeping at a constant height above the ground, rather than by flying on straight lines and at a constant altitude above sea-level; it has also been found that an aural signal is desirable to notify the ob-

server of an anomaly, and that it is desirable for the observer to be an experienced geologist who can make geological observations, attempt to discriminate from the air the source of the anomaly, and land nearby for an inspection if that seems warranted.

In summary, it appears that the Canadian Shield presents unusual difficulties for airborne prospecting for radioactive deposits because it contains many exposures of weakly radioactive rocks and many insignificant pegmatitic occurrences. These cause a background such that anomalies from significant deposits are overwhelmed and difficult to detect except at low altitudes. These problems may not be so serious for some other regions, but to date little airborne work has been done in Canada for uranium except over the Shield. For work in the Shield, either conventional aircraft or helicopters show promise for detecting fairly extensive deposits, but only helicopters, very low-flying conventional aircraft, or "birds" towed at a very low height seem suitable for the detection of small exposures such as those of veins, and then only if the aircraft passes less than 150 feet horizontally from the exposures. Helicopters appear to have the advantages of greater safety at low altitudes, of being able to fly very slowly to permit visual observation, and of being able to land on or close to many, but by no means all, outcrops whose examination is desirable.

7. JUDGING AND EXPLORING DISCOVERIES

The main principles of judging and exploring are the same as for mineral deposits in general. In brief, they comprise a system of elimination by which many discoveries are classed as not appearing to warrant any attention, and others as meriting preliminary exploration; increasingly large expenditures are risked on diminishing numbers of prospects, following successive re-appraisals. It is far from being a perfect system, because of the number of unknown or uncertain factors. Delays and mistakes are inevitable, and there is an element of luck as well as scope for the highest engineering and scientific skill and experience. It seems, however, to be the only system on which the mining industry can be based. The subject is well known to mining engineers and economic geologists, therefore, it is only necessary to point out here what appear to be the main special features of the judging and exploration of uranium deposits in Canada. The experience of the Eldorado company in this regard was summarized a few years ago in the paper by Buffam and Gillanders.[5]

First is the question of the ratio of discoveries to producing mines. For any kind of mineral deposits, it is well known to persons experienced in prospecting and mining that most mineral occurrences cannot be classed even as prospects, and that only a few prospects eventually become producers. The ratio is probably even more unfavourable in the case of radioactive minerals, because many of them occur as accessory minerals in intrusive rocks and in other sparsely distributed ways, and because the use of counters permits the detection of small or low-grade mineral occurrences that might otherwise be unnoticed.

In the examination of discoveries, counters are very useful in several ways, but they do not eliminate the need for sampling. They help in deciding whether it is necessary to take many samples. Furthermore, testing samples with the counter may indicate that they are so low grade that they can be discarded; and, for some fairly regular deposits, fewer samples need be taken than for, say, a gold deposit, if counter readings are substituted for a proportion of the samples that would normally be taken. It seems that, at best, counter readings can be considered only semi-quantitative, because the distribution of minerals in a deposit is not regular. Detailed grid surveys with a counter are often useful in judging discoveries and in planning their exploration, but such surveys must be made before any blasting is done, otherwise the area is likely to be contaminated by radioactive debris.

The method of exploration is determined by the characteristics of each deposit. In general, the tendency in Canada is now to do a minimum of surface stripping and trenching and to rely largely on diamond drilling, which is usually followed by underground exploration from an adit or shaft if drilling gives favourable results. Some deposits, however, are sufficiently regular in shape and mineral content to permit estimation of tonnage and tenor from drill-core alone. It is customary to test core with a hand counter, then to split the sections that show appreciable radioactivity, and to send one half for assay. It seems that only experience with a particular counter and type of deposit will indicate the reading at which core should be considered worth assaying; until this is learned, it is best to err on the side of obtaining too many rather than too few assays.

The custom is to have most assaying done radiometrically, because this can be done relatively cheaply, and to have a certain proportion checked chemically or fluorimetrically. The recently developed "equilibrium counter" has proved useful for making radiometric assays for uranium irrespective of disequilibrium and thorium content.

A few prospectors, engineers, and geologists working in remote places make approximate radiometric assays with a field counter, after the method described by Senftle, and make fluorescent bead tests to distinguish between uranium and thorium.

If an unusually large amount of core is to be tested for radioactivity, an apparatus may be arranged whereby a box of core is pushed along a bench, under a Geiger tube set transversely to the rows of core and slightly above it. The tube is shielded at the sides and top with lead blocks, and is wired to a counter having both a meter and an earphone that is amplified by a loud speaker. Trial and error will permit adjustment to what is considered a significant reaction. When this is obtained, the individual rows of core in the box are tested, and the meter readings are logged.

Testing drill holes with a waterproofed Geiger

probe has proved useful in deposits in which the uranium mineral or minerals are very erratically distributed, and where poor core recovery is obtained. The readings are considered only semi-quantitative, but serve to augment the results obtained from core assays. Probing was considered useful in the exploration of pitchblende deposits along the St. Louis fault in northern Saskatchewan, but was not considered necessary in the exploration of the more regular Gunnar, Pronto, and Algom deposits. Special jointed rods have been devised for pushing the probe in flat and upward drill holes.

The question of the amount of reliance that should be placed on samples from altered surface showings is a difficult one for which there is not yet a definite answer. The history of the Pronto property, reviewed in section 10 of this paper, suggests that it may be a serious problem in connection with some kinds of deposits. In general, the practice is to risk preliminary drilling if the structural conditions, width, length, and other factors are favourable, even if assays from altered surface showings are low.

Portable counters are useful for examining underground workings, in the same way as in examining surface showings, and they are also useful in a semi-quantitative way for deciding whether mined rock should be classed as ore or waste. When using a counter underground the operator usually has to accustom himself to a higher background than that prevailing at the surface. If much use is to be made of a counter underground, it is preferable to have a separate one for that purpose, because dust and mine-water are likely to contaminate it, thus causing a higher background than is desirable for surface use. Special counters equipped with end window tubes have been built for underground use, but they are not widely used.

8. GOVERNMENT SERVICES

Federal and Provincial mining departments assist prospecting and mining for uranium in the same ways as for other metals, and the Federal Department of Mines and Technical Surveys has also undertaken certain special services as official agent for the Atomic Energy Control Board. The normal Federal services are geological research and mapping, research in ore dressing and metallurgy, and the compilation and publishing of information on prospecting, mineral resources, demands, and markets. The Provincial authorities administer mineral resources in their respective provinces, control such matters as staking and mine safety, and several Provincial departments also undertake geological mapping and special studies. The large size of the country offers great scope for geological work, and mapping and research projects are undertaken by mutual arrangements. The National Advisory Committee on Research in the Geological Sciences fosters and coordinates geological research; this committee comprises representatives of the Geological Survey, the Provincial organizations, the universities, and the mining industry, and on its recommendations Federal funds are granted for geological research in universities. As a general service to prospectors the Geological Survey undertakes to identify, free of charge, specimens of minerals and rocks not requiring elaborate laboratory work, and most Provincial departments make a limited number of free assays for holders of staking licences.

Branches of the Department of Mines and Technical Surveys established various special services as agents for the Atomic Energy Control Board. The Mines Branch formed a special Radioactivity Division to study problems in the treatment of uranium ores and to make treatment tests on bulk samples from worthy prospects, and to perform research in methods of radiometric and chemical analyses and to advise and train staffs of mining companies therein. After a prospect has been shown to have encouraging dimensions and average uranium content, test work on a large representative bulk sample of unweathered material is important for confirming the average content and for suggesting the best method of treatment and its cost and percentage of recovery. The Geological Survey established a Radioactive Resources Division¶ to study the mode of occurrence of uranium deposits, to receive and compile data supplied by discoverers and holders of exploration permits as required by the regulations in order to provide an inventory for present and future needs and to permit generalizations useful in prospecting, to issue publications containing information on prospecting and the exploration of prospects, to try to give individual advice to prospectors and property owners having advanced problems, and to make radiometric tests and mineral identifications on prospectors' samples. After commercial firms became proficient in making radiometric and chemical assays for uranium, the number of tests made by the Geological Survey was limited to six from any one unstaked occurrence, or group of claims. Our present practice is to make a preliminary measurement of the total radioactivity, and if this is significant to follow it with an assay made by the equilibrium counter, which gives an adequate estimate of the uranium content. Many prospectors seem to place undue emphasis on precise mineral identifications for new discoveries; in general we believe that assays are much more important until it is shown that a deposit is of reasonable size and content and therefore worth extensive exploration, but early mineral identifications are sometimes desirable for confirming whether a discovery is hydrothermal or pegmatitic, or primary or secondary. Both the Geological Survey and Provincial departments examine as many discoveries and properties as their staffs will permit, but do so primarily in connection with their own studies rather than on behalf of the discoverers or claim owners, who are expected to engage a consulting engineer or geologist if they wish a special examination. Naturally, however, government geol-

¶ The work of this division has recently been incorporated in a broader Mineral Deposits Division.

ogists do their best to advise the discoverer or owners if and when they visit them.

9. CONTROLS AND MARKETING

The Regulations of the Atomic Energy Control Board are designed to give all possible encouragement to prospecting and mining by the public. The reporting of information is required, but restrictions apply only to the removal of bulk samples, the disposal of ores and concentrates, and figures on production and ore reserves of producing mines. The reporting of information is essential for the compilation of an inventory of uranium resources and for the organization of geological information beneficial in prospecting and in the exploration of deposits. To these ends, anyone who has reason to believe that he has discovered uranium or thorium in amounts of 0.05 per cent or more is required to report the particulars to the Geological Survey, and anyone wishing to undertake advanced exploration such as diamond drilling, underground work, removal of bulk samples, or detailed radioactivity or other geophysical surveys, is required to obtain an exploration permit from the Board. Such a permit stipulates that full reports, drill logs, and plans be supplied to the Geological Survey every three months. The holder of an exploration permit is then free to publish his results as he wishes. If and when the property nears production, the exploration permit is exchanged for a mining permit, which stipulates the manner of disposal of ores or concentrates and the limits on publication of information on ore reserves and production; it also requires that monthly reports of development work and production be supplied to the Geological Survey. Reports of discoveries and of work done are treated confidentially unless released by the discoverer or owner.

Neither Federal nor Provincial Governments pay a bonus for a uranium discovery, nor do they buy mining claims. Prospecting and mining for uranium are encouraged by the Federal guarantee of a base price for acceptable ores and concentrates, which expires in 1962. The base price is $2.75 per pound of contained U_3O_8, f.o.b. rail. With milling and development allowances that are also available under certain conditions, the guaranteed price reaches a maximum of $7.25 per pound. These prices were designed for ores shipped in the crude state or concentrated by gravity methods. With the advent of leaching plants, provision has been made for the negotiation of special contracts, but the published schedule of guaranteed prices is sufficiently close for appraising prospects approximately and deciding whether further exploration is warranted. Ores and concentrates may be disposed of only to Eldorado Mining and Refining Limited.

10. EXAMPLES OF SUCCESSFUL DISCOVERIES

The circumstances and methods of prospecting can be illustrated by brief "case histories" of some important discoveries. Because of the limitations of a short paper, mention is made only of the properties that are now operating under Mining Permits or those for which definite plans to erect treatment plants have been announced.

Eldorado Mine

In 1929, at about the time when travel with float-equipped aircraft began to revolutionize prospecting and the opening up of prospects in the Shield, G. A. LaBine, an experienced prospector, began prospecting at Great Bear Lake. He learned that, in 1900, an officer of the Geological Survey had made a reconnaissance of the lake shore and in his published report had mentioned seeing cobalt and copper "blooms" at a certain place which was not easy to re-locate because of the lack of detailed maps. In 1930 LaBine deduced the locality as well as he could, hoping that the "blooms" might indicate useful deposits of silver, copper, or some other metal. He searched the vicinity and found a vein carrying native silver, cobalt minerals, and pitchblende, the latter being recognized by LaBine as a result of his training. Parallel veins were soon found nearby, and the mine was brought into production in 1933.

Nicholson

Veins on the Nicholson claims in northern Saskatchewan were explored first for their copper content in 1930. The owners found pitchblende and showed specimens to G. A. LaBine, who thereupon visited the property a few years later, but the property was not developed at that time. In 1935 an officer of the Geological Survey studied and mapped the region mainly because of interest in gold discoveries. He collected specimens of the pitchblende at the Nicholson, had them confirmed by laboratory work, and in his report published the first authenticated description of a pitchblende occurrence in any part of Canada outside the Great Bear Lake region and the adjoining Hottah Lake region. The Nicholson claims were kept in good standing although no significant developments occurred on them for several years. Extensive work was resumed by a reorganized company in 1948. High-grade pitchblende-bearing bodies were revealed by diamond drilling and underground workings, but the amount was considered insufficient to support an individual treatment plant. Shipment of ore to the Beaverlodge plant of Eldorado Mining and Refining Limited was begun early in 1955.

Ace

When increased uranium production became desirable, geologists of the Eldorado company and the Geological Survey examined known uranium occurrences, particularly those containing pitchblende. They inspected the Nicholson property and advised concentrating on the region nearby because it seemed possible that other deposits might be found, and because this region is more accessible than the Northwest Territories. Prospecting and more detailed geological mapping were begun in 1945. Teams, each composed of two experienced prospectors, without previous experience in work for uranium, were equipped with Geiger counters and also used pan-

ning techniques. They were supervised in a general way by geologists and engineers. About 1000 pitchblende occurrences were found in this way from 1945 to 1948. In 1946 one team found radioactivity at the shore of Ace Lake and recognized the presence of a strong fault nearby. They began detailed systematic testing of the vicinity, with their counters, and found an extremely radioactive locality. After removing moss and picking into the rock they found small veinlets of pitchblende. Trenching was done in the following year, and although the actual showings were not as impressive as some others found in the district, the importance of the structural environment afforded by the fault, named the St. Louis Fault after the discoverer of the Ace showing, led to a decision to explore the vicinity by diamond drilling in 1948. This and subsequent exploration resulted in the outlining of the Ace orebodies.

Rix

The Rix-Athabasca mine, now shipping substantially to the Eldorado plant at Beaverlodge, was discovered by systematic prospecting of a concession. Under the direction of Technical Mine Consultants, Limited, combined radioactivity and geological surveys were conducted along fairly closely-spaced lines. This resulted in the discovery of many occurrences. Five zones were selected for detailed diamond drilling, which showed promising results for three zones. Underground exploration of two of these, the Smitty and Leonard, was undertaken. A moderate tonnage of ore of medium grade was revealed in the Smitty, and shipments were begun in May 1954. Further exploration of other zones is planned.

Gunnar

In 1949 the Government of Saskatchewan withdrew the unstaked parts of the Beaverlodge region from staking and issued concessions, most of which comprised 25 square miles. All concessions expired in 1952, after which those holders who had completed the requirements were permitted to hold a proportion of the ground as claims and the remainder came open for general staking in August, 1952. A concession covering part of Crackingstone Peninsula, 20 miles southwest of the Ace deposit, had been abandoned earlier—after inadequate prospecting, as was later apparent—and this ground was open for general staking in the Spring of 1952. At that time, two experienced prospectors, Zeemel and Blair, in the employ of Gunnar Gold Mines Limited, of which LaBine was president, began careful prospecting in this area, which was one of the few places in the region that were open for staking at the time. It was fairly close to the continuation of a prominent fault whose margins had been recommended as favourable in a general way for prospecting, but the area was underlain largely by gneisses which were not then regarded as being among the more favourable rocks of the district. These prospectors found a strongly radioactive outcrop, a few small pieces of radioactive rock that had been pushed to the surface by frost action, and discovered that a large area covered by overburden was markedly radioactive. A grid survey was made by taking readings with a scintillation counter at 50-foot intervals. A plan showing radioactivity "contours", and samples from the outcrop, were considered sufficiently favourable to warrant diamond drilling. Vertical holes were drilled at 75-foot intervals, the radioactivity plan being used as a guide in outlining roughly the area to be drilled. As a result, a very large orebody of substantial tenor was outlined. The information obtained by drilling, and that from a large bulk sample taken from the outcrop, were considered sufficiently consistent to warrant a decision to prepare for production, without further underground exploration.

Pronto

The events that led to the Pronto and other developments in the Blind River region of Ontario date from a discovery of pitchblende farther west, at the northeast shore of Lake Superior, more than a century ago. The first published account of this appeared in 1847, and several unsuccessful attempts to re-locate the occurrence were made. Another search, with the aid of a counter, was successful in finding at least the general area in 1948. Much staking and prospecting followed and several pitchblende occurrences were found, although none has yet been considered large enough for production. A prospector named Karl Gunterman, backed by Aime Breton, tested with a counter some old specimens in the local Mining Recording Office and found that one labelled "Long Township" was radioactive. This township is about 100 miles southeast of the Lake Superior occurrence. Gunterman searched here and found that conglomerate at old trenches excavated in search for gold or copper was radioactive, and he staked claims. The property, which is about 10 miles east of Blind River, became known as the Breton. Several geologists and engineers examined it, but their samples yielded low assays. Better assays, however, were obtained from a small discovery a few miles away, and when these results were published in 1951, Franc Joubin took a renewed interest in the Breton occurrence, which had been allowed to lapse and was acquired by Joubin's associates in 1952. Joubin suspected that the low assays despite fairly strong radioactivity might indicate that uranium had been leached from the surface exposures. Preliminary diamond drilling was undertaken, and the fourth hole yielded a favourable intersection. Subsequently, an extensive program of drilling outlined a large, low-grade orebody. A small adit was driven to obtain a bulk sample, a shaft was sunk later.

Before releasing news of the first significant drill intersection, Joubin and his associates, realizing that the conglomerate lay along a contact shown on a published geological map to extend for many miles, organized teams of prospectors equipped with counters, and flew them to lakes along this contact. As a result, several additional discoveries were found and large blocks of claims were staked. Drilling at one of these, at the Quirke Lake property of Algom Ura-

nium Mines Limited, has revealed a very large deposit, and drilling near the same contact on another group of claims held by the same company, without surface exposures, has revealed still another.

CONCLUSIONS

This short summary of Canadian experience in prospecting for uranium has shown that important deposits have been found by a fairly wide variety of prospectors and under a fairly wide variety of circumstances and geological conditions. The subject is therefore a complex one that does not permit simple generalizations. One of the most significant features is that most of the important discoveries have resulted from a series of events and from the work of several persons, often over periods of several or many years. Most of these discoveries are in areas for which geological maps and reports were already available, and which either pointed to discoveries or were useful as general aids in prospecting, often after many years had elapsed. We believe, therefore, that private prospectors and companies, on the one hand, and government services on the other, have cooperated usefully both in discoveries and in bringing the better ones to production. Competent prospectors working more or less independently, and organized prospecting schemes, have been successful, but few significant occurrences have been found by unskilled prospectors working independently. Airborne prospecting has not yet proved as fruitful as ground methods, but it shows promise for certain kinds of work and within certain limitations.

The improving of guides and methods for prospecting and for exploring prospects offers a challenge. Attempts to meet it are being made geologically by collating data on known occurrences and trying to establish their patterns of distribution and their common factors, and in other ways, by trying to adapt and improve geophysical and geochemical aids to prospecting. Also, recognizing the likelihood that important deposits may be found under geological conditions not now known to be favourable, and by techniques not yet conceived, we try to envision what these conditions and techniques may be.

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REFERENCES

1. Agocs, W. B., *Airborne Scintillation Counter Surveys,* Bulletin, Can. Inst. Min. and Met., 109–111 (March 1955).
2. Bateman, J. O., *Prospecting with the Geiger Counter,* Trans. Can. Inst. Min. and Met., *52,* 111–116 (1949).
3. Brownell, G. M., *Radiation Surveys with a Scintillation Counter,* Economic Geology, *45,* No. 2, 167–74 (1950).
4. Brownell, G. M. and Schaller, R. J. R., *Prospecting Local Areas with the Airborne Scintillometer,* Precambrian, *27,* No. 3, 6–11 (1954).
5. Buffam, B. S. W. and Gillanders, E. B., *The Exploration and Development of Canadian Uranium Deposits,* Trans. Can. Inst. Min. Met., *54,* 434–437 (1951).
6. Eichholz, G. G., *Routine Radiometric Analysis for Uranium in Ores,* Topical Report TR 120/54, Mines Branch, Dept. of Mines and Technical Surveys, Ottawa (1954).
7. Eichholz, G. G., Hilborn, J. W. and McMahon, C., *The Determination of Uranium and Thorium in Ores,* Journal of Physics, *31,* 613–628, (May 1953); also in Topical Report TR 99/52, Mines Branch, Dept. of Mines and Technical Surveys, Ottawa (1952).
8. Godby, E. A. et al., *Aerial Prospecting for Radioactive Minerals;* Rept. No. CRR–495, National Research Council of Canada, Chalk River, Ontario (1952).
9. Gregory, A., *Aerial Detection of Radioactive Mineral Deposits,* (a paper presented at the Annual Meeting, Canadian Institute of Mining and Metallurgy, (April 1955) to be published in the Bulletin and Transactions of the Institute).
10. Joubin, Franc R., *Some Economical Uranium Deposits of Canada,* Precambrian, *28,* No. 1, 6–8 (1955).
11. Lang A. H., *Uranium Orebodies—How Can More be Found in Canada?,* Canadian Mining Journal, 57–65 (June 1952).
12. Lang, A. H., *History of Uranium Discoveries, Lake Athabasca,* Canadian Mining Journal, 69–76 (June 1953).
13. Lang, A. H., *The Development of Portable Geiger Counters,* Canadian Mining Journal, 65–67 (April 1953).
14. Lang, A. H., *Prospecting in Canada,* Geol. Surv. Canada, Ec. Geol. Ser. No. 7, 3rd Ed. (in press).
15. Roberts, Leslie, *The Algoma Story,* Technical Mine Consultants, Special Publication.
16. Savage, W. S., *The Search for Uranium,* Bulletin 148, Ontario Dept. of Mines (1954).
17. Senftle, F. E., *Determination of Uranium in Ores by Field Analysis,* Memorandum Series No. 96, Mines Branch, Dept. of Mines and Tech. Surv., Ottawa (1949).
18. *Prospecting for Uranium in Canada,* Prospectors' Booklet, Geol. Surv. Canada, Ottawa (1954).
19. *A List of Publications on Prospecting in Canada, and Related Subjects, with Explanatory Notes,* Paper 54–1, Geol. Surv. Canada, Ottawa (1954).

Method of Prospecting and Surveying Uranium Deposits

By André Lenoble, France

A method can be considered valid only when it has given proofs of its efficiency, as sanctioned by success: therefore, even before going into the features of this method, we should clarify, by a rapid review, the results which it brought forth in the French Union.

PRESENT CONDITION OF THE FRENCH URANIUM RESOURCES

We shall not attempt here to make a quantitative estimate of the uranium reserves of France, nor will we present a detailed geological and mining survey of the various deposits—this will be covered in another report—but rather we shall give a general view of the size of the discoveries, which were made thanks to the methods which we developed and applied for several years, and yet often modified while field experience was broadening. Barely nine years have elapsed since the beginning of the prospecting work by the Bureau of Research and Mining; and the Commissariat de l'Énergie Atomique now is the owner, particularly in the Metropolis, where the major effort was made, of such a large number of deposits that France is without a doubt the most important uranium producer in western Europe: this in fact, is the opinion of the foreign specialists who looked over some of our deposits, which they consider as equivalent to the richest ones known in the world.

Our mining domain is represented by permits to mine and concessions distributed in four mining districts which are undergoing rapid development; in each one mines will be found which are actually being worked or explored: i.e. Bourbonnais, Forez, Limousin and Vendée; in addition, in those mining perimeters or elsewhere, there is a whole series of newly discovered deposits, partly explored, which will progressively be equipped and worked during the next years (Vosges, Allier, Creuse, etc.).

Aside from these deposits, the existence of which is well known, other indications are to be found which will make research work necessary for many years to come throughout the French Union. Some overseas territories are beginning to show, quite aside from the immense reserves made up by the uranium-bearing phosphates, some attractive, not to say very substantial, mineralizations, such for instance as the thorianite of Southern Madagascar while our first explorations in the Hoggar and Tibesti warrant strong hopes.

Until now, however, the activity of the Research Departments has been limited to the regions called "favorable", namely to the granite masses, and yet, these regions are far from having been entirely explored; indeed we must allow, at the present rate, approximately ten years before we finish with those of the metropolitan territory. No attempt was made to estimate how many years it would be necessary to continue with prospecting in order to cover the whole of the territory of the French Union, in connection with which a great effort is under way in North Africa, in French West Africa, in French Equatorial Africa, and in Madagascar. On schedule for the next few years, is an extension of prospecting to favorable regions of the overseas territories, as well as to the sedimentary formation, the study of which has barely been started.

This would hardly be natural if accurate data had been available from the start, namely in 1947. Actually it was necessary to start from indications which were not only slight, but very poorly understood, and which often pointed the prospectors in the wrong direction, for with the exception of a rather poorly defined occurrence of pitchblende at St. Remy-sur-Durolle (Puy de Dôme), most were made up of secondary mineralizations, often without any primary roots: this was the case of the first known deposits of St. Symphorien de Lachaux, of Grury, etc. where chalcolite and autunite constituted the only uranium-bearing mineralization.

The conditions under which uranium deposits were found in the French territory were very poorly known, and all the documentation available was not only scanty, but often inaccurate. The best studied deposits were represented by the pegmatite niobo-tantalates and titanates of Madagascar, deposits which very soon had to be given up, after a very complete inventory, in view of the unevenness of mineralization, since they yielded only minerals having mean contents too low to be worked.

Indeed, from the beginning of 1948, it appeared very clear that the data in our possession had no geological and metallogenic significance, and that we had to start all over again from scratch, while using the little we knew, and to draw up a method of prospecting and study which could be modified at any moment to accord with experience and results, and which would enable us to make a general inventory

Original language: French.

of the uranium resources of the territory as quickly as possible. For rapid success we simultaneously had to do the following:

1. Determine the geological guides which in any case can vary according to the region, together with the various lithological types, structures, etc.
2. Define the tactics adapted to each stage of research—organization and distribution of the teams, role of the various categories of personnel, etc.
3. Establish the characteristics of the equipment to be adopted for each stage, and have the practical work carried out on the types adopted.

In essence, everything remained to be done, since scientific contacts with foreign countries which had preceded us in this research were so loose that it was hardly possible to think of using even partially the results of their experience.

This may have been all to the good since by establishing a method which was well adapted to our special projects and terrain, the results obtained were an almost unexpected success.

METHODS OF PROSPECTING AND RESEARCH

Main Principles

From the outset this method was designed for the prospecting of crystalline masses, though it subsequently proved adaptable to the prospecting of sedimentary formations whose outcrop geometry makes them less difficult to study than the granites in which irregularity and a complex structure require much more methodical, detailed, and let us say, more disagreeable, work.

Principles Applicable to the Mineralizations of Crystalline Masses

The dispersion of the indices which were known, as of 1947, only for the perimeter of the Massif Central, indicated indeed that the favorable formations were made up of granite or granulitic granite (in the French sense of the term, namely acid granite, with the muscovite alone or dominant, generally with automorphous quartz) considered as hercynian, but no one had an accurate idea of the part played by the structure in the localization and concentration of the primary uranium ores.

Very rapidly, even before pitchblende analyses had given the additional data sought, it was found that the role of the post-granitic tectonics was essential, and most particularly that of the structures which had come into play again well after the settling down of the granite. The first discoveries of pitchblende in place (La Crouzille) demonstrated the value of this guiding principle to the prospector.

Unfortunately, the geological maps do not give many accurate data regarding granite tectonics, so that it became necessary again to take up, in detail, the geology of the regions of the major fractures and more especially of the edges of the mass, first centering the studies in the zones where the indices of secondary minerals were well known, and thereafter extending the prospecting along these fracture fields. It is indeed very unusual to find uranium deposits in veins, or in lodes localized in large fractures; much more frequently they are found in their vicinity, in the system of secondary faults which may or may not be accompanied by breccias and mylonites, generally oblique with respect to the major faults.

In fact, all the veins, and all the uranium lodes are found near the major tectonic faults which affected granite masses, either in the masses themselves, or in the metamorphic rocks which are on their edges.

This main principle is much more important than the mineralogical guides which had first been used, such as smoked quartz or even secondary uranium minerals, the irregular distribution of which has been ever more apparent, being found at times very far from the primary deposits and even without any connection with them.

The fact stands, none the less, that the presence of secondary minerals in place in tectonic zones, particularly if these minerals are not made up exclusively of uranium phosphates, is a very valuable guide.

There is a second principle which is important, and drawn up on the basis of a number of findings: the large uranium deposits are associated with a chalcedonic gangue, not made up of quartz, and very often with fluorized mineralization, more particularly black fluorite. The chalcedony containing gangue is a particularly important guide for prospecting in view of its resistance to alteration and destruction.

The rubefaction of the rocks which very frequently appears in the vicinity of the veins or lodes of uranium makes it possible, when alteration is not too deep, to localize the vicinity of these deposits, but it is not symptomatic of the uranium-bearing deposits alone, since it is due in great part to the pyrite which is to be found in the mineral associations of the French uranium deposits, and is the only consistently present mineral; the reddish zones due to easy circulation of the water often show abnormally high radioactivity, at times related with uranium-bearing formations, but also often without any connection with a deposit already in place; accordingly the presence of these reddish zones is not a specific guide to be used when seeking uranium-bearing deposits.

The same applies to vein rocks of the lamprophyric or other types, which are more alkaline than granite, and which were considered, originally as a nearly unequivocal guide; however they may have played a part which is not too clear as yet. It could be physico chemical, or purely mechanical, affecting the mineralizing occurrences with which they met. Nevertheless, they are of interest, because of the concentrations of secondary minerals which may be workable incidentally, and which they bring about. At any rate, there is no direct genetic connection between the localization of the mineralization and that of the rocks.

Very often, to this set of principles which are of a very general character, we may add a series of regional guides which, for the prospector, are of major importance: such, for instance, as localization of the mineralization in the zones where there are varia-

tions in the facies. The guides of this type are many and varied; it is only after long studies in a given region that it is possible to form an idea of their importance.

Special geochemical and geophysical techniques show the existence of certain principles which, unfortunately, cannot be used by all prospectors, since they require special knowledge and equipment. It would seem, in particular, that the concentration of mineralizations takes place at the contact of zones of different resistivities; however, the principle may conceivably not be specially applicable to uranium deposits. By way of conclusion, the main principles of uranium prospecting in granite masses can be summed up as follows:

1. The tectonic features are of essential interest, the most favorable being those which came into play again and again, at times long after the settling down of the granite masses; but among those, the hercynian masses always remained the only privileged ones, more particularly in the tectonic zones on their edges.

2. The veins or lodes localized not in the major faults, but in the breccias or mylonites which accompany the secondary fractures.

3. The gangue of the lode deposits is essentially made up of chalcedony and fluorinated.

4. The associated metallic ores are not very varied; among them, the most characteristic is pyrite; accessorily some other sulfides would accompany the uranium-bearing ores: galena, blende, chalcopyrite, bismuthinite.

Principles Applicable to Sedimentary Formations

Experience in this category of deposits is rather limited, even though the prospecting surveys bore on deposits of a wide variety of types—sedimentary deposits with syngenetic mineralization, such as deposits of uranium-bearing phosphates; deposits in sedimentary rocks with mineralization of hydrothermal origin containing pitchblende, or an unexpressed mineralogic species such as uranium-bearing stephanian schists and the copper-bearing carbonaceous sandstones of the Triassic.

As regards the first, there are no well established guides; only radioactivity measurements on the outcrops make it possible to define the existence or extent of the exploitable zones. For the schists or sandstones with a mineralization of hydrothermal origin, the stratigraphic, lithological and tectonic study is of first importance, since these mineralizations are localized in continental series which are indubitably connected with the presence of tectonic feed faults; in every case the uranium is intimately associated with the presence of organic material which fixed it, as a matter of fact, at the same time, as other metals, such as lead or copper; but it must be assumed that one of the important conditions of concentration of uranium mineralization is not known since this mineralization took place preferentially in the schists, which were not so rich in organic materials as the coal strata.

These deposits in schist or sandstones are, at any rate, very plainly distinct from those we know at Madagascar and in France, in old or recent peats, in which uranium mineralization made up exclusively of secondary minerals (autunite or uranocircite) surrounds or impregnates vegetal debris.

Methods Followed in the Research

Organization of the Research Division

The Service des Recherches, which is attached to the Direction des Recherches et Exploitations Minières, directs, controls and coordinates all the activities of the personnel assigned to prospect and to study uranium deposits. Its very varied functions include, besides prospecting as such, the carrying out of mining research, guidance of operations, the control of test drillings, the determination of assays and tonnages, the development of tests and maintenance of various types of equipment used for research, such as counters, radio core drilling and transported prospecting equipment, etc.

In order to meet this multiplicity of obligations, three large groups share the various activities, both in the field and in the research laboratory:

1. The preliminary missions, which are essentially mobile, the purpose of which is to seek, over any territory, new indications of uranium mineralization. When a discovery is made this organization should make it possible to determine whether it is advisable to set up larger and more permanent teams, research centers, or even mining divisions, if the number and size of the deposits warrant such a move.

2. The research centers, which belong integrally in the preliminary missions, some of which have the task of making a study by digging, test drilling and mining work, starting from the indications they themselves have found; these research centers are made up of stabilized teams set up for a variable period of time, according to the volume of the work to be carried out, i.e. according to the interest and size of the deposits they have to study.

3. The divisional research departments: These departments make a detailed study of some well-defined regions, which have been found to be rich in uranium deposits, and are administratively attached to a mining division in which several deposits are grouped, some of which have already been worked, while others are being explored, and yet others are being prospected.

The overseas missions are considered, either as divisions or else as preliminary missions, according to their importance.

It will be seen elsewhere that, in practice, the distribution of the work among those groups is not so clearly limited as has just been defined, just as the personnel is not immutably and finally distributed among these groups. Instead, allowance is made in the appropriations, and as imperatively as possible, for the scientific, technical and physical aptitudes of all concerned, as well as for their personal preferences. It is essential indeed, if one is to obtain maximum output, that the personnel, whether geol-

ogists or prospectors, should work in the specialty chosen by its members, and in their most favored climate.

The distribution of the research personnel among the various groups, the role and attributions of which were defined above, currently are as follows: preliminary missions; 18 geological engineers and 44 prospectors; research centers; 2 geological engineers and 8 prospectors; divisional research departments; 14 geological engineers and 46 prospectors; and special sections (geochemistry geophysics); 2 geological engineers and 4 prospectors.

To these, we should add a certain number of engineers, of technicians and of non-specialized prospecting technicians, who belong to various sections, particularly to the radio section in charge of equipment and distribution of electronic equipment for prospecting and test drilling.

The Technique of Prospecting

Prospecting is carried out in various stages, defined as follows:

Preliminary Survey

Carried out with light equipment by small teams—one geologist and two or three prospectors—the purpose is to note the indices of abnormal radioactivity which will determine the zones to be prospected in detail.

Preliminary prospecting is carried out by profiles, the network of which is all the tighter as the region is found more favorable (meshes of grid 200, 100 and 50 m); the profiles are drawn as close as possible in a direction normal to the structure, but the prospector must make the best possible use of the terrain, and omit neither the outcrops nor the topographic features, situated outside the profiles defined, which might strike him as interesting.

The only absolute rule in this work, if success is not to be jeopardized, is that of *continuous measurement* of radioactivity; to this end, use is made of a light headset counter which allows all possible freedom of movement, even on a very uneven terrain—something which cannot be done without difficulty of great fatigue with ordinary visual reading equipment; the measurements in preliminary prospecting need not be accurate; they amount to a qualitative determination of abnormal activity which draws attention to the possibility of the existence of a deposit or only of an index. A prospector, in one day, will cover one to two square kilometers, according to the size of the gridwork.

Aerial prospecting follows the same technique. It is now in common use and we resort to it in regions the geographical characteristics of which are such that the utilization of the common methods is entirely impossible.

Each time, however, when the country lends itself to it (accessibility, livability, habitability, etc.) we prefer the traditional prospecting, namely, with a ground team. The cost is higher than it is by airplane; the work takes longer. However the observations are much sharper, since the prospector can observe all the geological details, take samples, etc. Airborne prospecting, despite its unquestionable advantages, is more mechanical.

In order to get a general idea of the terrain we first use recording counting devices mounted on vehicles which can travel anywhere, but this only in countries such as France, in which the road network is dense enough to make this method worthwhile.

Semi-Systematic Prospecting

It is intermediate between preliminary prospecting and the systematic prospecting which will be described below. It is used only where preliminary prospection does not succeed in defining the zone to be investigated by systematic prospection with sufficient accuracy. Use is then made of more sensitive counting devices of the visual reading and headphone type, and the profiles are taken closer to one another. Some minor scraping of the soil is also resorted to in order to define more accurately the limits of the area of abnormal radioactivity.

Systematic Prospecting

Once the preliminary or semi-systematic prospecting has shown the existence of a line along which the activity is abnormally high, suggesting the possible presence of a deposit—confirmed, if need be, by some minor excavation at the most active points making it possible to recover some mineralization—systematic prospection then is carried out.

This obviously is not done if the rocks are bare, and if preliminary prospecting has shown the existence of a deposit which can be followed and studied on an outcrop; on the other hand, it is indispensable in those areas where the outcrops often are masked by an overburden of sterile soil: let it be remembered that most worthwhile deposits are in highly tectonized zones, and therefore always deeply altered.

The purpose of systematic prospection is to define, by radioactivity measurements, the general appearance of the deposit, or to define the size of it once a portion of it is known. The most important work here is the plotting from a counter survey.

First Stage—The "Counter Map"

The "counter map" on which the activity is represented by isoactivity curves is drawn by plotting on a large scale the measurements carried out according to a grid which will be all the tighter as the linear arrangement or extent of activity seems more uneven; the map scale is to be determined as a function of the precision sought; one thus works with scales ranging from $\frac{1}{200}$ to $\frac{1}{1000}$, but $\frac{1}{500}$ is more commonly used. The activity measurements are carried out according to a grid of 5 m, 2 m or even 1 m according as the incidences and the points plotted are connected by continuous curves. These radioactivity figures give an idea of the general orientation of the deposit, which generally corresponds to the greater activity; however, it is necessary to interpret these counter maps, allowing for the sterile overburden,

the topography (creep) etc. In a country of sharp relief, made up of deeply altered rocks, it will be noted that the maxima of activity of the superficial formations do not follow the alignment of the deposit: the readily soluble uranium minerals concentrate downriver in secondary products, at times quite a distance from the original deposit.

Furthermore, in a granitic tectonic background the structure is always very complex, making up a network of faults which cut up the deposit, whether they be contemporaneous or of later date than the deposit. These faults make up as many channels through which the secondary mineralization is dispersed, which destroys the simplicity of the counting map, and makes it at times very difficult to interpret.

The radioactivity measurements are carried out with specially designed counters which can give an approximate idea of the uranium content of the superficial zone, and thus a first approximation of the possible richness of the deposit.

Second Stage—Minor Surface Work

Once the counting plane has given all the information required on the general appearance of the mineralized line, trenches are dug in order: (1) to confirm the existence of the deposit at the points of highest activities; (2) to define its geometry—dip and trend—which will be necessary in order to start future work, particularly drilling; (3) to allow the taking of samples in the formations already emplaced, in order to carry out a study of the mineralization and make an evaluation of the assays of the superficial zone; and (4) to get greater accuracy on the appearance of the tectonic features which determine the deposits.

These trenches must give all the geological and mineralogical details which will make it possible to form an idea of the value of the deposit, and thus to justify the work.

We need not insist on the importance of the selection of the position of the trenches, their depth etc., but must indeed insist on the advisability of a very detailed geological survey, (generally at a scale of $\frac{1}{50}$) of the edges of each trench; showing the mineral courses with the utmost care, the occurrences no matter how small, and just exactly where the samples were gathered.

Systematic prospecting completes the surface work. On the basis of the data so established the work in depth is begun, namely test drilling and exploratory mining. This puts an end, at least in principle, to the role of the preliminary missions, as well as to the research centers, though research continues at the division level.

Test Drilling

As the prospecting work is concluded (an outline of which has just been given) and assuming that it yields favorable results, both geologically and metallogenetically, it is then decided whether to complete the superficial data by accumulating further details on the extension of the deposit in depth, at various levels, first by test drillings, then by exploratory mining if the results of the drilling confirm the first data. This is the normal procedure for any exploratory work; for uranium, it offers but one point of originality, the use of special drills with which the radioactivity can be recorded, giving some rough idea of the richness of the deposit.

In the study of uranium deposits, radioactive core drilling is the essential operation, for despite all the care and the technical precautions, mechanical drilling nearly always is unsatisfactory due to the nature of the rocks in which the deposits generally are found.

Other data supplied by the drillings on the petrography, tectonics, mineralogy and radioactivity, as well as certain technical details (casing, percentage of core drillings) are drawn on graphs which show, by direct reading, the exact position of the points of maximal radioactivity, as well as the value, in cps, which, by past experience, makes it possible to get some idea of the assay.

A study of the shape of the radioactivity curve is of major importance: it gives an idea of the distribution of the mineralization: for instance, a succession of peaks, even very high ones, indicates dispersed mineralization which must finally give a lower average content than that shown by a somewhat less intense activity curve which increases more regularly as the formation is being crossed.

In cases where mechanical drilling is perfectly feasible, which happens only in sedimentary formations of a homogeneous type, the cores are used for the determination of the content and are sawed lengthwise; the veins or other deposits are too heterogeneous (breccia, silica passes, clay on the sides, fragile mineralization) to make such an operation possible, so that one has to rely only on activity readings on these cores.

The research department is not concerned with the technical details of core drilling, which is left to the Operations Department working as a mining enterprise would; but the geologists do have the responsibility of choosing the positions, the technical specifications as regards coring, depth, radioactive coring etc. and the interpretation of the results.

Mining Research

Once the above operations have shown the existence of a deposit, the geometry of which is defined by the test drills and the average assay of which is given by radioactivity readings on the cores, what then remains to be done is an accurate determination of the contents, characteristics and distribution of the mineralization, the paragenesis, and evaluation of the minimum tonnage.

It is necessary, in order to obtain accurate values on all these points, to carry on mining work at different levels, which become deeper as the alteration increases; on this point, the drillings should give the indications sought.

It is not advantageous, under any circumstances, to organize work at a depth of less than thirty meters. Indeed the galleries must be well below the

oxidation zone in order to give accurate data on the mineralization type; data which will be necessary, not only in order to define the value of the deposit from the mineralogical standpoint, paragenesis etc. but also to provide for all the studies required in connection with the mechanical and chemical treatments of the ore. In addition, this work must provide all possible data which might be necessary for the miner (consistency of the soil, etc.).

In general, mining research is carried out in wells 40 to 50 m deep, or across a bench when the nature of the relief allows it, following which galleries are driven along the extent of the mineralized formation. If the latter is very promising the work is completed by crosscuts going to the limits and by horizontal soundings, after which radioactivity readings are taken on the cores. In order to reach the closest possible estimate of the minimum tonnage on sight, cross passages are used to connect the galleries. As the work goes along, samples are taken by the application of somewhat different methods, according to cases; but in vein-type uranium deposits, in which mineralization is irregularly distributed, it is better to resort to fairly voluminous notching of continuous, crown type, and at times extending to the sides of the galleries.

Activity measurements are generally carried out at the same time at the center of the gallery in order to get the average radioactivity.

Each time, the geological and mineralogical data pertaining to the mine face are drawn with great accuracy; on the same tracings, the activities measured at every point on the progressing front are written down. As soon as the mining and research work have given all the positive data sought about the mineralization content and size of the deposit, and after a minimum tonnage has been determined, making it possible to determine whether the deposit might be exploited, the work of the Research Department is over as regards prospecting. Nevertheless, at a later time, namely during exploration of the deposit as it is being prepared for mining, its work is still not finished; it must continue to direct the mining work by a geological study of the deposit, and evaluation of the reserves. Thus detailed surveys and samples are carried out in the same manner as in the exploratory phase of the mining work.

This study and research method for uranium deposits may seem awkward and cumbersome. However, experience has shown that there are very few cases in which it is possible to dispense with any of the operations; as a matter of fact the results show that this method affords the only reasonable certainty of understanding the problems of the whole enterprise as the various stages are reached. Nothing is quite so costly as an incomplete or poorly carried out job of prospecting.

Rock Alteration Criteria in the Search for Uranium

By Paul F. Kerr,* USA

Alteration criteria associated with uranium mineralization have received less attention than the phenomena merit because: (1) radioactivity counters and scintillation devices often furnish a direct indication of ore bodies, (2) thick sedimentary sections occur in which alteration criteria often are not recognized, (3) very localized effects such as the red stain which accompanies some pitchblende veins are also found to be significant.

Alteration effects associated with uranium mineralization in igneous or metamorphic rocks appear to be more readily detected than those in sediments. The argillic halos which accompany the veins at Marysvale, Utah, in quartz monzonite, are easily recognized features. However, alteration effects in Colorado Plateau sediments are more subtle.

This paper outlines the types of alteration found with uranium mineralization excepting those in pegmatite occurrences, since they have not proved to be of economic significance. This investigation is based on data from the literature as well as recent detailed studies of uranium deposition at Marysvale, Utah; a current investigation of Temple Mountain on the San Rafael Swell, Utah; reconnaissance in the western United States and Canada; and previous studies of hydrothermal alteration associated with copper mineralization at Santa Rita, New Mexico and Silver Bell, Arizona.

Few, if any, of the alteration criteria associated with uranium deposits differ appreciably from those of copper, zinc, tungsten, and other metals. However, their applicability to uranium is selective. The term alteration is applied here to the development of clay mineral halos, chloritization, alunitization, fluoritization, carbonatization, silicification and ferrugination. It is perhaps noteworthy that the criteria of contact metamorphism in general have not been applicable to the United States uranium deposits.

ALTERATION TYPES

The significant alteration effects in certain uranium and metal deposits are believed to be indicative of hydrothermal activity. Much applicable information is found in the studies of Lovering;[1] Sales and Meyer;[2] Stringham;[3] and Leroy.[4]

Hydrothermal solutions traversing faults, fractures, or shear zones generally react with the wall rock so that a sequence of alteration develops. Although the sequence may vary with the character of the rock, chlorite and montmorillonite are two of the earliest minerals to form at the expense of the wall rock; they tend to be prevalent around the margins of altered areas. Somewhat later, and in a more centralized position, kaolinite, some montmorillonite and often illite (hydrous mica) occur. At the core of the altered area dickite may be associated with kaolinite, or kaolinite with illite. Often sericite and silicification are found at the center. Although no two districts in which alteration of this type has been described are identical, most exhibit a progressive sequence of various degrees of wall rock replacement. Maps of these altered areas frequently reveal important trends in metallic mineralization which may favor certain of the alteration stages. Such maps have been made of the copper deposits at Santa Rita, New Mexico[5] and Silver Bell, Arizona.[6] More recently a similar study (Fig. 1) has been made of the uranium-bearing area at Marysvale, Utah.[7]

The types of hydrothermal alteration, believed to be related to the general process of uranium emplacement, particularly in the western United States include: ferrugination, fluoritization, chloritization and argillization, alunitization and dolomitization.

Ferrugination

Iron is one of the most common elements associated with uranium. In fact, the identification of pitchblende may be hindered by the intimate mixture of fine grained pyrite. In the replacement of wood in logs and other plant remains of the Shinarump conglomerate at White Canyon, Utah, cells of wood may be filled either with pyrite, chalcopyrite or bornite, and cell walls may be replaced by pitchblende. H_2S derived from decayed vegetation is thought to have fixed the iron in the sulphide form.

Hematitic alteration produces various shades of red which are found with certain veins in the Canadian Shield, and in the Sunshine Mine, Idaho[8] where color intensity varies directly with the amount of pitchblende. It is thought that during hypogene vein formation, given sufficient temperature, the ferrous ion may change the uranyl ion to the uranous ion and thus cause the precipitation of pitchblende. At the same time the resultant ferric iron forms hematite which is essentially colloidal and acts as a pigment for the accompanying colloidal silica. Dawson[9] has called attention to the hematitic alteration of wall

* Columbia University.

Figure 1. A portion of an alteration map which indicates alteration channels. Size of area is 15,000 × 17,000 feet. (*1*) Unaltered rock; (2) moderate alteration; (3) advanced alteration; (*4*) destructive alteration. (*T*) bleached tuff; (*AA*) mixed argillic and alunitic; (*Al*) predominately alunite; (*Si*) silicification. In some places the N60°E channels in the lower left are producing veins

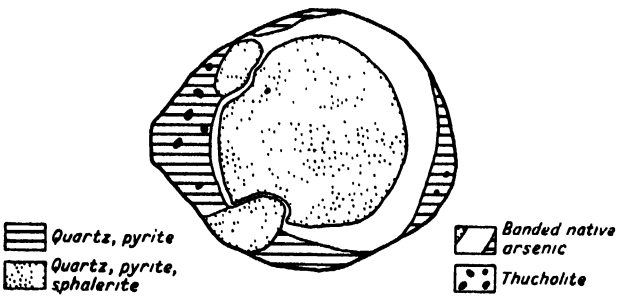


Figure 2. Cross section of pyrite-native arsenic nodule, Temple Mountain, Utah

rock with pitchblende bearing veins in the Goldfields Region, Saskatchewan, Canada. A somewhat similar coloration is found at depth in some of the Marysvale veins.

Masses of siderite are found near the uranium ores of Temple Mountain, Utah. Field and analytical data seem to indicate that the upward moving thermal solutions removed iron from the underlying ferruginous sediments, and redeposited it as siderite

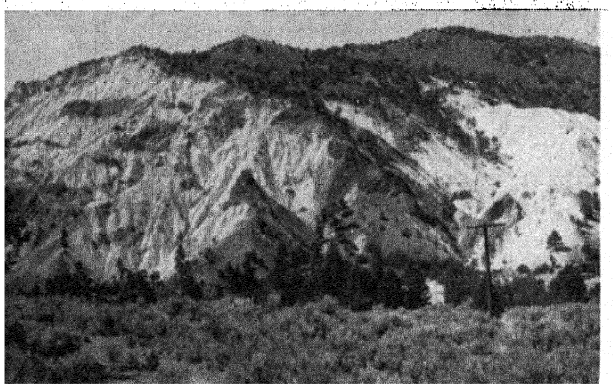


Figure 3. Big Rock Candy Mountain near Marysvale, Utah. An argillic and alunitic area formed at the expense of a volcanic agglomerate

in veins and replacement masses at a higher level. Although the uranium occurs in asphaltite, it may be closely associated with pyrite. See Fig. 2.

Fluoritization

Since the oxides UO_2, ThO_2, CeO_2, and CaF_2 all have a face-centered cubic "fluorite" lattice with a unit cell close to 5.50Å, it is not surprising that they prefer the same geochemical environment. According to Phair and Shimamoto[11] who describe euhedral uranothorite inclusions in fluorite, it seems probable that the association of uranium, thorium and rare earth minerals may prove extensive in fluorite-rich hydrothermal deposits. Kerr and Dahl[12] note microscopic particles, presumably pitchblende, in highly radioactive fluorite at Grants, New Mexico. Brown and others[13] note an interesting radioactive anomaly which is associated with fluorite at Hicks' Dome, Illinois. Bray[14] reports pitchblende in fluorite which is associated with pyrite, galena and sphalerite at Jamestown, Colorado, and Lovering[15] describes radioactive fluorite in veins and pipe-like bodies east of Beatty, Nevada. Often black or extremely dark purple fluorite is associated with radioactivity at Marysvale. In fact, the prevalence of this material in a western area, is frequently considered significant in the search for uranium.

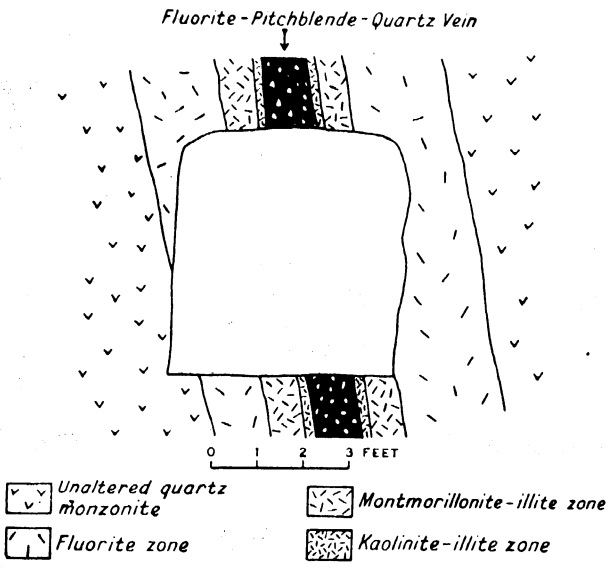


Figure 4. Pitchblende vein, Marysvale, Utah

Chloritization and Argillization

Argillic alteration associated with uranium mineralization is illustrated at Marysvale, Utah[7] where an airborne radiometric survey of the mining area shows anomalies which correspond to areas of alteration. The area in which the effects (Fig. 3) are most noticeable is about 7 miles square, and it is clearly outlined by white or iron stained clay. The clay filled channels (Fig. 1) which constitute the veins at Marysvale vary widely in their clay and uranium content. However, they provided the conduits along which uranium bearing solutions migrated upward, as shown by a radiometric comparison of the wall rock and vein. The principal uranium mineral of the veins is pitchblende (Fig. 4), although secondary uranium minerals are found near the surface, and the rare uranium molybdenum mineral, umohoite,[16] occurs in one of the mines.

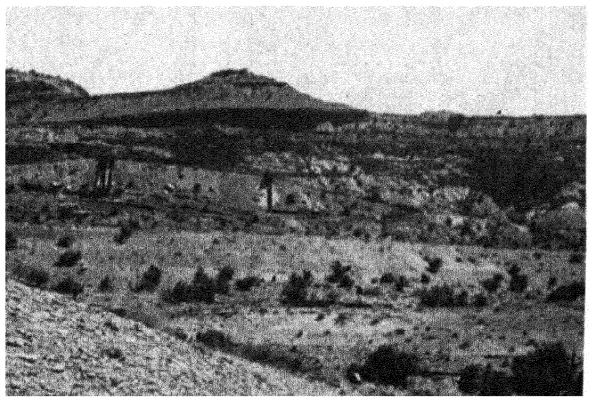


Figure 5. Vanadium King workings east of Temple Mountain, Utah. A kaolinized zone below Mossback strata (100 feet) with mine workings at the base

The association of argillic alteration and pitchblende is most frequent at Marysvale in the quartz monzonite. Preceding alteration the feldspars are lustrous and the ferro-magnesian minerals, if present, are usually unchloritized. As alteration is initiated, a chloritic zone develops in which plagioclase tends to become dull and biotite, chloritized. This occurs not only at Marysvale, but at places in the Boulder batholith in Montana,[2] in southwestern New Mexico near Silver City[5] and along the Colorado Front Range. Rocks in which ferromagnesian minerals are scarce may yield a montmorillonite rather than a chloritic zone.

The two most prominent clay minerals of the dominantly argillic stage at Marysvale are montmorillonite and kaolinite. As alteration becomes more intense, rock texture is destroyed, and illite develops. In places this stage is accompanied by the introduction of fluorite. The main precipitation of pitchblende and pyrite is believed to occur toward the close of the argillic stage, or perhaps later.

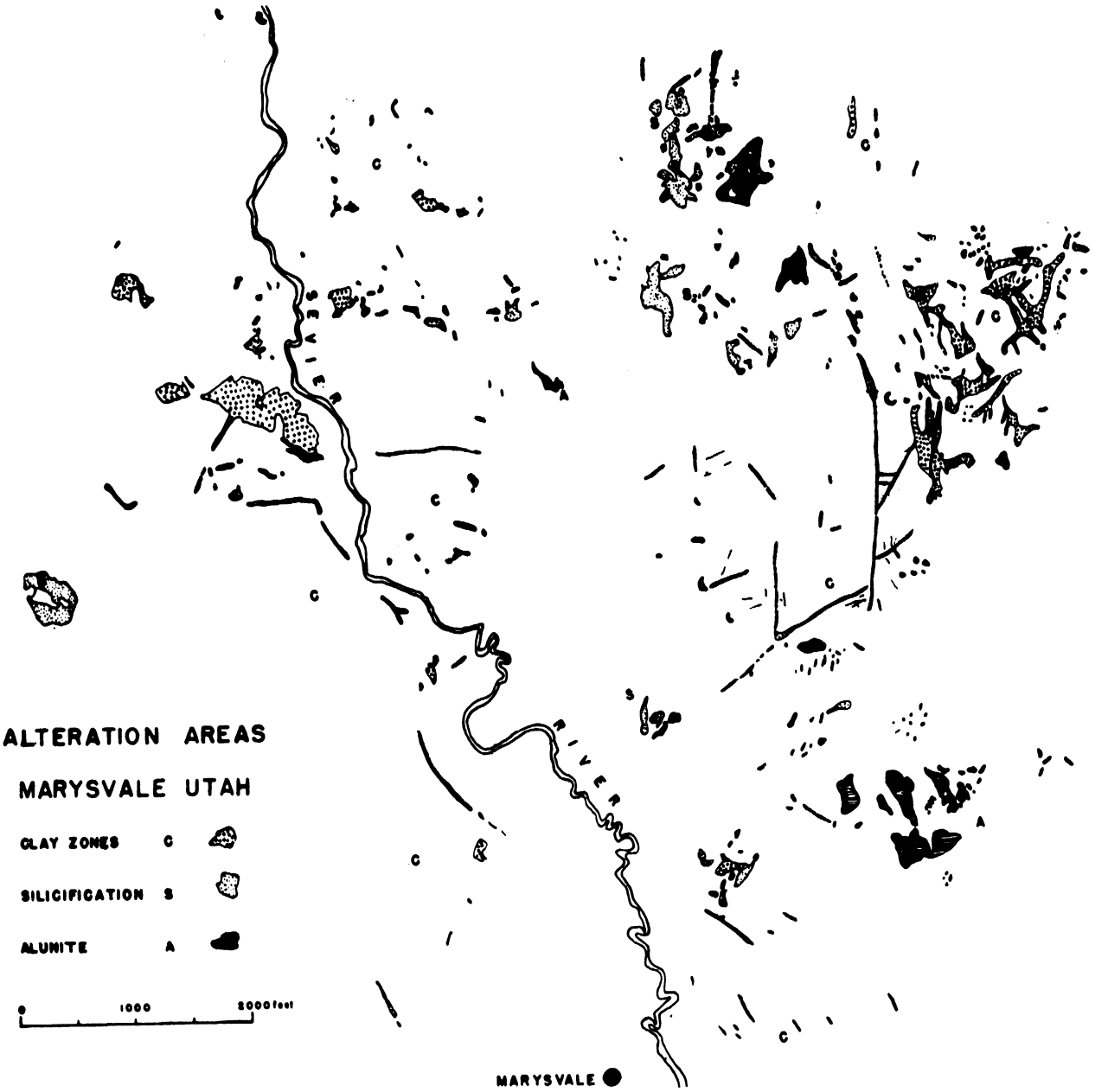


Figure 6. An early reconnaissance in the vicinity of Marysvale, Utah. The general distribution of clay zones, silicification and alunite bodies is shown. These were subsequently mapped in detail

Patches of alteration which are similar to those at Marysvale are found within a radius of 20 miles. It would appear, therefore, that the alteration is widespread, and comparatively recent as determinations of the Marysvale pitchblende by Kulp (personal communication) indicate an age of about 10 million years. It is of interest to note that patches of alteration, perhaps an extension of the Marysvale pattern have been observed in volcanic rocks near the margin of the Colorado Plateau. A center of hydrothermal activity, if concealed beneath the sediments of the Plateau, could have provided a source for the accumulation of uranium in sediments.

Recent studies along the San Rafael Swell[17] and elsewhere contribute criteria which may provide an approach to the problem of alteration and uranium in sediments. Weeks[18] reports gray shale at the Scenic No. 4 claim in the White Canyon area, Utah, which is completely kaolinized. Green clay zones, although widely distributed in the Mossback conglomerate of the San Rafael Swell, have not as yet been found to be related to ore deposition. However around the inward facing escarpment, faults accompanied by bleaching and sometimes uranium mineralization, cut the Mossback conglomerate and related members of the Chinle formation. These bleached areas (Fig. 5) are yellowish brown in contrast to the adjoining red or dark brown strata, and appear to extend up along fault lines with an appearance of enlargement in the Chinle siltstone below the Shinarump.

Laboratory study of this bleached material indicates

the presence of kaolinite and illite. Although further investigation is necessary, it would appear that the form and mineralization of the bleached zones suggests upward migrating solutions. Since significant uranium mineralization occurs in connection with one such zone at Temple Mountain, this criterion seems worthy of consideration.

Alunitization

The presence of alunite in the vicinity of uranium deposits is frequent, although the relationship and significance remains largely undetermined. At Marysvale, extensive areas of alunite (Fig. 6) have formed by hydrothermal alteration of tuffs and pyroxene andesites. The major hydrothermal alunitization seems to precede uranium mineralization, but there is some alunite which is an end stage effect.

Alunite and kaolinite have been found in veinlets in the Mossback conglomerate at Temple Mountain where they occur around the margin of the orebearing area, and seem to resemble caliche in outcrop. Alunite is reported in several of the other Plateau uranium deposits. Gruner and Gardiner[19] report it in the Moenkopi of the Capitol Reef area, Utah; at Deer Flats north of White Canyon, and southeast of Fruita, Utah. Weeks[18] finds alunite at the Skyline claim, Monument Valley, Arizona, where it fills joint cracks in altered arkosic sandstone.

Dolomitization

Dolomitization of the Wingate sandstone (Fig. 7) occurs at several places on Temple Mountain where it forms distinctive brown patches. This remarkable change from a rather pure aeolian sandstone to a massive dolomite is gradual, but it occurs in three stages.

The first stage of dolomitization is "nodular impregnation" in which nodular dolomite surrounds suspended unaltered sand. These forms have an average diameter of about one half inch, and occur in areas which vary from a few to hundreds of feet. They tend to follow the Wingate sandstone, but may extend across the beds or occur in irregular masses which penetrate the underlying Chinle sandstone. The second stage is "interstitial impregnation". Here, replacement by dolomite of the quartz grains within the nodules as well as in the areas between the nodules, occurs. In thin section a radial strain which is relict of the nodular form may be present. The third stage is "massive replacement" in which the nodular development is completely obliterated and the Wingate sand grains are completely replaced.

The relation between dolomitization and uranium deposition is indirect. The dolomite at Temple Mountain occurs near areas of solution stoping which are referred to as "collapse features"[17] These have been interpreted as breccia pipes, but it seems likely that they result rather from solution and collapse. Thermal solutions which penetrated carbonate and arenaceous sediments have produced cavities into which great blocks of overlying strata have fallen. The collapses seem to be funnel shaped in cross section and to originate along faults. Their surface exposure is circular or elliptical with a maximum diameter of 1000 feet. Although uranium is sparse in these areas, it occurs nearby in larger amounts. The uranium-bearing asphaltite is found in vein-like masses which cut the dolomite. The emplacement of uranium seems to be later than dolomitization.

It seems reasonable to postulate that the same sequence of solutions which removed calcium and magnesium from the underlying strata and deposited them in the Wingate sandstone as dolomite also could have introduced the uranium. Scattered uranium occurrences throughout a vertical length of 1500 feet of exploratory drilling seem to support this theory. It is likely, therefore, that the dolomitic areas at Temple Mountain are indicative of solution action on sediments. This, in turn, may indicate that on the San Rafael Swell at least, dolomitization may suggest nearby uranium emplacement.

Silicification

The relation of silicification to uranium mineralization is worthy of consideration. Often there is no immediate application to uranium discovery, as illustrated by the silicified logs in the uranium deposits of the San Rafael Swell. Large masses of Mossback

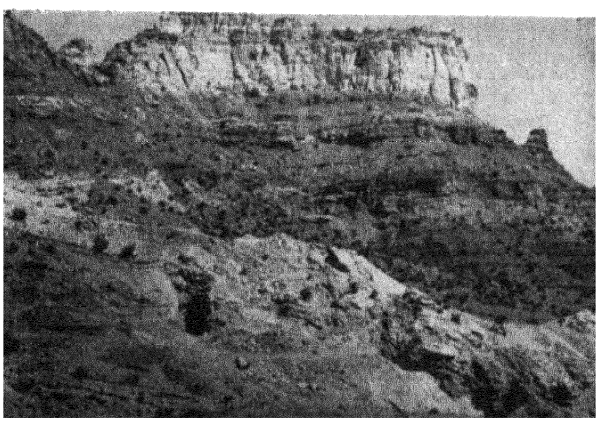


Figure 7. Alteration and collapse features at Temple Mountain, Utah. Dark dolomitic area (crest of hill left) with normal Wingate strata on right. The bleached area in the foreground is a collapse feature. The cut in foreground produced uraniferous asphaltite

conglomerate are silicified, although as yet they have failed to yield uranium. Nevertheless, areas of silicification in the vicinity of uranium deposits merit investigation. One surface mass of silicification at Marysvale overlies an extension of the Bullion Monarch vein system, a system which has been highly productive of uranium. In this area, cherty quartz stringers are associated with high grade pitchblende ore, and the fluorescense of chalcedonic nodules may be due to contamination with uranium. The role of silicification probably varies with the type of deposit, the generations of mineralization, and the associated rock types.

CONCLUSION

The criteria of rock alteration which are useful in the search for uranium bear a striking resemblance to those for other metals. However, conditions may

vary with the locality, and render recognition much more difficult. This is true of the Colorado Plateau sediments when compared with igneous or metamorphic areas. Argillic alteration and dolomitization are believed to represent earlier stages in the ore-forming process in the sediments at Temple Mountain. Significant alteration features in hydrothermal uranium deposits appear to include: ferrugination, as shown by widely distributed pyrite and hematitic coloration; fluoritization, as shown by the association of fluorite and pitchblende; chloritization and argillization as shown by wall rock alteration which follows or accompanies uranium emplacement; alunitization, depending upon depositional environment; and dolomitization, as shown by its proximity to uranium deposition.

REFERENCES

1. Lovering, T. S., *Rock alteration as a guide to ore—East Tintic District, Utah,* Econ. Geol. Monograph 1 (1954).
2. Sales, R. H., and Meyer, C., *Wall rock alteration at Butte, Montana,* Am. Inst. Min. Met. Eng. Trans. 178: 9–35 (1948).
3. Stringham, B., *Granitization and hydrothermal alteration at Bingham, Utah,* Geol. Soc. Amer. Bull. 64: 945–992 (1953).
4. Leroy, P. G., *Correlation of copper mineralization with hydrothermal alteration in the Santa Rita porphyry copper deposit, New Mexico,* Geol. Soc. Amer. Bull. 65: 739–768 (1945).
5. Kerr, P. F. et al., *Hydrothermal alteration at Santa Rita, New Mexico,* Geol. Soc. Amer. Bull. 61: 275–347 (1950).
6. Kerr, P. F., *Alteration features at Silver Bell, Arizona,* Geol. Soc. Amer. Bull. 61: 275–347 (1951).
7. Kerr, P. F., et al., *Alteration and uranium mineralization, Marysvale, Utah,* Geol. Soc. Amer. (in press).
8. Kerr, P. F. and Robinson, R. F., *Uranium mineralization in the Sunshine Mine, Idaho,* Min. Eng. 5: 495–511 (1953).
9. Dawson, K. R., *A petrographic description of the wall-rocks and alteration products associated with pitchblende-bearing veins in the Goldfields region, Saskatchewan,* Dept. of Mines and Technical Survey, Geol. Survey of Canada Paper 51–24 (1951).
10. Kerr, P. F. and Lapham, D. M., *Report on a nodule from Temple Mountain,* Annual Report, US Atomic Energy Comm., RME–8096: 7–15 (1954).
11. Phair, G. and Shimamoto, K. O., *Hydrothermal uranothorite in fluorite breccias from the Blue Jay Mine, Jamestown, Boulder County, Colorado,* Amer. Min. 37: 659–666 (1952).
12. Kerr, P. F. and Dahl, H., *Uranium-fluorite association in the Todilto limestone, Grants, New Mexico,* US Atomic Energy Comm. RME–3051 (1953).
13. Brown, J. S. *et al., Explosion pipe in test well on Hicks' Dome, Hardin County, Illinois,* Econ. Geol., 49: 891–902 (1954).
14. Bray, J. M., *Minor chemical elements in fluorites from Jamestown, Colorado,* Amer. Min. 27: 769–775 (1942).
15. Lovering, T. S., *Radioactive deposits of Nevada,* US Geol. Survey Bull. 1009–C (1954).
16. Brophy, G. P. and Kerr, P. F., *Hydrous uranium molybdate in Marysvale ore,* US Atomic Energy Comm. RME–3046 (1953).
17. Kerr, P. F. et al., *Collapse features, Temple Mountain Uranium area, Utah,* Annual Report US Atomic Energy Comm. (in press).
18. Weeks, A. D., *Summary report on mineralogic studies of the Colorado Plateau,* US Geol. Survey, TEMR 431 (1952).
19. Gruner, J. W. and Gardiner, L., *Mineral associations in the uranium deposits of the Colorado Plateau and adjacent regions with special emphasis on those in the Shinarump formation,* Atomic Energy Commission Annual Report, Part III (1952).

Drilling Techniques in Search of Uranium

By John W. Chester,* USA

Drilling patterns employed on the Colorado Plateau are generally either a grid or a "fence" (row) of holes. The grid pattern is used where little is known about the area, and it is desired to make subsurface favorability criteria studies. It is also used in testing for ore bodies not confined to a linear paleostream channel, and having random distribution as well as variable size and shape. As information is gained through drilling on a grid, definite trends of either favorable ground or ore deposits alignment are established and a fence drilling pattern oriented perpendicular to such trends is used. Hole spacing is greater when searching for favorable ground than when looking for orebodies within a favorable area. There is a great difference between the size of orebodies and the size of favorable areas, hence no definite rule can be set for spacing of holes in the search for either. The quest for purely geological information may not require definite spacing. In areas of rapidly changing structure or lithology, hole spacing must be rather close to permit subsurface correlation.

In the Shinarump formation, orebodies are found in paleostream channels. In most cases these channels show on the outcrop and the problem is to follow the concealed channel back from the outcrop by drilling. A fence pattern is usually most economical, and once the trend of the channel is determined by the first row of holes behind the outcrop or from any two adjacent rows of holes, spacing between fences can be increased. Once the channel is located, further drilling within the channel—the area of favorable ground—in search of orebodies may be on a grid pattern for uniform coverage. This may be followed by closer spaced offsetting of mineralized grid holes in order to outline any orebodies.

DRILLING

Types of Drills

Diamond Drilling

The diamond core drill, of standard mining type, is that most frequently used in search of uranium on the Colorado Plateau. Most have a hydraulic feed, are truck mounted, and are motivated either by the truck motor or a separate motor. Usually, the water and hydraulic pumps and, in some instances, a water tank to supply water to the drill, are also mounted on a truck bed. Trucks vary in type, but either the tandem or four-wheel drive truck is best suited to the rough country in which the rigs must work. The larger rigs have masts, raised or lowered by hydraulic cylinders, tall enough to allow 30-foot pulls of drill rod.

Rate of drilling for this type rig is slower than many others, but averages from 20 to 30 feet a day at depths over 800 feet, and from 60 to 100 feet a day in shallow holes. Although diamond core drilling is more expensive than other types, the capital outlay for equipment is less than that for a rotary drill.

The double-tube, swivel type core barrel is used almost universally on the Plateau, and modifications which have increased its efficiency include enlarging of the space between inner and outer barrel so that fluid may pass more readily, and extending the inner barrel near to the bit face to reduce the amount of washing of core. A few years ago, much of the drilling was done in AX size; now, almost all is BX NX. Coring in the larger diameters allows greater core recovery in friable sandstones as well as enabling the driller to complete holes to greater depths. Furthermore, the larger the drill rod, the less the vibration and consequently the greater the core recovery.

In most cases, water is used as the circulating medium to cool the bit and to lift the cuttings to the surface. Drilling muds have not been used extensively on the Plateau.

Rotary Drilling

Air, as the circulating medium, is now used more than in the past, and in dry ground, where it can be used, it results in faster drilling and lower cost. Although rotary drills are used chiefly for drilling where core is not desired, they can be adapted to take NX or larger core. Because they use lower rotational speeds, coring is slower than with the standard diamond core drill. Drilling dry, the rotary will average 300 to 600 feet a day, a rate which surpasses that of any other type drill. As high as 1300 feet have been drilled during an 8-hour shift. Drilling wet, the rate of penetration is slower.

The chief advantages of air rotary drilling are its low cost and high speed. Rotary drilling costs from one-half to one-sixth that of diamond core drilling, (Table 1) although the capital outlay for a rotary drill is greater than for a diamond drill.

Percussion Drilling

The air percussion deep hole drill, the "wagon drill", has been developed in its present form almost entirely on the Colorado Plateau. The drill, hoist and compressor customarily are mounted on a truck.

* US Atomic Energy Commission.

The rig consists of a drifter type or large sinker type air percussion drill, mounted on a slide attached to a mast. Up and down motion of the drill is controlled by either a vane or piston type air motor through an endless chain attached to the drill. A cross-type, tungsten carbide insert bit is used. With the large hammers and larger multi-stage compressors, this type drill, in dry formations, can drill readily to a depth of 250 feet; maximum depth attainable is about 350 feet. Drilling costs are low as is the capital expenditure.

The wagon drill is even more limited by wet ground than is the dry rotary drill. With the latter, when excessive moisture is encountered, it is possible to change to wet drilling. Water as a circulating medium with the wagon drill has been unsuccessful.

Underground exploratory drilling is usually accomplished with a percussion drill, and holes, usually limited to 100 feet in length, are fanned ahead of or to the sides of an underground heading.

Cable Tool Drilling

Some drilling is done with cable tool drills or spudders. This type uses a chopping bit suspended on a cable, and is given an up and down motion by an eccentric drive. Its chief use has been as an auxiliary to diamond drilling where such is hampered by unconsolidated overburden.

Calyx Drilling

A few calyx drills have been used on the Plateau, chiefly for drilling utility and air shafts to orebodies. Hole diameters range from 24 to 72 inches.

Information Obtained from Drilling

More and better geologic information is obtained through use of the diamond drill than from other types used on the Colorado Plateau. In dry drilling, where no core is obtained, much information is lost. However, it is possible, by careful study of the cuttings, to obtain some subsurface lithologic information and even if all samples are lost, information can be obtained by electric and gamma-ray logging of the hole. The gamma-ray log indicates presence of radioactive minerals, but the technique is not yet sufficiently well developed to permit calculation of grade of ore with consistent accuracy.

The greatest problem of dry hole drilling is moisture. The moist particles can be blown from the hole, but after the bit has passed the moist zone, the dry cuttings adhere to that zone, cutting off air circulation and usually sticking the tools.

Dilution of samples is another problem in dry drilling with either rotary or percussion drills. Unless there is a minimum of overburden and the underlying formations are well cemented, material falling from sides of the hole can lead to erroneous interpretation of composition of the beds drilled.

No adequate sampling method suitable for use with small rigs has been developed for wet rotary drilling. The rapid drilling rate and attendant necessity for mobility of sampling equipment make the standard methods of collection sludge samples impractical. With this type of drilling, gamma-ray logging and electric logging must be relied upon to give subsurface information.

The majority of the drilling done on the Plateau is in vertical holes and most of the drill rigs now used are not designed to do angle drilling without modifications to the mast and the rig.

If removed from the truck mount and mounted on skids, the diamond drill can be used for angle hole drilling. However, rigging up is complicated and requires time and increases costs. For this reason the angle hole is not economic for shallower holes unless the savings in total feet drilled more than offset the higher cost per foot.

Standard hole sizes most frequently drilled with diamond drills on the Plateau are 2⅜ inches to 3 inches. Most rotary-drilled holes are larger, being 3⅞ inches to 5 inches. A minimum hole size of 2⅜ inches is necessary to permit logging of the hole by radiation detection equipment since the probe of the scintillation gamma-ray logging equipment most frequently used is 2 inches in diameter.

Economics of Drilling

Of the three types of exploration drilling commonly employed on the Colorado Plateau, diamond core drilling is the most expensive in cost per foot for equivalent depths. Rotary and percussion drilling costs are about equal and range from approximately one-half to one-sixth the cost of diamond core drilling. Penetration rates for percussion and rotary

Table 1. Average Drilling Prices—Colorado Plateau Area (per foot)

	Type Drill				
Depths	*Diamond drill core*	*Diamond drill non-core*	*Rotary—wet*	*Rotary—dry*	*Non-core percussion*
0–100	$1.75–2.50	1.00–1.75	1.25–1.75	0.40–1.00	0.60–0.75
100–200	$1.85–2.75	1.50–2.25	1.25–1.75	0.60–1.25*	0.75–1.00*
200–300	$2.75–3.50	2.00–2.75	1.50–2.50	1.25–2.00*	1.25–2.00*
300–400	$3.00–4.00	2.50–3.00	1.50–2.50	1.25–2.00*	2.00–3.00*
400–500	$3.50–5.50	3.00–4.00	2.00–3.00	2.00–3.00*	
500–750	$5.50–7.00	3.50–4.50	2.50–4.00	**	
750–1000	$7.50–9.00	4.50–6.00	4.00–5.00	**	

* Denotes holes for which completion is not guaranteed if wet ground is encountered.

** Quotations below 500 ft. not reliable due to wet ground conditions.

drilling are approximately three to eight times the rate for diamond core drilling. Table I lists prevailing prices for drilling on the Colorado Plateau showing variances for type of drill and depth range.

Inherent in the direct cost per foot of drilling are related costs of operating equipment and supplies. For a diamond core drill, these are the most expensive. Water for circulation is an additional expense for core drilling, either by diamond or rotary drills, and on the Colorado Plateau most drilling areas are remote and water is scarce. Of the three major types of drilling, operating equipment and supplies for the percussion type are the most economical and easiest to obtain.

Geologic Prospecting for Uranium and Thorium

By L. R. Page,* USA

The search for uranium and thorium ores in the United States during the past ten years has emphasized the value of geologic guides in prospecting. The discovery of many new districts is in a large part the result of prospecting based on the geologic appraisal of large regions and subsequent reconnaissance examinations. The guides used at the start were of a very general nature, but they have been and are being constantly refined. Within both new and old districts, hundreds of new deposits have been found by the application of specific geologic guides to the problem of ore finding used in conjunction with detailed radiometric, panning, geochemical, botanical, and geophysical studies in advance of physical exploration.

All known characteristics of uranium and thorium deposits must be used to make geologic prospecting successful, and because our knowledge changes from day to day, good prospecting is the result of theories based on continuously changing hypotheses. Although there are only two main groups of deposits that are sought—epigenetic and syngenetic—there are many theories to explain the origin and localization of each deposit.

Many of the geologic guides, described in this paper, have been developed and tested over a period of time by a large number of individuals. It is, therefore, considered inappropriate to attempt to give specific credit for each guide, rather the reader is referred to the more general papers on the subject. Grateful acknowledgment is made of the assistance of colleagues and coworkers, who through discussion, have contributed greatly to the formulation of this summary of the writer's ideas on the application of geology to prospecting.

The search for epigenetic and syngenetic deposits can be narrowed down to specific types of terrane that have little or no relation to stratigraphic or geologic time tables, but rather are related to the depth of erosion and to major magmatic, sedimentary, or tectonic environments. In the United States epigenetic deposits of ore grade are most abundant in: (1) areas of deep-seated tectonic structures, particularly those related to small, near-surface intrusive and associated extrusive rocks of alkalic affinities; (2) depositional basins containing terrestrial sediments, particularly sandstones; and (3) deeply eroded granitic batholiths. The syngenetic deposits, mostly below ore grade, are limited to areas of: (1) granitic igneous rocks; (2) continental shelf organic- or phosphatic-rich sediments; (3) placers derived from granitic batholiths and high-grade metamorphic rocks; and (4) terrestrial and near-shore marine sediments. Areas of ultramafic rocks and plateau basalts, as well as marine sandstones and limestones, have as yet yielded little radioactive material.

If we assume an ultimate magmatic source of uranium or thorium (or both) for each of the terranes mentioned, different structural, lithologic, and chemical environments delimit the distribution of ground favorable for the occurrence of uranium- or thorium-regions or districts and within this favorable ground determine the localization of ore deposits.

GUIDES TO MAJOR AREAS

The localization of uranium and thorium regions within the earth's crust is the result of the interplay of complex geologic processes that tend to concentrate these metals in particular petrographic and metallogenic provinces. The search for new major ore regions is, therefore, fundamentally one of applying our knowledge of the geochemical cycle of uranium and thorium in the earth's crust.

All major areas of relatively high-grade uranium deposits in the United States contain intrusive or extrusive igneous rocks of alkalic or calc-alkalic affinity. The deposits are closely or distantly related to exposed or unexposed intrusives depending upon the available conduits for ore solutions. In impermeable igneous and metamorphic terranes where the porous structures are relatively short fractures, faults, and shear zones, the source rocks and the deposits show a close spatial relation. In terranes of permeable sedimentary rocks where single beds, or groups of interfingering beds, are continuous aquifers over large areas, the source rocks and uranium deposits may be either close together or many miles apart. Thorium, however, has a different field of chemical stability and consequently is deposited much more closely to its parent alkalic igneous rocks in associated carbonatites and veins; in fact, it occurs in the igneous rock itself and rarely is concentrated in porous sedimentary rock, except as detrital grains.

Apparently the most favorable terranes for both metals, in the United States, are those containing small, near-surface intrusive, and associated extrusive, alkalic igneous rocks that cut Mesozoic and Cenozoic terrestrial sedimentary rocks; less favorable are terranes containing deeply eroded granitic batholiths and their related pegmatites that cut

* US Geological Survey.

Paleozoic and Precambrian rocks. The absence of associated uraniferous pegmatites, of similar age, with most veins or bedded deposits of uranium indicates that deeper parts of igneous intrusives are less favorable loci for deposits than are the upper and peripheral parts of these masses. Marine sedimentary rocks rich in organic and phosphatic matter may be sources of low-grade syngenetic uranium deposits of large extent; they, like the impermeable terrestrial sediments, are hosts for high-grade epigenetic deposits only where adjacent to favorable tectonic structures that have been mineralized.

Broad geologic features commonly are delimited on maps at scales of 1:2,500,000 or larger in sufficient detail to focus attention on regions favorable for prospecting. Examples of favorable regions of igneous and terrestrial rocks of this order of magnitude include the Colorado Plateau and the Precambrian, Paleozoic, and Triassic areas intruded by Triassic dikes and sills in the northeastern United States. The Central Mineral Belt of Colorado and its possible extensions are an example of combined igneous and metamorphic terrane. By inspection of stratigraphic charts and logs, together with maps, it is possible to pick marine terranes favorable for syngenetic deposits such as the Northwest phosphate area of Idaho and Montana, the Florida phosphate area, and the Chattanooga shale area in Tennessee.

Because small-scale maps of major areas show only the larger intrusives exposed at the surface, the outer borders of favorable regions may be well beyond the limits of the igneous rocks mapped, perhaps by as much as several hundred miles, depending upon the presence or absence of permeable rocks and broad zones of deep-seated tectonic structures along which buried intrusives occur.

GUIDES TO NEW DISTRICTS

Within these broad regions the search for epigenetic deposits can be narrowed down to the smaller district areas characterized by large faults, shear zones, folds, crypto-volcanic structures, diatremes, and buried or exposed intrusives. Structure contour maps of basement and other surfaces showing these important structures are most useful in conjunction with maps of structural features at the surface, in delimiting the most likely locations of new districts. These favorable areas are in some places associated with abnormal though local increases in geothermal gradients as indicated by hot springs and high bottom-hole temperatures of deep wells. Such districts may be tens of square miles in extent, though their shape is commonly irregular, and within them the ore deposits are commonly localized in clusters.

The problem of finding new districts in permeable sedimentary terranes is one of finding large areas where physical traps favorable for the precipitation of uranium are numerous. Various guides have been successfully used in this phase of prospecting. These are the presence of favorable structures, host rocks, and chemical environment. Especially favorable are anticlinal or terrace structures—tectonic, erosional, or depositional in origin—or other structures that might cause the accumulation of gases or liquids such as CO_2, H_2S, natural gas, and oil that could result in direct precipitation of uranium, or in precipitation of other solutes that in turn would reduce the solubility of uranium compounds. Some of these structures are places where fractures may allow the escape of dissolved gases and result in precipitation. Fault, shear, and fracture zones crossing sedimentary horizons at an angle to the direction of flow of solutions and primary sedimentary structures, such as channel, cross-bedding, and interfingering porous and less porous beds may change the velocity and pressure relationships and thereby result in precipitation.

Uranium and other metals also can be precipitated where the host rocks are not only structurally but chemically favorable; commonly both physical and chemical factors must be satisfied before an ore deposit can form. In metamorphic and igneous rocks porosity is usually low, except where influenced by tectonic structures; favorable chemical environments in these rocks are rare except in areas of marbles and high ferrous iron-rich rocks such as hornblende schist and gneiss. In the unmetamorphosed sedimentary rocks the porosity is greater and the ore is deposited as pore fillings. Coarse-grained sandstones with variable texture commonly make the best host for ore minerals; many uniformly sorted sands, though of high porosity and located in uraniferous terranes, are barren of ore. Below the zone of oxidation wood and plant and other carbonaceous materials, carbonates, and clay minerals change the pH or otherwise cause reactions that result in precipitation; under oxidizing conditions iron and manganese oxides fix uranium readily.[1]

GUIDES TO ORE DEPOSITS

Once a district has been found to contain abnormal concentrations of uranium, even though well below ore grade, various guides can be applied in the search for ore deposits. These can be grouped as structural, lithologic, mineralogic, and chemical; no single guide, or group of guides, is infallible. The guides for different types of deposits are discussed below.

Many methods have been used graphically to show these geologic guides. Structure contour and isopachous maps, on scales commensurate with the size of the feature being studied, have been used to good advantage to show the configuration and thickness of favorable formations, beds, lenses, and channel fills as well as ore bodies, ore shoots, mineralized ground, and alteration zones. In the Black Hills of South Dakota and Wyoming, where uranium deposits appear most abundant on anticlinal and terrace structures, structure contours drawn on the top of the sandstone host rock have been used successfully in finding concealed deposits. Similar maps drawn on the base of the sandstone host in the Colorado Plateau have been used to delimit channels in which concealed deposits were found by drilling. Such maps used in conjunction with isopachous maps of the sandstone fill and of alteration zones in the under-

lying siltstones allow more accurate prediction of buried ore. Structure contour and isopachous maps also allow the location of zones of interfingering of sandstones and shales, a favorable area for deposits. Contour maps of facies changes and of the sandstone-shale ratio are also used; areas with a sandstone-shale ratio of 1 :1 are very favorable for ore in these regions.

Maps showing the frequency of distribution of rock types, mineral types, grain size, and element or compound content of rocks, soils, plants, and waters are commonly used, together with other data, to outline areas for prospecting, and in some places, to direct exploration. Contour maps of the ground water surface, together with maps of fluorine content in the water, have been used by Sheridan (personal communication) in the Red Desert area, Wyoming, as guides to the caliche-type schroeckingerite deposits. In North and South Carolina, heavy mineral content obtained by panning gravels has been used to contour the favorability of broad areas as sources of monazite. These and many other techniques in common use by other scientists have been adapted to the search for uranium and thorium with some success.

Epigenetic deposits of uranium in igneous and metamorphic terranes occur as fillings in fractures, faults, and shear zones; less commonly as replacements of limestone and other wall rocks. Veins containing Co, Ni, and Ag or Cu, Pb, Zn, and Ag minerals appear more favorable for pitchblende deposits than do other metal associations;[2] Mo minerals commonly occur with brannerite; and Ti minerals with davidite. In the United States the epigenetic deposits are commonly clustered in areas close to post-Cretaceous igneous rocks and structures. Guides useful for finding ore in districts of this type are given below.

Structural Guides

Explosion breccia and solution pipes, diatremes, or dikes, open or tensional parts of faults, fractures, and shear zones; contacts of dikes and sills; ore shoots at intersection of faults and fractures.

Lithologic Guides

Dikes, sills, and small stocks of alkalic and fluorine-rich intrusives; carbonate, hornblende-biotite-, or garnet-rich wall rocks.

Mineralogic Guides

Scattered yellow and green secondary stains and minerals on fractures or in altered wall rock; radioactive iron and manganese gossans; Co, Ni, and Ag minerals; Pb, Zn, Cu, Ag minerals; Mo minerals; Ti minerals; fluorescent silica druses; smoky quartz; dark purple to black fluorite; golden beryl; carbonate-feldspar gangue.

Chemical Guides Fe^{+++}

More K than Ca and abnormal F in probable source rocks; more Fe^{++} than Fe^{+++} or high Ca in wall rocks; more Fe^{+++} than Fe^{++} in the veins; Bi, Co, Ni, Ag in vein material.

The guides to epigenetic deposits of thorium are similar to those for uranium except that ferrous iron in wall rocks does not appear to control deposition; secondary yellow stains are rare; abundant deep red to purplish red iron oxides are common; Nb, Ba, P and rare earths are abundant; carbonatite masses or veins are distinctive lithologic guides.

In the United States increasing numbers of uranium deposits are being found in deposition and structural basins filled with terrestrial sandstones, mudstones, and low-rank coal. Geochemical, botanical, and radiometric prospecting in such areas have been useful. Abnormal amounts of selenium, arsenic, iron, zinc, manganese, as well as uranium and vanadium in plants, soils, waters, and petroleum products aid in outlining areas favorable for the occurrence of uranium deposits. Many of these rocks are of Tertiary age and many contain, or are associated with, abundant volcanic debris, either as ash beds or as ash mixed with sand or mud. Considerable success in prospecting has been had by examining areas of porous or carbonaceous beds beneath formations rich in volcanic debris on the assumption that uranium has been leached from this debris and concentrated in favorable beds in depth.[3] These basins, however, are at altitudes of 3000 to 8000 feet and are areas of relatively recent crustal movement. These basins may have been much closer to sea level at the time of formation and later have been uplifted with concurrent mild flexing and faulting. Subsurface information in some places shows a general geographic correlation of "basement" highs—possible intrusives or deep-seated tectonic structures—and uranium districts; in other places buried faults appear important. The localization of individual deposits,[4] however, appears to be more closely related to local favorable structure, host rocks, and chemical environment. Any of these factors may be the dominant control in any ore deposit, within a single area or between several areas. Guides that have been used to locate deposits are summarized below:

Structural Guides

Low anticlines, terraces, domes, or other structures showing abrupt changes in dip of permeable host rock below an impermeable cap rock; channels and swales cut in a relatively impermeable formation below the channel-filling sandstone host rocks; faults, fracture and shear zones, and breccia pipes cutting porous or nonporous beds; zones of sandstone interfingering with shales; thickened parts of lenses.

Lithologic Guides

Cross-bedded, medium to coarse, variable textured sandstone; carbonaceous sandstones and shales; subbituminous coal and lignite, especially in contact with porous beds; pyroclastic-rich beds overlying coal and sandstone; areas of abnormal quantities of iron and manganese oxides, carbonate, silica, or clay cements; clay pellet conglomerate and sandstone; carbonized wood; sandstone-shale ratio of about 1 :1; abnormal colors in sandstone or shale, for example, white sandstone or mudstone grading into buff, yellow, red, brown, pink, or purple; colored sandstone altered irregularly white, gray, or green; red

shale or siltstone altered to gray, green, or white below sandstone; abundant concretions of iron or manganese oxide, carbonate, silica; arkosic rocks.

Mineralogic Guides

Yellow or green secondary encrustations or grains; jarosite; iron-manganese carbonates; vanadium, silver, or copper minerals; carbon.

Chemical Guides

Abnormal quantities of V, As, Se, Mo, Zn, Cu, Co, Ni, Mn, Fe, Ra, He in rocks, soils, natural gas, petroleum, asphaltic residues, surface and subsurface water; silicification of sandstone and shale enclosing carbonate-cemented sandstone; phosphate-rich sandstone.

BATHOLITHS

The batholithic areas of the United States have to date been relatively unproductive of uranium deposits. Few occurrences, other than in relatively small high-grade veins, have been found. The Boulder batholith in Montana has a few associated base metal-silver-uranium and chalcedony veins; the Sierra Nevada batholith contains only a few fissure-filling deposits; post Devonian batholiths of the eastern United States contain pegmatites, but few veins; the Pikes Peak and associated batholiths of the Rocky Mountains contain some deposits, but these are much younger than the batholith. Thus it would appear that unless the batholith is cut by much younger rocks, such areas are not good prospecting ground for epigenetic deposits. Uraniferous pegmatites, however, are commonly associated with the Precambrian, late Paleozoic, and in places Jurassic-Cretaceous batholiths. Thorium, as monazite, allanite, or thorite in igneous rocks, veins, and carbonatites is often associated with the satellitic bodies of the batholiths.

In prospecting batholithic terranes particular attention should be given to: (1) the smaller satellitic alkalic intrusives and associated carbonatites and veins as possible sources of thorium; (2) pegmatites, particularly those in country rocks of high metamorphic grade; and (3) veins that may be of younger age than the batholith.

CONTINENTAL SHELF SEDIMENTS

Phosphorites and black shales are the only marine sediments that are known to contain abnormal amounts of syngenetic uranium. Prospecting for such low-grade deposits is a matter of analyzing radiometrically or chemically those shales and phosphorites found in field mapping, or in petroleum prospecting. In the United States the gamma-ray logging records of oil and other deep wells in sedimentary terranes is a common starting point, although normally an evaluation of the area to be considered involves the delimiting of continental shelf areas favorable for such sedimentation. The relative horizontal uniformity of composition of the shales and phosphorites over large areas necessitates prospecting for minor differences, but rarely is the order of magnitude of the grade changed.

PLACERS IN AREAS OF GRANITIC BATHOLITHS

Monazite, zircon, and other minerals refractory to weathering that contain thorium and uranium are usually present in granitic batholiths in small amounts. Upon weathering of the batholiths these minerals commonly accumulate as placers, either as colluvial or alluvial material and as beach sands. Prospecting for such syngenetic deposits is based on: (1) knowledge of the petrology and mineralogy of the igneous rocks of the area; and (2) interpretation of recent or past drainage patterns and coastal history. Panning, rather than radiometric techniques, is the most useful method of prospecting alluvial placers, but airborne surveying is most efficient for scouting present day and fossil beach placers. Airborne equipment also is most useful in delimiting source areas for placers.

TERRESTRIAL AND NEAR-SHORE MARINE SEDIMENTS

Many near-shore marine sediments formed in deltaic, lagoonal deposits, and other shore environments contain interlayered terrestrial phosphatic sands, carbonaceous debris, or coals that are capable of adsorbing uranium from sea water. Such rocks may then become low-grade syngenetic sources of uranium.

REFERENCES

1. Lovering, T. G., *Progress in Radioactive Iron Oxides Investigations,* Economic Geology 50: 186–195 (1955).
2. Everhart, D. L. and Wright, R. J., *The Geologic Characters of Typical Pitchblende Veins,* Economic Geology 48: 77–96 (1953).
3. Love, J. D., *Preliminary Report on Uranium Deposits in the Pumpkin Buttes Area, Powder River Basin, Wyoming,* US Geological Survey Circular 176 (1952).
4. Weir, D. B., *Geologic Guides to Prospecting for Carnotite Deposits on Colorado Plateau,* US Geological Survey Bulletin 988-B (1952).

Heavy-Mineral Prospecting

By W. C. Overstreet, P. K. Theobald, Jr., J. W. Whitlow, and J. Stone,* USA

A method of geologic prospecting was developed for use in areas underlain by crystalline rocks whereby the relative abundance and distribution of detrital heavy minerals are compared to show regional relations among the rocks and minerals. It is based on the assumption that differences among the suites of detrital minerals from streams with small drainage basins reflect variations in the composition of bedrock if other factors, such as hydraulic influence, are similar. As originally developed the method was used to study the occurrence of monazite in igneous and metamorphic rocks, but the system is adaptable to rapid reconnaissance studies of the distribution of other economic minerals.

The method is well suited to intensely weathered regions with deep residual soil where heavy minerals recovered from the headwaters of small streams have been derived from underlying or adjacent rocks. Similar methods can be used for geologic prospecting wherever the stream density is adequate and there is no interference from glacial deposits.

METHODS

Normally, heavy-mineral prospecting is divisible into field, laboratory, and office stages, hence discussion of methods will follow that order.

Field work consists of taking heavy-mineral concentrates and making normal reconnaissance geologic studies. Collecting concentrates is done first because it is merely manual labor, progresses rapidly, and allows the geologist to become acquainted with the terrain. It is followed by geologic studies at a reconnaissance scale suited to the over-all needs of the problem. No innovations have been introduced into the reconnaissance; it involves familiar geologic procedures planned to give the desired knowledge of types, trends, and distribution of the rocks.

Heavy-mineral concentrates are collected from equal-size samples of gravel taken from riffles in the channels of small streams. Areas of the distributive provinces of the streams above the sites sampled should not exceed 2 square miles. Uniformity in the position in the stream channel and grain-size distribution of the samples is desirable to reduce the effect of variable hydraulic influences upon the heavy-mineral suite. If external influences are similar, then changes in the concentrates will reflect variations in the aggregate composition of the rocks underlying the distributive provinces of the streams.

Similarity in position of the alluvial samples can be assured by adequate planning before entering the field. The most desirable localities, as regards size of distributive province, length and gradient of stream above locality sampled, and proximity to adjoining samples, are plotted on suitable maps. Once field work is begun the net of proposed localities is modified to fit actual conditions and to increase uniformity among the samples.

Uniformity in grain size distribution is maintained by visual inspection and selection of samples that contain gravel having the same maximum intermediate dimension. Equal-sized samples of alluvium are measured volumetrically since no system of dry weighing is adapted to rapid reconnaissance, and the wet weights of the samples are too variable to be meaningful. Enough gravel is taken from the stream (generally 0.3 cubic foot) to provide a volume, after screening to minus ⅛ inch, of a clay- and silt-free product, adequate to make one charge for a standard 16-inch gold pan.

The screened product is panned to produce a concentrate that contains from 5 to 20 per cent quartz and other minerals of low specific gravity. Panning, which takes about 20 minutes per sample, is carefully done and is the only form of concentration used either in the field or laboratory. No further cleaning is required.

The gold pan is not used as a quantitative tool; mineral distribution is interpreted on a comparative basis; hence, total recovery of the heavy minerals is not required. All that is needed is consistent panning of each sample from one sample to another to insure similar effective concentrations.

Heavy-mineral concentrates are also prepared from bulk samples of bedrock or residual soil so that relations can be determined between the suites of detrital minerals and rocks in the area. There is some danger that this might become a study in itself and impede heavy-mineral prospecting. To forestall such a shift in emphasis during reconnaissance, not more than 5 per cent of the total number of samples should be taken from bedrock.

No improvement in geologic resolution is gained by doubling the number of samples taken in a given area. Significantly greater resolution can be attained if the number of samples is increased to scores per square mile, but the method can then no longer be regarded as reconnaissance.

Periodically the samples are shipped to a central laboratory for examination. Mineralogic identifica-

* US Geological Survey.

tion, grain counts, and computations are done in the laboratory by a staff who are acquainted with the field problem. Since the usual study involves several thousand samples per year, mineralogic work must be reduced to a routine consonant with the time available and the accuracy required. Mineralogic analyses of the concentrates are done most efficiently along "assembly-line" plans with the operation divided into: (1) removal of magnetite from the concentrate and weighing; (2) sieving the magnetite-free concentrate and weighing the fractions; (3) splitting; (4) counting; and (5) calculating. The first three operations are done by an aid, the fourth is done by the mineralogist, and both participate in the calculations.

Magnetite is removed from the concentrate with a hand magnet and weighed. The magnetite-free concentrate is separated into three to five sieve fractions, depending upon the range in size of grains in the concentrate, and the weights of the fractions are recorded. A split of 100–200 grains from each fraction is poured into a narrow groove milled in a plastic slide designed for use with a binocular microscope. The slide is placed on the stage of the microscope and passed along as the split is examined. All the grains of one mineral are counted in one traverse; all the grains of a second mineral are counted in the second traverse, and so on until all mineral species in that sieve fraction of the concentrate are counted. Two concentrates can be counted per hour. Use of the binocular microscope decreases the time consumed in preparing slides for counting, reduces fatigue, and permits other analyses to be made on any grain.

Large splits are counted periodically to check representation of the smaller cuts, and the spot identifications of minerals are supplemented as required by oil immersion, spectrographic, and X-ray techniques.

Computations performed in the laboratory are those needed to convert grain counts to weight per cents of the concentrate. Conversions relate specific gravity, size, and frequency distribution to weight per cent through assumptions that specific gravity is constant in a given species, and that all species in a given sieve fraction have the same volume. Obviously, the specific gravity of a given species and the volume of grains in a given sieve fraction vary, but as long as all grain counts are recalculated in the same fashion, the relative differences among the concentrates are preserved.

The calculations can be performed in about 5 minutes and consist of the following: (1) weight per cents of the magnetite and the sieve fractions are calculated directly from their weights and that of the concentrate; (2) the grain counts of each mineral are converted by specific gravity factors into units equivalent to the number of similar-sized grains of quartz needed to equal the weight of the heavy mineral; (3) the units in each sieve fraction are totaled; (4) the weight per cent of a sieve fraction is divided by the total number of units in the fraction and the quotient is multiplied by the number of units of each mineral in the fraction to give weight per cent of that mineral in that fraction; (5) the last three operations are repeated for each sieve fraction; and (6) the sum of the weight per cents of a given mineral in all the sieve fractions equals the weight per cent of that mineral in the concentrate.

The mineralogic analyses are reported to the field where they are plotted and interpreted in the office stage of the investigation.

Mineralogic analyses of the alluvial concentrates are compiled on maps showing sample numbers and localities. Separate maps are used for each mineral. The compositions of concentrates obtained from bedrock or residual soil are not shown on maps used for alluvial concentrates.

The weight per cent of a mineral is plotted at each locality where it is 1 per cent or more of the quartz-free concentrate. Recalculation of the mineralogic analyses reported from the laboratory to a quartz-free basis is readily done by means of a nomogram. Recalculation is most conveniently accomplished at the time the minerals are plotted on maps, because the geologist may wish to exclude several other minerals, such as feldspar, biotite, and hematite, from the recalculated concentrate.

The abundance of each mineral, expressed as weight per cent of the quartz-free concentrate, is contoured at suitable intervals on a transparent overlay, which protects the base map from the corrections incident to contouring. Final copy is prepared from the overlay and is reduced photographically to a scale appropriate to the area and the density of sampling. A compilation scale of 1 inch equals 2 miles and a final scale of 1 inch equals 4 miles was satisfactory for an area of 4000 square miles where 2500 samples were taken.

Contours are drawn at intervals suited to the range in weight per cents spanned by the different heavy minerals. Supplementary contours at partial intervals are an excellent means of showing detail in critical ranges of weight per cent. The contour intervals (Table 1) were used satisfactorily in the 4000 square mile area mentioned above.

Black and white patterns or color introduced between the contours emphasize the distribution of the minerals.

The mineralogic analyses of concentrates from bedrock and residual soil are plotted at the same scale, and data from the reconnaissance geologic studies are similarly compiled to assist interpretation of observations.

INTERPRETATION

The heavy-mineral contours are interpreted to guide selection of areas where further geologic studies would have the greatest probability of revealing ore deposits.

The sources of most of the detrital minerals are shown by the heavy minerals concentrated from bedrock or residual soil. Thus the general pattern made by the mineralogic contours can be related to changes

Table I

Mineral	Initial contour (weight per cent)	Contour intervals (weight per cent)	Maximum contour (weight per cent)
Ilmenite	10	10	90
Magnetite	1	10*	90
Rutile	1	5	20
Garnet	1	10†	70
Zircon	1	10‡	50
Monazite	1	10*	80
Xenotime	1	10*	20
Tourmaline	1	5	30
Spinel	1	1	6
Sphene	1	1	3
Staurolite	1	5	90
Kyanite	1	5	25
Sillimanite	1	5	35
Epidote	1	5	80
Hornblende	1	5	50

* Included a supplementary contour at 5 per cent.
† Included supplementary contours at 5 and 15 per cent.
‡ Included supplementary contours at 2 and 5 per cent.

in proportions of the different major rocks in the area examined, and the pattern of the contours will conform to the regional trends discovered in reconnaissance. The grain of the information shown by the heavy-mineral contours is generally coarse. The structure and nature of the rocks are broadly outlined, and, ideally, abrupt mineralogic differences locally refine the grain of the pattern. Examples of resolution are cited below to show features that can be recognized.

Antipathetic zones of metamorphic minerals reflect different grades of regional metamorphism and differences in the composition of the bedrock. The first appearance of detrital chloritoid, staurolite, kyanite, garnet, and sillimanite is as precise a guide to the position of an isograd as is location by petrographic study.

The general concordance or discordance of granitic rocks is shown by the conformity of contours for zircon and monazite to the contours of metamorphic minerals; an angular difference between the contours shows the trend of discordant plutons. Typical contact metamorphic minerals appear peripheral to the bodies that produced them.

Local mineralogic "highs", where one or more minerals abruptly rise in abundance over their average distribution, reflect changes in the gross composition of the bedrock. Such "highs", where resistant ore minerals or resistant heavy minerals associated with soluble ore are concentrated, become the loci for normal geologic study.

SUMMARY

Geologic reconnaissance based on systematic studies of the distributive pattern of detrital minerals, here called heavy-mineral prospecting, is best suited to regional search for ore deposits. Various modifications of the technique, such as contouring weights rather than weight per cents, and integrating heavy-mineral with appropriate geochemical and geophysical methods, readily suggest themselves to fill special exploratory needs. Heavy-mineral prospecting should precede and guide, but not supplant, normal geologic studies.

Subsurface Techniques for Outlining Favorable Zones Using Widely Spaced Core Drilling

By Robert K. Pitman, Philip H. Dodd, Charles W. Tom,* USA

Subsurface mapping techniques for outlining zones favorable for the occurrence of uranium-vanadium ores were tested in the Cottonwood Wash mining area, San Juan County, Utah by holes spaced 500 to 1000 feet apart in the search for the small uranium deposits in the Morrison formation. The techniques employed may be useful in uranium search in other areas where outcrops are few or nonexistent.

COTTONWOOD WASH MINING AREA

Geology

The uranium-vanadium ores of this locality were discovered in the Salt Wash member of the Morrison formation in 1930 although little ore was mined until 1936.

The Cottonwood area is on the east flank of the Comb monocline where the eastward dip of the sedimentary rocks changes from six degrees near the monocline to one degree near the mines. On the eastern flank of the Comb monocline and in the drilling area the formations range from the lower Jurassic Navajo sandstone to the upper Cretaceous Mancos shale. The Jurassic Bluff sandstone pinches out along an irregular line through the Cottonwood drilling area. Of special interest is the overlying Morrison formation which includes the Salt Wash, Westwater, and the Brushy Basin members. Sandstone, siltstone, and mudstone beds of the Salt Wash total approximately 210 feet in thickness in the mining area and they interfinger with the brown Recapture shales about 12 miles to the south. The Westwater sandstone is approximately 150 feet thick and pinches out a few miles north of the Cottonwood mining area. The Brushy Basin shale is the uppermost member of the Morrison and averages 400 feet in thickness.

Vanadium and uranium deposits in the Cottonwood Wash area are of the carnotite type. Mill settlement sheets indicate an average ratio of vanadium to uranium of 10:1.

Drilling

Drilling, aimed at the discovery and blocking out of orebodies was done over an area of approximately 11 square miles.

Mapping of stream lineation and cross-bedding[1] indicated that the Salt Wash streams flowed from west to east, which agrees with the regional trends established by Craig and others.[2]

The drilling program was designed to extend geologic information east of the known mines and under deeper cover. Holes were drilled on 500 foot centers along north-south lines, spaced approximately 1000 feet apart along the indicated east-west direction of flow of the Salt Wash streams. Drilling depths range from 300 feet in the western portion to as much as 850 feet in the eastern portion of the drilling area. Construction of subsurface maps of the area was supplemented by data taken from previous drilling in the area.

Hypothesis on which Techniques Are Based

Geological investigation of the Salt Wash member has resulted in a concept of Salt Wash deposition by a multitude of anastomosing water courses which became filled with sand and sub-sand-size particles. The resulting surface received deposition throughout Salt Wash time until the total thickness of sediments is today represented by tens to hundreds of feet of interbedded sandstone and mudstone.

Facies of sedimentary rocks are believed to reflect environments of deposition in such various zones of the stream as fast water channel zones, slow water channel margin zones, and slack to semi-stagnant flood plain zones which are periodically inundated. Each facies is elongate parallel to flow directions, thus causing rapid facies changes to be found in directions normal to the flow. Many facies are superimposed one above the other throughout the Salt Wash section. No time horizons are recognizable within the Salt Wash member, and rock units do not represent exact time units. Rapid lateral facies change resulting from different environments of contemporaneous deposition of sandstone and mudstone require acceptance of different rock types within small time units.

The direction of flow and deposition by a single stream in a restricted time interval is not necessarily the same as the mean direction of all the Salt Wash streams in one locality. Lack of recognizable time units requires correlation of rock units within a limited area, with subsequent division into depositional units or cycles. These are believed to represent a limited time interval.

If one such depositional unit is found to contain uranium deposits and is suspected to contain others

* US Atomic Energy Commission.

it becomes necessary to trace this unit with a minimum number of drill holes. If several such units are known to be ore-bearing each must be treated, in terms of favorability, as a separate entity. This is particularly true when facies within a single depositional unit are to be projected.

The thickness of depositional units is not constant. Therefore the unit, rather than a constant thickness, is believed to present the best vehicle in subsurface mapping. Mapping of a single unit is preferred over mapping several combined units or the entire Salt Wash member. Mapping a combination of units results only in the assumed distribution of a synthetic mean-facies of a number of noncoeval discrete units.

It has been assumed for the general case that during a single depositional cycle the first sediment laid down is sand in the channel and mud on the flood plain; and that, as the cycle progresses, the channel zone will become filled with both sand and mud, and the final layer of the unit will be a mud which covers deposits in the old stream bed as well as the flood plain.

Method of Correlation

The method of correlation begins with construction of an isometric diagram for all the holes drilled. With such a diagram it is much easier to trace time equivalents because all plotted holes are in their proper spatial relationships. With drill logs plotted, the sandstone and mudstones are correlated (Fig. 1). Where a sandstone or a mudstone could not be correlated from one hole to the next but other beds do correlate, it is shown as pinching out. After all units are correlated, the top of the first dominant and persistent mudstone below the potentially ore-bearing sandstone is selected as the base of the unit. In the same manner, the first persistent mudstone above this sandstone is selected as the top of the unit.

It has been found expedient to have more than one geologist make such a correlation diagram of the same area as a means of discovering fallacious correlation where personal opinion must substitute for concrete and adequate evidence.

Once a depositional unit has been established it is then possible to construct subsurface maps of the various lithologic characteristics of the unit. The accuracy of any map is dependent upon the relationship between the persistency of the characteristic mapped and the density of control. Many types of subsurface maps are possible where hole density is sufficient, but for reconnaissance type drilling with widely spaced holes, only features of considerable magnitude and persistence can be mapped.

Subsurface Maps

A lithofacies map employing the ratio of mudstone to sandstone content of the depositional unit was found to be most diagnostic where holes are spaced 500 to 1000 feet apart (Fig. 2). The ratio type map is preferred over a sandstone isopach or percentage map. The use of a relatively small contour interval served best to define areas of facies change and to force careful interpretation. After contouring, the choice of interval to be shaded was based on a geometric interval to outline areas of significant differences.

Elongate patterns representing similar mudstone-sandstone facies not only indicates the trend of deposition, which can be projected for at least 1000 feet along the trend, but also presents a close approximation of distribution of environments represented by the facies.

Hypothesis Concerning Favorable Ground

Criteria for recognition of favorable ground, other than mineralization itself, have long been a subject of conjecture. It is believed that the ore deposits, as found today, are localized in a zone of facies change where both the greatest number of changes, and the greatest rate of change occurs. The effect of changes or combination of changes is unproven; it could be tectonic or sedimentary structure, wall rock chemistry, physical properties of the host rock, some unknown change, or combinations of these. It is imperative to map as many changes in as much detail as possible.

The mudstone-sandstone lithofacies map of a depositional unit of the Salt Wash in the Cottonwood area shows the position of a significant facies change; rate of change obviously being indicated by the density of contours (Fig. 2). The interface between a dominantly sandy section and a dominantly muddy section is interpreted as the interface of change for many physical phenomena such as porosity, permeability, and resulting transmissivity. There is also variation at this interface in mineral content and chemical composition such as abundance of carbon and variation in iron and sulfide content with all the related changes in *e*H and *p*H.

Several worthy attempts have been made to relate statistically the ore deposits in the Salt Wash to a favorable thickness of host sandstone.[3] The values determined by these studies are presumably correct for the area investigated but do not agree. It is possible that the thicknesses designated favorable in each area may all represent a similar environment between the fast and slow water sedimentation for that area. The same may be true for other features found to be statistically favorable in some localities but not in others.

In the mudstone-sandstone lithofacies map, random coincidence is displayed between the location of mineral deposits and the position of facies or environment change (Fig. 2). If for no other reason than this empirically derived evidence it is probable that the interface between the clean sandstone and the mudstone areas are most favorable for ore accumulation. Such interfaces can be located by the exploration geologist using data from widely spaced drill holes. Better maps, outlining more types of change, can be drawn when density of control is increased by closer spacing of drill holes.

To emphasize the areas of rapid facies change, a map may be constructed by placing tracing paper

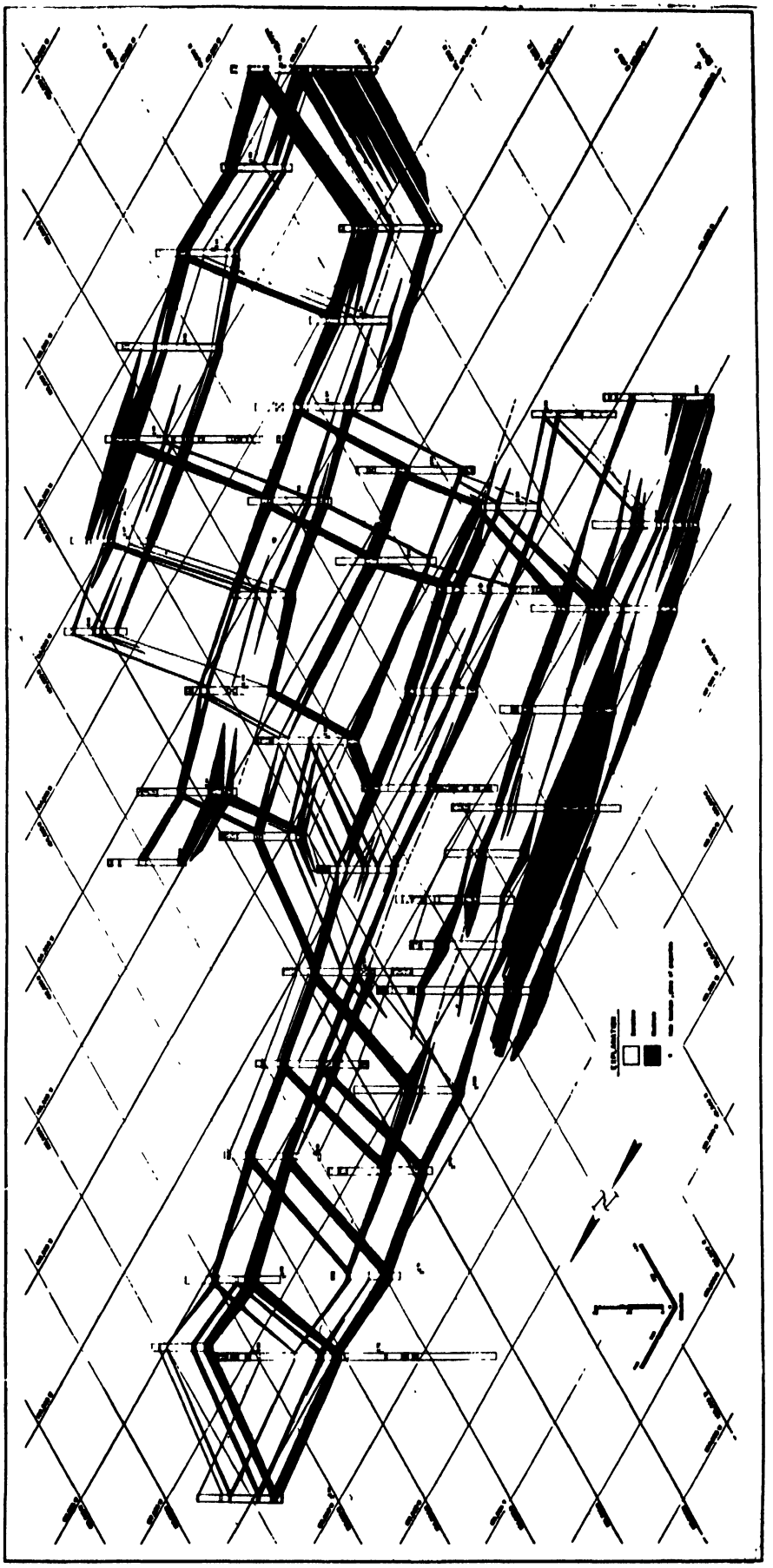


Figure 1. Isometric correlation diagram; portion of Salt wash member, Morrison formation, Cottonwood Wash, San Juan County, Utah

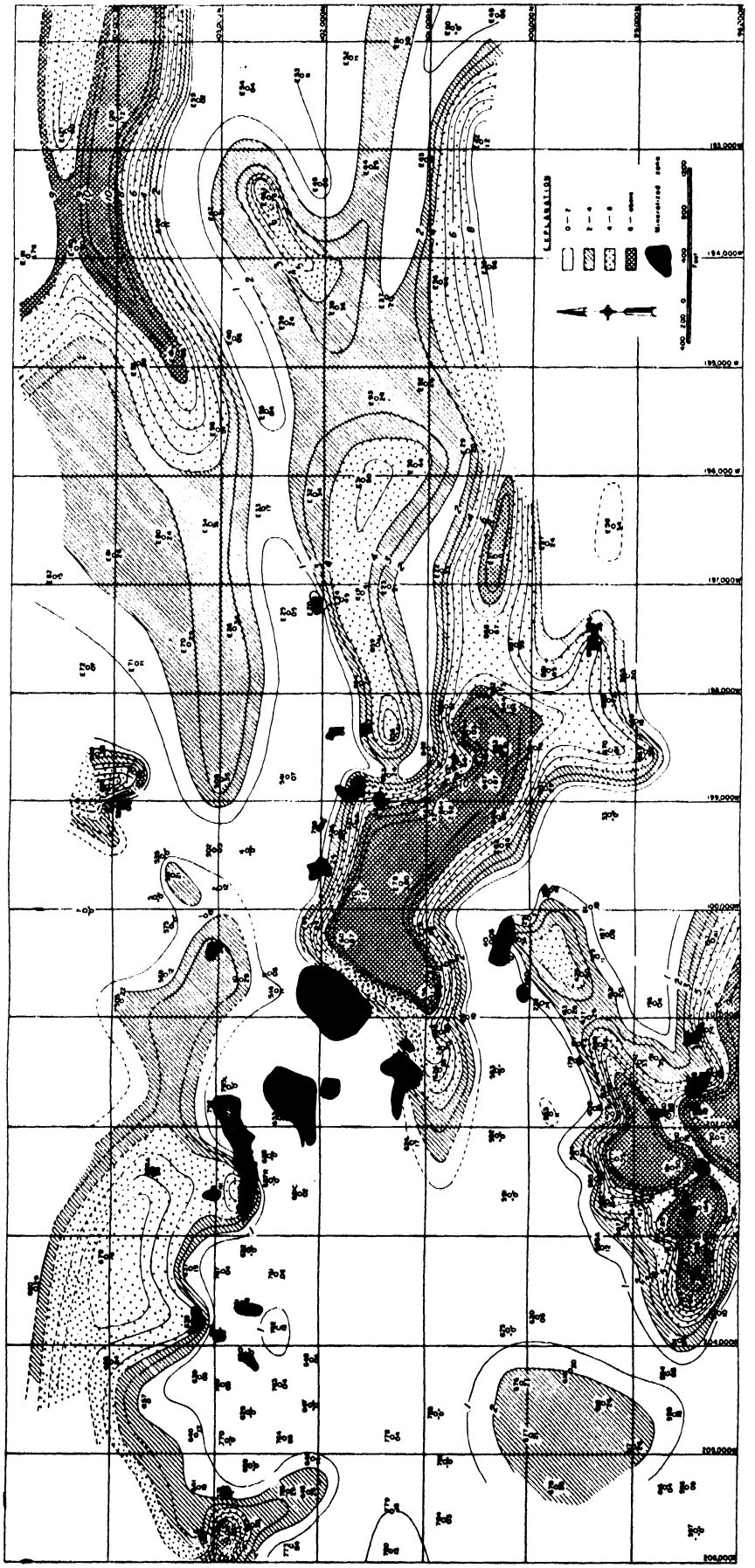


Figure 2. Mudstone-sandstone lithofacies map; Saltwash member of Morrison formation, Cottonwood Wash, San Juan County, Utah

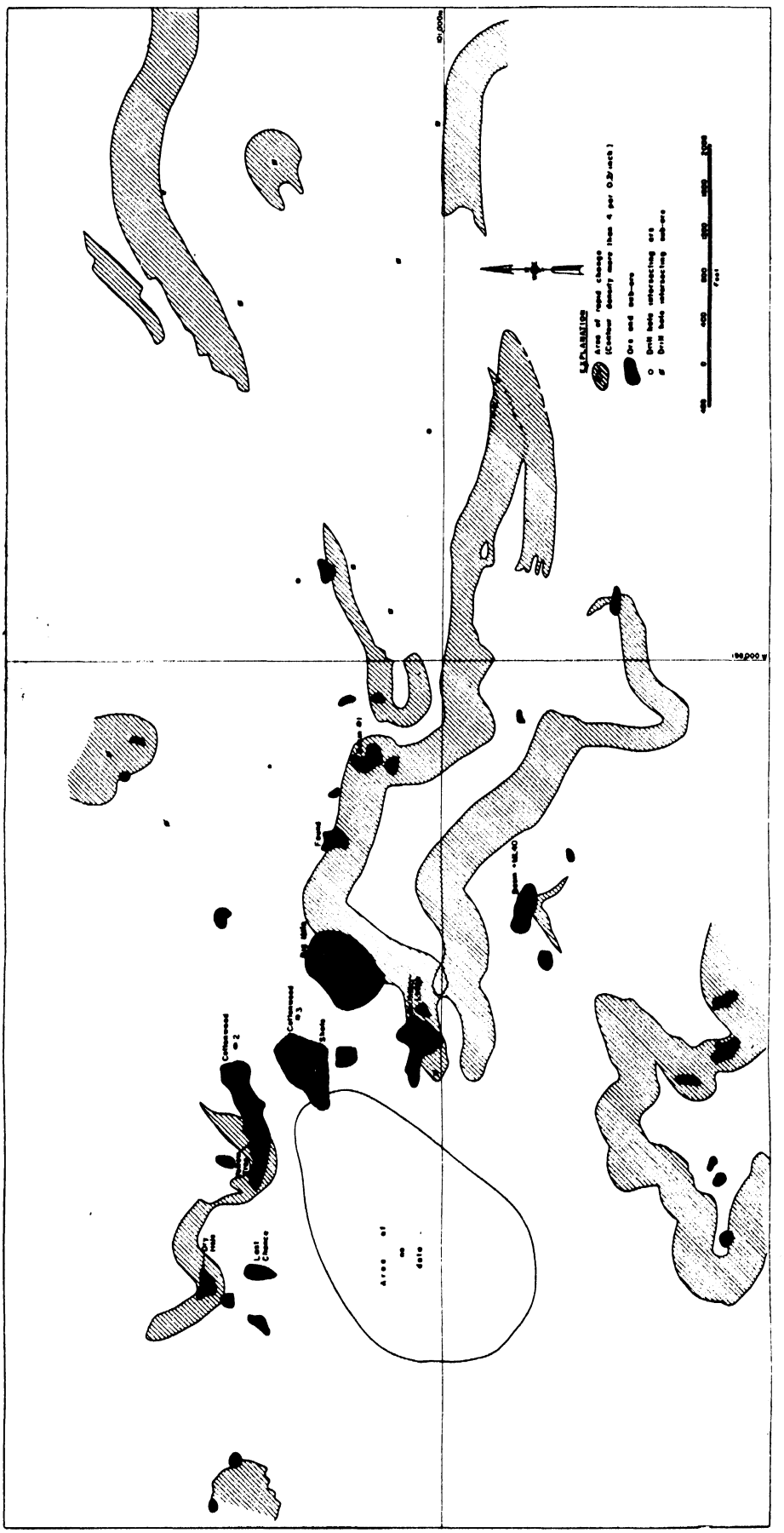


Figure 3. Area of rapid change, mudstone-sandstone lithofacies Cottonwood Wash, San Juan County, Utah

over the lithofacies map. A circle of arbitrary radius is then inscribed on acetate, and a hole punched in the center. By placing a pencil in the center hole of the circle and placing the circle on the overlay it is possible to draw a line while moving the circle in such a manner that the same number of contours always appear within the circle. This system can be used to inscribe a figure which will enclose the area of equal rate of change. It can be seen by superimposing the outline of mineral deposits on the resulting map that a close correlation exists (Fig. 3). This does not illustrate anything startlingly new as distinct from the mudstone-sandstone lithofacies map, but does serve to highlight the point stressed—that uranium mineralization is most likely to be found at or near the point of rapid facies change.

REFERENCES

1. Stokes, W. L., *Relation of Sedimentary Trends, tectonic features, and ore deposits in the Blanding district, San Juan County, Utah,* US Atomic Energy Comm. RME-3093 (Part I) (1954).
2. Craig, L. C., Holmes, C. N., *et al., A preliminary report on the stratigraphy of the Morrison and related formations of the Colorado Plateau regions,* US Geol. Survey TEI-180 (1951).
3. Weir, D. B., *Geologic guides to prospecting for carnotite deposits on Colorado Plateau,* US Geol. Survey Bull. 988-B (1952).

Techniques and Guides for Exploration of Shinarump Channels on the Colorado Plateau

By H. B. Wood and W. D. Grundy,* USA

Paleostream channels filled with Upper Triassic Shinarump clastics, which in many places on the Colorado Plateau contain uranium orebodies, may be traced by drilling based on information derived from contour maps of the lower contact of the Shinarump. Such maps, if corrected for the effects of regional dip, are reasonable approximations of the pre-Shinarump erosion surface. The probable presence of ore in the paleostream channel-fills may be suggested by various empirical criteria. In White Canyon, 22 channels, six containing ore, and in Monument Valley 14 channels, seven containing ore, were located by recognition of certain geologic criteria and traced by drilling based on information provided by paleotopographic maps.

GEOLOGY OF PALEOSTREAM CHANNELS

Monument Valley is at the southern end of the Monument uplift, the north end of which is near the junction of the Green and Colorado Rivers; White Canyon is on the west flank of the same anticlinal structure; Circle Cliffs, another area where Shinarump channel ore deposits are frequent, is a northwest trending uplift in Utah (Fig. 1). These uplifts are much younger than the paleostream channels. The influence of structure on primary uranium mineralization and its subsequent redistribution is not clear.

Shinarump clastics normally lie on Moenkopi (Triassic) redbeds, but where these have been removed by pre-Shinarump erosion, the clastics rest on formations of Permian age. After deposition of Moenkopi redbeds, ancient streams removed portions or all of that formation and left channels of varying sizes cut into the erosion surface. The intervening areas were carved to an irregular surface of low relief. A period of deposition followed, and swiftly flowing Shinarump streams deposited clay, silt, sand, and gravel over much of the erosion surface, filling the old stream channels (Fig. 2). Some paleotopographic highs were left free of Shinarump deposits and at various places the overlying Chinle formation into which the Shinarump grades laterally and vertically, rests directly on the Moenkopi.

Paleostream channels vary in length, width, depth, cross-section profile and trend from region to region and place to place within the same region. They may be sub-parallel or convergent; some meander, bifurcate and rejoin; some may die out against paleotopographic highs. A few channels may be traced for miles; others only a few thousand feet.

Most channels in Circle Cliffs and Monument Valley are from 300 to 3000 feet wide and 30 to 275 feet deep. Depths of scours within a channel vary as much as 60 feet, a situation similar to that in the channel of the modern Colorado River. Channels in White Canyon are from 75 to 300 feet wide and 10 to 50 feet deep. Here depths of scouring within the same channel vary as much as 40 feet.

Paleostream channels vary in cross-section as do their modern equivalents; they may be symmetrical or asymmetrical, and flanks may be gently sloping to nearly vertical; channels floors may be nearly flat or contain local scours.

Many paleostream channels are easily recognized at their outcrops by truncation of underlying Moenkopi beds and thickening of Shinarump clastics on the unconformity. Others, such as that of the Happy Jack mine at White Canyon, are not evident at the outcrop, but clearly show on paleotopographic maps.

Sediments filling paleostream channels are a heterogeneous mixture of cross-stratified sandstones interbedded with lenses of mudstone and conglomerate. In general, coarser clastics—sandstone and conglomerate—are most abundant in the lower portions of a channel, but sandstone is dominant throughout the channelfill. Carbonized vegetal debris, silicified wood, and asphaltic material are present in minor quantities, and locally in concentrations. The asphaltic material, obviously epigenetic, may extend downward into the underlying Moenkopi.

URANIUM ORE IN CHANNELS

Size, Shape and Distribution of Ore Deposits

The largest orebody in Monument Valley is measured in hundreds of thousands of tons; in White Canyon in tens of thousands of tons; and in Circle Cliffs in a few thousand tons. All orebodies in these regions are roughly tabular, generally parallel to stratification and elongated parallel to the channel trend.

Most orebodies are in the coarser clastics near the base of a channel, and mineralization may extend across the contact into the underlying formation. In Circle Cliffs, 80 per cent of the production is from

* US Atomic Energy Commission.

the Moenkopi formation underlying channels. At the Rainy Day mine, ore has been mined from the upper eight feet of gray asphaltic Moenkopi claystone under the Shinarump. At Monument No. 2 mine, in Monument Valley, the upper six feet of the Permian De Chelly sandstone underlying the Shinarump channel contains ore. In this exceptionally large deposit most ore is near the channel base, but some occurs in the uppermost part of the channel-fill.

At White Canyon and in Monument Valley, most ore is in the deeper scours within channels; a lesser quantity occurs along channel flanks. At Circle Cliffs, nearly all deposits are along channel flanks; only one deposit has been found in a channel trough.

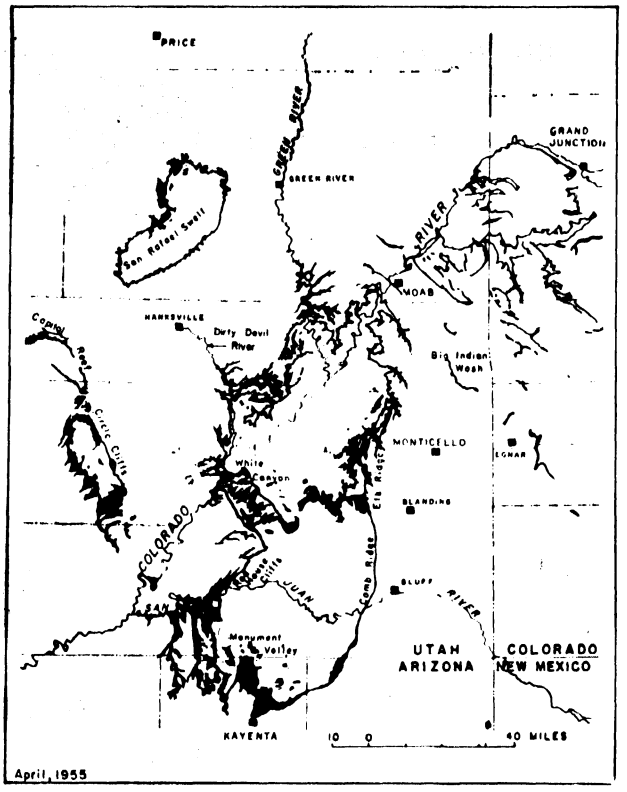


Figure 1. Location of Shinarump and Chinle outcrops, Colorado Plateau

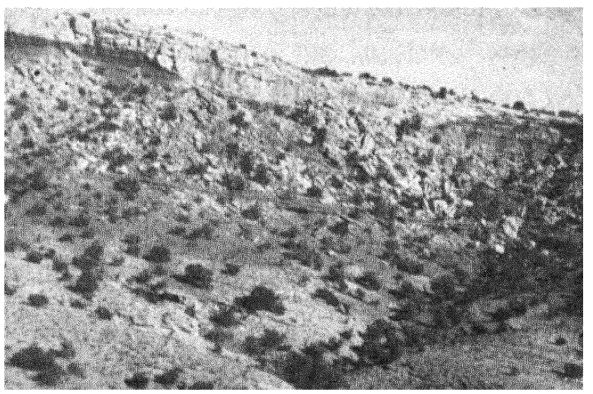


Figure 2. Aerial view of a Shinarump channel, Colt Mesa, Circle Cliffs, Garfield County, Utah

Geologic Controls and Guides

Geologic controls are those geologic conditions which influence the movement of uranium-bearing solutions and the precipitation of uranium minerals. Guides are those mineralogic features which are repeatedly associated with uranium deposits. The order of importance of recognized controls and guides varies from region to region, and none are definitely established. The more of these found at one locality, the greater the probability of encountering ore there.

1. The most important and large-scale control is the presence of a paleostream channel filled with Shinarump clastics.

2. Within channels, irregular depths and trends appear favorable for mineralization. Deeper scours which form closed basins are most favorable.

3. An abundance of carbonized vegetal debris and asphaltic material in the lower portion of a channel is favorable. In many localities, carbonaceous trash is impregnated or replaced by uranium minerals. Not all carbonaceous material is so affected, however, and many uranium orebodies are locally devoid of carbonized plant debris.

4. Moderately to poorly sorted, coarse-grained, friable, arkosic sandstone containing moderate amounts of interstitial clay, claystone seams, and clay pellets, associated with carbonaceous material is favorable lithology. The content of argillaceous material in the lower 10 to 20 feet of a channel-fill, however, should not exceed 25 per cent of the total.

5. A thin zone of bleached Moenkopi immediately beneath the Shinarump is almost universal. A thickening of the altered zone and an intensification of bleaching generally occur beneath mineralized channels.

6. Copper sulfides, sulfates, and carbonates; iron sulfide, sulfates, and hydrous oxides; and cobalt arsenate, sulfate, and carbonate are conspicuous associates of many uranium deposits; hence their presence on an outcrop of channel sand is a suggestion that ore may be nearby.

7. In regions of non-vanadiferous uranium deposits, channels extending beneath thick, relatively impervious cover, or below a water table, offer more favorable ground for exploration than channels under thin pervious cover which are exposed to oxidation and leaching by ground water. The White Canyon and Circle Cliffs non-vanadiferous uranium ores of pitchblende associated with base metal sulfides commonly form highly soluble uranyl sulfates when oxidized. The White Canyon deposits have been protected from oxidizing ground waters by thick, impervious cover, whereas in Circle Cliffs nearly all deposits underlie pervious sandstone benches and have been oxidized and leached. The uranium-vanadium ores of Monument Valley form relatively insoluble uranyl vanadates when oxidized, so the thickness of permeability of the cover there are unimportant.

The above list of controls and guides is not com-

plete. Those omitted are not proved to be applicable to the regions discussed. A more complete listing of guides is given by Miller[1] and Mitcham and Evensen.[2]

EXPLORATION TECHNIQUES

Mapping Techniques for Reconstruction of Paleotopography

Because all known uranium orebodies in the regions under discussion are in Shinarump channels, prospecting has been confined to a search for paleostream channels using the criteria listed above. Where such a channel or a suggestion of a channel is found, the base of the Shinarump and at least three points on some marker bed below it are mapped with a plane table and alidade. Elevations on a marker bed are used for the determination of regional dip by solution of three-point problems. Elevations of the base of the Shinarump must be corrected for the effects of regional dip in order to show the paleotopography by contours. In areas over which there is no appreciable change in regional strike, the dip correction is straightforward.[3] Where both strike and dip vary across an area, another procedure may be applied. This method requires numerous exposures of marker bed around the area. The base of the Shinarump is mapped as well as a marker bed below the Shinarump. A structure contour map of the marker horizon is next prepared. Allowing the highest structure contour to serve as a hinge (the line of no correction), to each surveyed elevation point on the base of the Shinarump is added that figure (dip correction) which is the difference between the elevation of the hinge and that of the structural contour on the marker bed immediately below that point of the Shinarump. Then, using the dip corrected elevations of plane table points on the base of the Shinarump, the Shinarump paleotopography may be reconstructed by contouring. The trend of the trough or low indicated by the contours is projected from the rim outcrop and the validity of the projection is tested by drilling.

Drilling Patterns

Exploration of a Shinarump channel should begin with a row (fence) of holes a short distance behind the outcrop and across the projected trend to determine the channel axis by an alignment of the lowest channel point on the rim with the lowest point in a drill hole. Single holes, spaced no wider than the width of the channel, are then drilled on the axis projection. Immediately after completion of each hole, the basal Shinarump contact elevation is corrected for dip and the inferred contours are extended for locating succeeding drill holes.

If the last single hole on a projected axis finds the contact at a much higher corrected elevation than predicted from the extended contours, it may have been drilled either on a flank near a change in channel trend or on a rise in the channel floor from a local scour. The uncertainty of the interpretation is resolved by drilling a fence half-way between the last two holes at right angles to the last known channel trend. If the results of any of the fences are inconclusive, they are extended on either end, or additional holes are drilled between the primary holes. Wherever the interpretation of subsurface data is questionable, fences should be drilled in preference to single holes.

In channels where ore most frequently occurs in troughs, the distance between single holes should not exceed the maximum size, known from others in the area, of anticipated orebodies. In channels where ore occurs predominantly on flanks, it is necessary to test those areas between fences with additional holes after the channel is delineated.

REFERENCES

1. Miller, L. J., *Uranium Ore controls of the Happy Jack deposit, White Canyon, San Juan County, Utah,* US Atomic Energy Comm., RME-33 (1953).
2. Mitcham, T. W. and Evensen, C. G., *Uranium ore guides, Monument Valley district, Arizona,* Econ. Geol., 50: 170–176 (1955).
3. Nevin, C. M., *Principles of structural geology,* John Wiley and Sons, Inc., New York (1949).

Instrumental Developments in the Prospecting, Mining and Chemical Processing of Nuclear Materials

By H. Bisby, E. Franklin, and D. Taylor,* UK

The development of special instruments for nuclear measurements has been the responsibility of the Electronics Division at the Atomic Energy Research Establishment, Harwell, since the project came into being in 1946. The present paper describes some of the novel instruments development by this team in the past few years, and deals specifically with instruments required in connection with the prospecting, mining and chemical processing of fissionable material, in particular, uranium.

RADIOMETRIC PROSPECTING INSTRUMENTS

Most radiometric prospecting instruments comprise the same basic constituents. The radiation detector is nearly always a Geiger counter, or a scintillation counter, each of which produces electrical impulses at a rate dependent upon the radiation intensity. The size of these impulses depends upon the supply voltage and, also, in the case of the scintillation counter, upon the energy of the incident radiation. These impulses are fed into a trigger circuit, which, for each counter pulse, produces a pulse of much greater energy, the latter pulses being constant in size, shape and duration irrespectively of the size or form of the initial counter pulses. A counting-rate meter circuit then converts this train of constant size pulses into a steady current of magnitude proportional to their mean rate of occurrence and this is displayed on a meter.

In the United Kingdom designs of radiometric prospecting instruments have been based, to a very large extent, on the use of a special type of Geiger counter, known as the "halogen-quenched type", which is characterised by extreme ruggedness and almost infinite life. These counters have been described in a paper by Franklin and Loosemore.[1]

Cold-cathode trigger valves, or more recently transistors have generally been chosen in preference to hot-cathode valves for use in the trigger and ratemeter circuits. The latter are much less economical of battery power, owing to the heating required for cathodes, and also the fact that, in general, at least one valve in the circuit operates with appreciable standing anode current. In addition, under the arduous conditions of use in the field, cold-cathode valves have tended to prove more reliable, and it seems likely that transistors also will show an advantage in this direction, though there has been insufficient field experience so far to confirm this.

Figure 1(*a*) shows a typical cold-cathode trigger and ratemeter circuit, as used with a Geiger counter. The anode-cathode gap of the valve normally passes no current, but a small "keep-alive" current of 10^{-8} to 10^{-6} amp, depending on the type of valve, is fed via the resistor R_3 into the trigger-electrode-cathode gap. This current, which is insufficient to cause breakdown of the main anode-cathode gap, serves the dual purpose of keeping the trigger electrode at the correct voltage for breakdown and of maintaining sufficient ionisation in the valve so that breakdown can occur rapidly on the application of a triggering pulse. When the Geiger counter tube produces a pulse, it causes a momentary increase in this "keep-alive" current, which causes, in turn, breakdown of the anode-cathode gap of the valve. Capacitor C_2 then discharges through the valve until the voltage across it has fallen to a value equal to the valve's extinction voltage. Since the resistor R_2 is chosen so that the current which can flow through it is too small to maintain the anode-cathode discharge, the latter then extinguishes and C_2 commences to recharge through R_2 to its original voltage. The cathode potential of the valve therefore rises rapidly when the discharge is triggered and falls exponentially towards earth with a time constant C_2R_2 after extinction of the discharge. At some point during the fall, the potential across the trigger-electrode-cathode gap reaches the breakdown value and the "keep-alive" current is re-established. Resistor R_4 is inserted to limit the peak discharge current through the valve, and the combination R_1 and C_1 serve to limit the discharge pulses of the Geiger counter.

It has been seen that each pulse from the Geiger counter causes a discharge of capacitor C_2 from the H.T. supply voltage down to the extinction voltage of the valve, and the recharge current is taken from the power supply. The mean current taken from the power supply is therefore proportional to the Geiger tube mean counting rate, and a measure of the latter is therefore obtained by inserting a current meter M in series with the power supply. Capacitor C_3 and resistor R_5 serve to integrate the pulsating current over a sufficient long period to reduce the meter fluctuations to an acceptable value.

* Atomic Energy Research Establishment, Harwell, England.

Figure 1(b) shows a similar circuit in which the radiation detector is a scintillation counter and the cold-cathode valve is a four electrode valve. In this valve, the "keep alive" current flows between the trigger electrode, 3, and the auxiliary cathode, 2, the main discharge, when triggered being between anode, 4, and cathode 1. Triggering is accomplished by means of either a negative pulse on the auxiliary cathode, or a positive pulse on the trigger electrode.

These simple circuits have been used successfully in both portable, transportable and installed equipment. One equipment designed for carborne survey work consists merely of the circuit of Fig. 1(b) together with a power-supply circuit and a 0–50 microamp chart recorder which is inserted in series with meter M. The use of the high-sensitivity spark recorder, which is described below, avoids the necessity of having current amplifiers.

Figure 2 shows the circuit of Fig. 1(a) rearranged for gamma-ray logging of deep boreholes. The use of the cold-cathode valve makes it possible to employ a single-core cable from the underground probe to the surface instrument, without the use of a filament battery in the probe, or complicated supply circuits. The trigger and ratemeter circuits of the underground probe are as in Fig. 1, except that the meter is coupled into the circuit in a different manner. The current pulses of the trigger valve V_1 are passed via the transformer T_1 and the cable into a "diode pump" circuit consisting of capacitor C_5 and rectifiers $MR1$ and $MR2$, and the meter measures the rectified current. The same cable conductors carry current down to the probe at the voltage required by the GM tube, the latter obtaining its supply via the pulse transformer secondary winding. Capacitor C_4 de-couples the transformer pulses from the GM tube. Current passing from the GM-tube supply through resistor R_5 operates the voltage stabilising valve V_2 and supplies the necessary operating voltage (135 volts) for the trigger valve V_1.

The circuits of Fig. 1 are attractive for portable instruments, because they can be made extremely economical of battery power. It has been adopted as more or less standard practice, on the grounds of robustness, that no meters of greater sensitivity than 0–50 microamperes shall be used in portable or transportable equipment. However, by the use of current transformers, it has been found possible to design a satisfactory multi-range trigger and ratemeter circuit taking a total power of only 2 milliwatts. Since this is comparable with the power taken by the Geiger counter itself there is little to be gained in overall power economy by the use of junction-type transistors. Point-type transistors show a distinct disadvantage in this direction (10–15 milliwatts), if the circuit is designed to operate up to the temperature limit of 60°C which is usually specified, owing to the much higher value of standing collector current with zero emitter current.

However, transistor circuits are gradually replacing cold-cathode trigger valve circuits in most

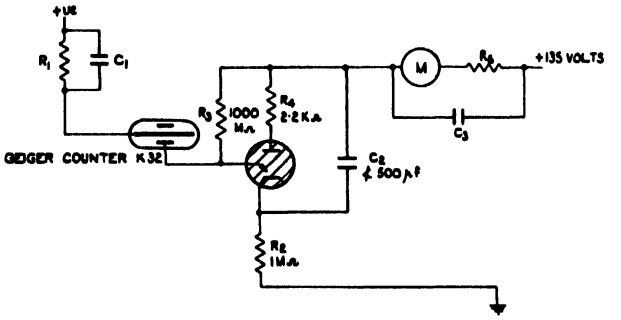


Figure 1a. A cold-cathode trigger circuit used with a Geiger counter

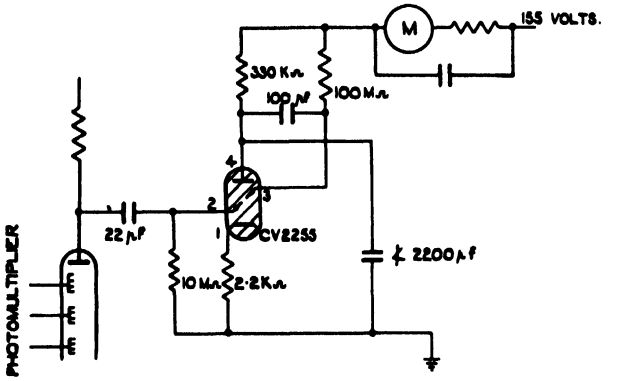


Figure 1b. A cold-cathode valve trigger circuit used with a scintillation counter

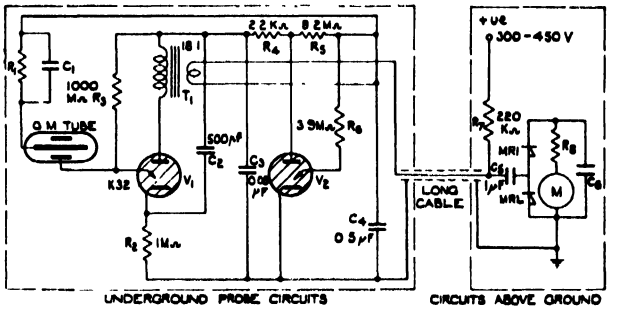


Figure 2. A cold-cathode valve trigger and ratemeter circuit arranged for borehole logging

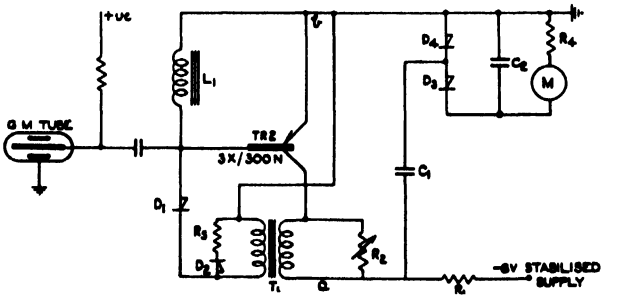


Figure 3. Junction transistor trigger and ratemeter circuit

applications, because they give greater flexibility of design. The most serious limitations of the cold-cathode valve arise from the measures which have to be taken to ensure correct and permanent extinction of the anode-cathode discharge when the capacitor potential has fallen to the extinction value. If continuous discharge or multiple discharges are to be avoided, each of the components C_2 and R_2 (see

Fig. 1(*a*)) must have a certain minimum value, depending on the type of valve. This sets a limit to the mean current which can be drawn from the valve, and also to the maximum frequency at which it can be triggered, the latter being the more serious limitation. If a fairly linear calibration of meter reading against Geiger counter counting-rate is required, no existing types of valve which are suitable for use in instruments of this type can be operated at mean frequencies higher than about 300 counts per second.

In the heavily conducting state, the collector-base voltage drop is much greater in the point type transistor than in the junction type, and for stable operation in trigger and ratemeter circuits, the former type therefore requires a higher operating voltage. This, together with the much greater power consumption already mentioned makes the point type much less attractive than the junction-type.

Figure 3 shows a typical junction transistor trigger and ratemeter circuit triggered from a Geiger counter. The trigger circuit is essentially a grounded emitter amplifier with positive feedback via the transformer from collector to base of the transistor. The base and emitter of the transistor are short-circuited, as far as dc conditions are concerned by the choke L_1, in order to keep the standing collector current down to the minimum. In between pulses, therefore, the emitter-base current is zero and the collector current is only a few microamperes. When a sufficiently large negative pulse is applied to the base from the Geiger counter, the emitter begins to take current, therefore turning on the collector and taking the base heavily negative. Practically the whole of the voltage between points *a* and *b* then appears across the collector winding of the transformer, and the emitter current is determined by this voltage, the transformer ratio and the emitter-base circuit resistance. The transistor remains in this turned-on state until the transforming magnetising current has risen to a value equal to the emitter current multiplied by the transistor current gain. No further increase beyond this is possible and so the transformer voltage collapses, the emitter current ceases and the transistor turns off.

By suitable circuit design, it is possible to ensure that well before the transistor turns off, the potential between points *a* and *b* has fallen to a small fraction of the 6 volts of the stabilised supply. The amplitude of waveform at *a* is therefore well defined, and the "diode pump" circuit consisting of capacitor C_1, and rectifiers D_3 and D_4 give a rectified current in the meter M which is proportional to the rate at which triggering occurs and also to the value of C_1. Rectifier D_2 prevents self oscillation of the circuit due to "ringing" of the transformer and the silicon rectifier D_1 stabilises the triggering sensitivity of the circuit by providing a non-linear resistance in the feed-back loop which does not vary seriously with temperature.

This basic circuit is being used in many types of equipment including borehole logging instruments. In the latter case where a Geiger counter is used, the underground probe becomes very simple since the trigger circuit can be kept above ground. The probe contains merely a Geiger counter with its discharge-limiting capacitor and resistor, a pulse transformer to match the counter into the cable and a condenser to decouple the pulse circuits from the GM-tube power supply. A single concentric cable is used as in Fig. 2.

Permanent records can again be obtained without further power amplification by using a 0–50 microampere spark recorder.

A part of the specification of prospecting equipment for general use is that it shall operate satisfactorily over the temperature range −20°C to + 60°C. The circuit of Fig. 3 shows some change of triggering sensitivity over this range but this is not sufficient to give trouble in Geiger-counter instruments. However, in scintillation-counter instruments, where high stability of triggering sensitivity is essential, it has been found necessary to stabilise the sensitivity of the trigger circuit itself at a low value by the application of a positive bias voltage of about 1.5 volts to the base of the transistor and to recover the high overall sensitivity by means of a two-stage transformer coupled transistor amplifier between the photomultiplier and the trigger circuit.

Transistors are also finding application in the power supplies of instruments of the type discussed above. Figure 4 shows a typical power supply circuit for a portable instrument.

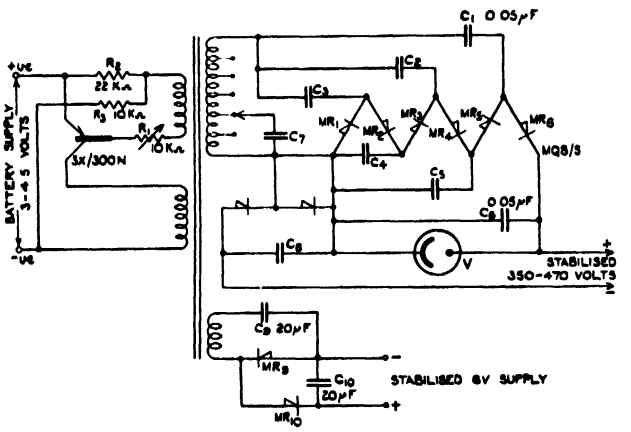


Figure 4. Junction transistor oscillator power supply

It has not been found satisfactory to use ink recorders in transportable equipment. Two types of electrical recording have generally been used. One uses Teledeltos facsimile paper and the pen to which a potential of about 300 volts is applied is a wire contact which touches the paper. In the other type, a heat-sensitive paper is used, and the marking is applied by a series of electrical sparks passed between the earthed pen and a strip of metal under the paper, which is pulsed from an ordinary motor-car ignition coil and contact breaker. The latter type has the great advantage that the pen doesn't touch the paper, and therefore sensitive meter movements can be used. This avoids the necessity for current

amplification. When using the former type of recorder, current amplification has been obtained using a magnetic amplifier, or an arc discharge valve.

CHEMICAL PLANT INSTRUMENTS

One of the significant developments during post-war years in chemical plants with industrial-scale production has been the changeover from batch treatment to continuous-flow techniques. This has also been the case in the atomic energy field.

For the process instrument engineer, continuous-flow schemes have brought their problems. It has now become essential to provide contemporary monitor information of the various process conditions, to assure control of the process and the maintenance of product quality. This contemporary requirement has led to a great deal of ingenuity in the procurement of a representative "up to the minute" sample of the product stream for analysis; experience has shown that the success of a process monitor rests or falls on this one consideration alone. The established techniques remain for recording the physical conditions of temperature, pressure, volume, etc., however the monitoring of these is becoming secondary to that of monitoring product quality, from which information, direct control may be exercised. This fact in itself has introduced new analytical techniques with instruments which have erstwhile been considered the tools of the laboratory analyst and which are now being incorporated into process plants. The continuity of analysis, now demanded to a finite degree of consistency and for 24 hours each day, has hastened the development of reliable and long-lived devices, yet this requirement forever still poses the dilemma as to what limits of complexity of instrumentation can be reached before reliability begins to suffer. Furthermore, the realization of continuous-flow schemes holds out to the process engineers the challenge of automatic control from the monitoring instrumentation.

Automatic control is particularly attractive for plants which today are processing radioactive materials on an industrial scale, because of the implied reduced health hazard to operators; however, as yet, developments in the United Kingdom Atomic Energy projects are far short of this, although the "monitor for record" stage is developing into "monitor for control" and even "monitor for automatic control".

Consider now in more detail, the arrangement for a continuous-flow monitor, which is: (1) to obtain a representative sample from the product stream; (2) to prepare this sample for analysis; (3) to perform the analysis; (4) to produce output information from the analysis which is contemporary; (5) to continuously operate with reliability and incorporate self standardization; and (6) to provide a fault-condition alarm.

On sample taking there appears to be no general principles which can be adopted; the means employed are specific to a particular product process method and analysis, though all are designed to give reliability within stated limits of desired accuracy of monitoring. It does not necessarily follow that continuous-flow monitoring implies continuous-flow sampling, quite often static sampling may reduce the complexities involved. In the atomic energy projects, the product is invariably radioactive, a notable exception is heavy water, and this introduces special techniques. Where alpha-beta-activities are the only product characteristics available, direct sampling by the use of probes remote from the main bulk of equipment is adopted. For gamma and neutron fluxes, more indirect methods can be used.

Sample preparation ranges from chemical treatment, as a prelude for analysis by absorptiometry, spectrometry, polarometry, to making the sample conform to a fixed geometry for radioactive assay. The type of preparation is often the main consideration in the choice of flowing or static sampling.

Analysis now involves quite a large range of instruments such as mass spectrometers, infra-red spectrometers, absorptiometers, polarometers, etc., which have been engineered to be suitably robust for plant-operating conditions and for some applications these are competent rivals to radioactive assay by their development to high-order sensitivity. The choice between radioactive assay and more conventional analysis is influenced by the degree of instrument complexity, and therefore unreliability, and the time lag introduced by sample preparation on the one hand and statistical accuracy on the other.

Standardization is a very necessary procedure. By its use, instrumental errors arising from supply, component, and temperature variations may be automatically compensated. In many cases, however, periodic standardization is a possibility. This could readily be done by the maintenance engineer whose regular visits to the monitor are part of plant-operational routine. In this connection the use of existing process personnel may be most valuable in reducing the complexity of instrumentation. This serves to emphasise the fact that the process instrument should be considered as a part of the integral

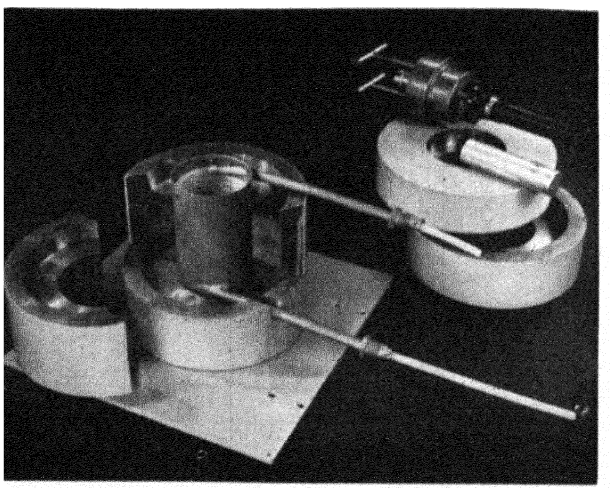


Figure 5. Beta-gamma monitor type 1278A

plant installation, since the value of a process instrument is often judged by its ease of co-ordination with plant routine.

Some typical examples of developments in process instrumentation in the UK AEA which follow, support the philosophy and basic principles already discussed and particularly illustrate the way in which special techniques have been evolved for the solution of specific problems.

A beta-gamma monitor of a liquid process stream may be quoted which uses the ideal, but often the impracticable optimum, of representative sampling by using 100% of the process flow. The process flow is small and Fig. 5 shows how the liquor is made to flow upwards through a small-bore polyvinyl tube wound as a helically coil round a Geiger-Müller counter. By this means the coil contains a constant volume of sample with a fixed geometry to the counter and calibration by liquors of known activity is made possible. By the insertion, manually, of a cylindrical absorber in the annual gap between counter and coil, discrimination against the beta-activity is obtained.

A second example[2] shows the technique of direct sampling for alpha-assay of a process stream in which the sampling device presents the liquid sample with fixed geometry to a scintillation detector and at the same time permits some measure of discrimination against gamma radiations from the process stream. Automatic self-standardization is incorporated in the system. Figure 6 shows the rotating metal drum which dips deeply into the process stream and carries on its surface a thin layer of the alpha-active liquor to a position which is in close proximity to the zinc sulphide screen of the scintillation-counter system. In this way an accurate definition of source/detector geometry is maintained. Further, the speed of rotation of the drum is sufficient to ensure that the liquor layer thickness at a point beneath the detector is greater than the range of alpha particles in liquor, so that variations of layer thickness due to unpredictable changes in surface tension, viscosity, etc., are rendered unimportant. The zinc sulphide screen is viewed by a photomultiplier through a six-inch light-guide. This, combined with the screening introduced by the drum, minimises the effect of beta-gamma radiations on the photomultiplier response.

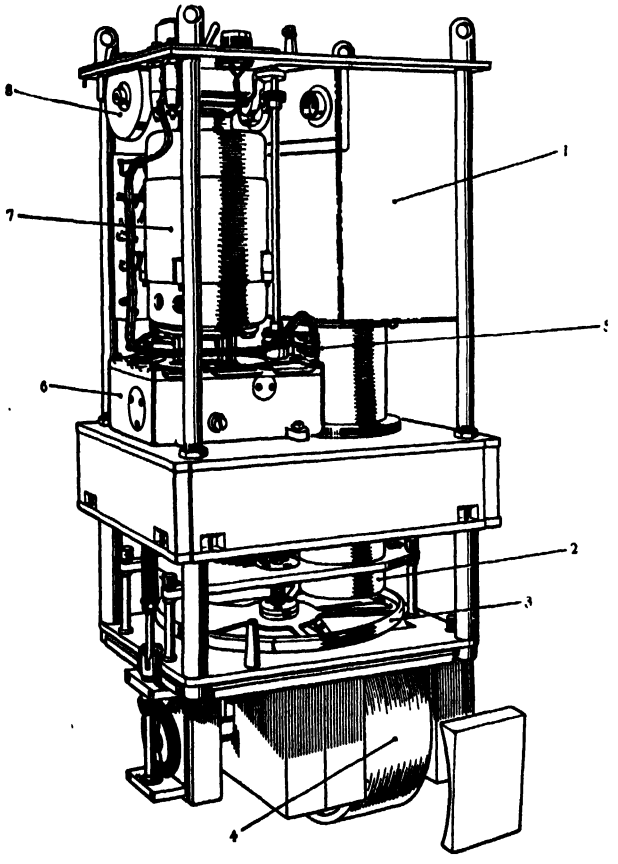


Figure 6. Scintillation alpha counter for liquid samples

With such an infinitely deep source, the alpha-particle energies reaching the scintillation screen range from zero to a maximum, corresponding to surface emission, and this introduces some difficulty in defining and maintaining an operating point on the voltage discrimination characteristic of the photomultiplier output. This is overcome, and standardization also introduced, by taking the ratio of count rate observed from the sample with that from a simulated deep alpha-active "standard" source. This source is mounted on a disc which rotates round a vertical axis and is interposed between the liquid sample and zinc sulphide screen. By cutting away segments of this disc, the screen is alternatively subjected to alpha radiations from sample and standard source, and by suitable in phase switching of the detector outputs into separate counting channels, the count rates measured can be applied directly to a potentiometric recorder to give a ratio which is substantially independent of the detector system voltage output characteristic.

The last sampling technique is subject to failure if the liquor film is affected by the presence of non-wetting agents in the process stream, in one specific process this was more than a possibility and a new technique was developed. The process is one in which the alpha-active material is being exchanged by a continuous process from an aqueous to a solvent "phase", so that the bulk of the activity, by a factor 104:1, is being taken up in the solvent. A check on the exchange efficiency can be made by monitoring the alpha activity remaining in the aqueous effluent. The dipping or surface viewing techniques may be rendered ineffectual unless separation, to 1 part in 10^6, of the less dense solvent from the aqueous solution is carried out. Although some monitor time lag could be tolerated, it would be most undesirable for this to be as long as was implied by conventional settling tank storage and Fig. 7 shows the design of a separator which was both efficient and provided a small hold-up time lag. The full aqueous flow is caused to perform a series of vertical and lateral movements, as a thin stream, by the disposition of baffles in the separator tank. This technique provides

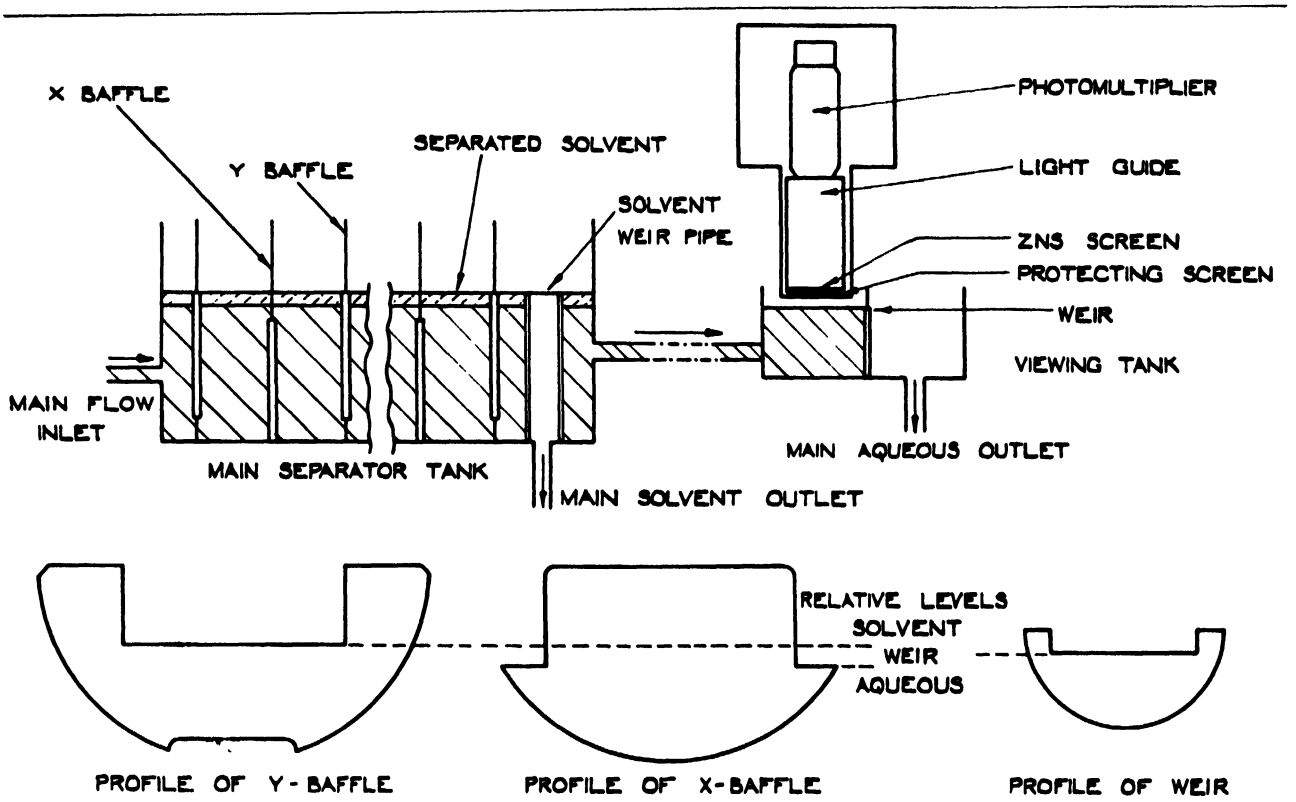


Figure 7. Sketch layout of main separator and viewing tanks

a long flow path in which the solvent droplets have opportunity to coalesce and the repeated upward motion of the stream induces these to the upper layers of the compartments. The surface viewing tank is fed from the main separator by an underwater pipe.

The final instrument to be described and which is demonstrated on the UK AEA Exhibit in the Palais de Nations shows a development in the following respects: (1) automatic multi-point monitoring of continuous flow systems using a single instrument; (2) automatic chemical preparation of samples for analysis; and (3) the use of an ultra-violet absorptiometer for the analysis. This instrument, although designed for uranium analysis of process streams from an ion-exchange plant, has much wider applications of its inherent mechanisms to routine chemical analyses. The Automatic Uranium Analyser will, in the first instance, provide "monitor for manual control" information, but again it has a potentiality for automatic control.

The ion-exchange column process for the concentration of uranium liquor, after leaching from the naturally occurring minerals, employs a 3-column

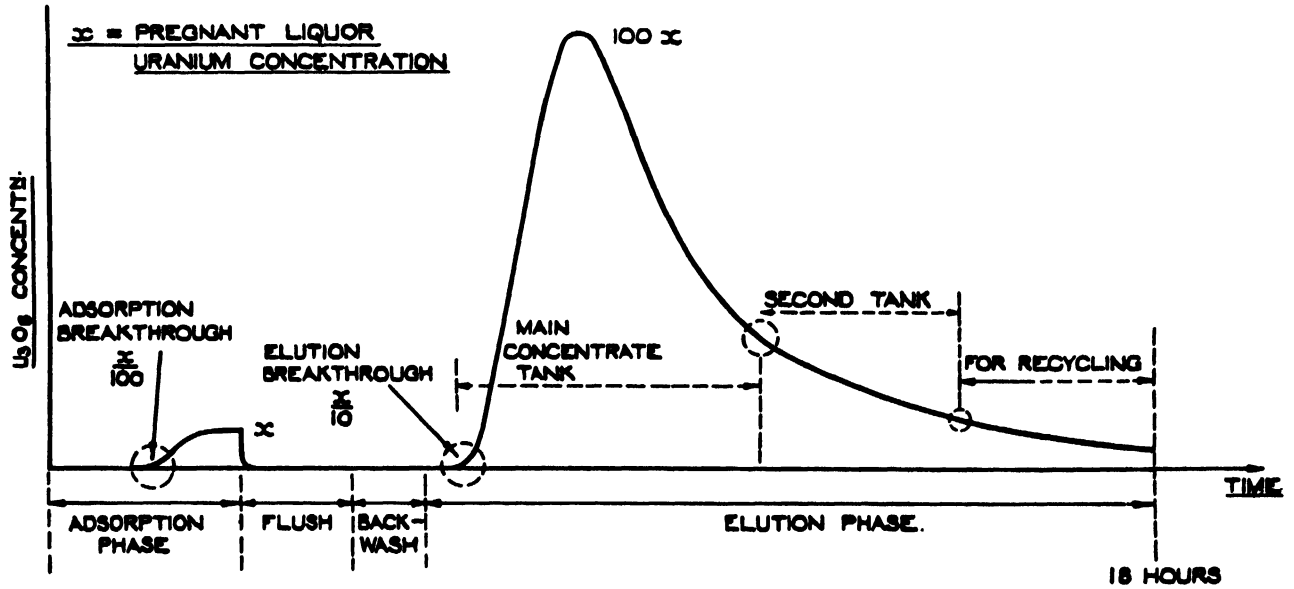


Figure 8. Automatic uranium analyser, uranium output characteristic from ion-exchange column

unit and standard column-operating techniques. Vital control information is necessary on break-through of the ion-exchange zone during absorption and elution and further, if the peak of concentration obtained on eluting, as illustrated in Fig. 8, is to be conserved, information also on when the column output reaches specific concentration of uranium, dictating the diversion of this output into separate storage tanks.

The type of analysis to be used, a physical method rather than alpha-particle assay, is dictated by several factors of which the main is the low break-through concentration (5 milligram/litre). The choice of a colourimetric ammonium thiocyanate method was made after due consideration by the G.M. Laboratory, South Africa. This technique involves a measurement of the percentage transmission of the colour complex produced when proportionate volumes of uranium bearing liquor sample and titrated ammonium thiocyanate are mixed together. An ultraviolet absorptiometer is used (at 3650 Å). Interference from the ferric thiocyanate complex is eliminated by reduction of the ferric to ferrous ions with acidified stannous chloride and hydrogen gas. Blank errors due to other impurities are constant to within ± 1% and may be allowed for.[3,4]

The technique for sample preparation is shown diagrammatrically in Fig. 9. A static representative sample is taken automatically in cyclic order from each of the three main columns and the pregnant liquor storage tank. Volume measurement is done using capacity-change detectors, situated at preset heights on the cylindrical mixing vessel, operating electromagnetic diaphragm valves on the input lines. Each sample in turn is put through an automatic

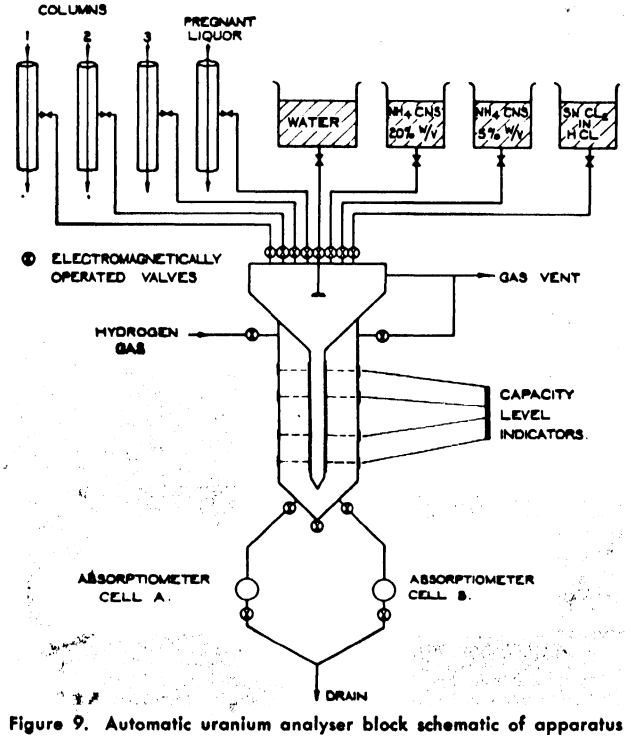


Figure 9. Automatic uranium analyser block schematic of apparatus

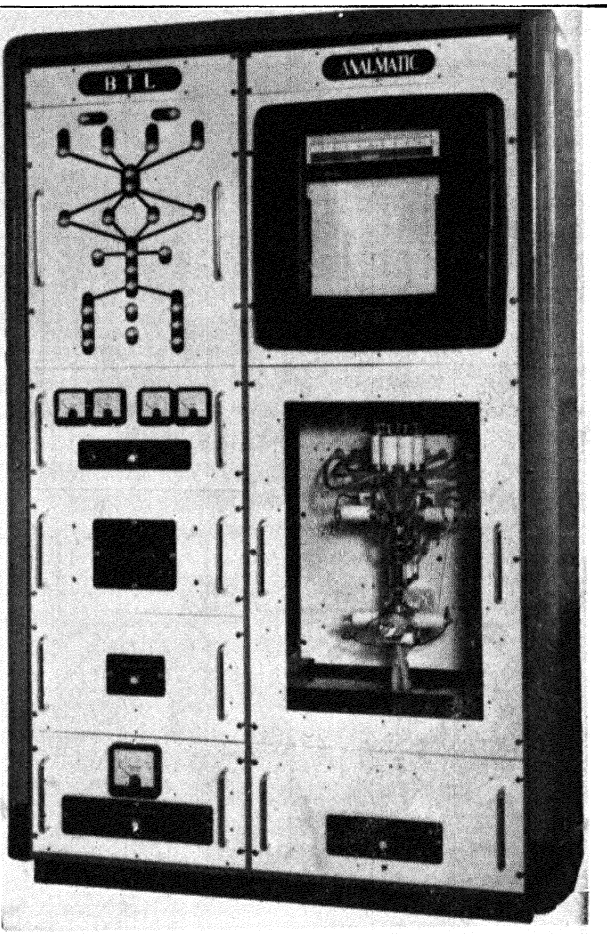


Figure 10. Uranium analyser — complete apparatus

sequence of events which are either capacity-relay or time controlled. These events include the addition of ammonium thiocyanate, stannous chloride in hydrochloric acid (50% w/v), mixing and reduction of Fe^{+3} to Fe^{+2} with hydrogen gas, discharge into the approximate absorptiometer cell and followed by cleansing of the liquid-handling parts.

To give the requisite sensitivity for low concentrations of uranium, a sample is first treated with 20% w/v NH_4CNS and to cover the greater range of concentrations, a repeat sample is treated with 5% w/v NH_4CNS.

The absorptiometer is novel in having two sample cells in addition to the "blank" cell, one being used for $\%T$ measurement of original sample complex whilst the second is being washed through in readiness to receive the repeat sample complex, and vice versa. The repeat sample is taken only if the concentration shown on the original sample is above a value at which the Beer-Lambert law becomes non-applicable. Further a sample is not taken at all if the column due for sampling is neither on absorption nor on elution.

The maximum possible interval between sampling on any one of the four positions is 28 minutes although in practice this figure will be considerably

reduced, by sampling cancellation, to 15 minutes which is thought satisfactory on a 20 to 24 hours process-time duration.

The final form of the analyser, ready for connection to plant lines and reagent stores is shown in Fig. 10. The adoption of a graphic panel to indicate the present stage in the automatic sequence is also significant to an operator reading the scales of the recorder. Porous stainless steel filters are installed in the sample lines and stainless steel trays are used to give protection against leakages.

The whole system is protected by a fault-condition alarm.

REFERENCES

1. Franklin, E. and Loosemore, W. R., *A Survey Equipment using Low-Voltage Halogen-Quenched Geiger-Müller Counters,* Proceedings I.E.E., 98 Part II, 237–247 (1951).
2. Taylor, D. and Abson, W., *Radiation Measuring Instruments for X-rays To Cosmic Rays,* Proceedings I.E.E., 98, Part II, 760–770 (1951).
3. Curran, J. E. and Beamish, F. E., *Colorimetric Determination of Uranium with Thiocyanate,* Anal. Chem., 19, 609 (1947).
4. Crouthamel, C. E. and Johnson, G. E., *Spectrophotometric Determination of Uranium by Thiocyanate Method on Aceton Medium,* Anal. Chem., 24, 1780 (1952).

Radiation Detectors with Halogen Counters for Use in Prospecting

By A Milojevic, V. Kostic and M. Petrovic,* Yugoslavia

Among the wide range of different methods and developed devices available for geological research, Geiger Müller and scintillation counters have been successful and most useful in prospecting radioactive ores. Although the scintillation detectors have a greater sensitivity and are, undoubtedly, irreplaceable particularly in scientific research work, the instruments with Geiger Müller counters still have many advantages for routine prospecting. In general, it can be considered that the instruments with Geiger Müller counters are more practical in radiometric field survey and in large scale technical service for radiation detection, where high precision is not needed and where radiation intensities remain relatively low.

Especially after the success of the type of halogen self-quenching counters, characterized by practically infinite life, devices of simple and useful design, not using conventional electronic circuits, became possible.

In the study of different instruments for radiation detection with halogen self-quenching counters, detectors were constructed, running from the low-level radiation to the highest value of radiation intensity registered by the halogen counters. The detectors were developed without using thermionic vacuum tubes, and the registration can be recorded acoustically, optically or through normal μa instruments, according to the purposes and radiation intensities. Detectors with instruments, or perhaps with acoustical or similar warning signal devices for greater radiation intensities, were developed especially for the continuous technical services of radiation survey.

In the construction of the detectors special attention was paid to some of the following conditions:

1. The detectors must be of extreme ruggedness and reliability, tropicalized, light in weight and simple in construction, handling and repairing.

2. They must have low consumption, without hot-filament valves, permitting the detector to be in operation for a long time (a couple of months) without changing the battery supply.

3. All components must be "long-life".

On the laboratory scale, three types were especially elaborated:

1. A type of detector, mainly for prospecting work, for low-level radiation intensities up to a few times the background, with acoustical registration. The design is extremely simple: halogen self-quenching counter, crystal earphones, a switch and low power batteries for the counter-operating voltage supply. The pulses of the counter lead, without any amplification, directly to the earphones.

2. Type of detector for prospecting and radiometric field survey, from low level to greater radiation intensities, having optical indication, earphones, and μa instrument indication. For the optical indication, neon-bulb indicators were used.

The pulses from the halogen counters, led through a pulse transformer, fired the neon-bulb indicator (Fig. 1).

The potential of the capacity C is held below the starting voltage of the neon-bulb indicator by adjustment of the potentiometer P. The produced pulses fire the neon bulb and discharge the capacity C, the potential falling under the extinction voltage of the neon indicator. The time constant RC is regulated to permit the deionisation of the neon bulb, keeping the potential of the capacity C below the critical value for refiring the neon indicator. The measuring range of the radiation intensities can be selected through the value of C and R, on condition that the value RC is always somewhat greater than the time of gas deionisation. The deionisation time of commercially available neon bulbs is of the order of a few hundred μsec, and can be easily measured experimentally. The corresponding value of RC determines the upper limit for the counting rates. The deflection of the microammeter is approximately linear as a function of the counting rate, the losses being negligible.

Instead of a potentiometer P, a system with a second neon bulb can be used, having the firing voltage somewhat below the neon-bulb indicator. In general, there is a large variety of possibilities, using units of neon-bulb indicators for many combinations in constructing simple devices, permitting the discrimination by the right selection of the value of capacity C, between different ranges in counting rate.[1]

3. The third type of detector is the most suitable for prospecting and radiometric survey, ranging from low level to the highest value of radiation intensities recorded by halogen self-quenching coun-

* Institute of Nuclear Sciences "Boris Kidrič", Vinča.

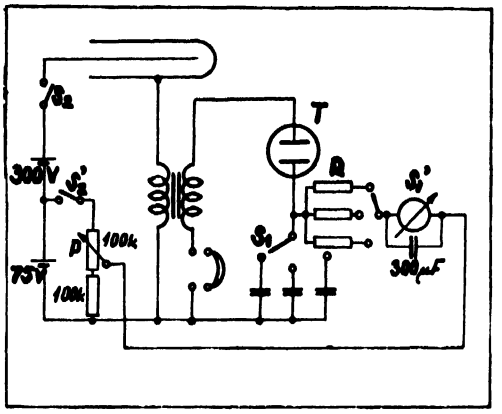


Figure 1. Detector based on halogen self-quenching counter and neon bulb indicator system. Acoustical, optical and normal μa instrument indication

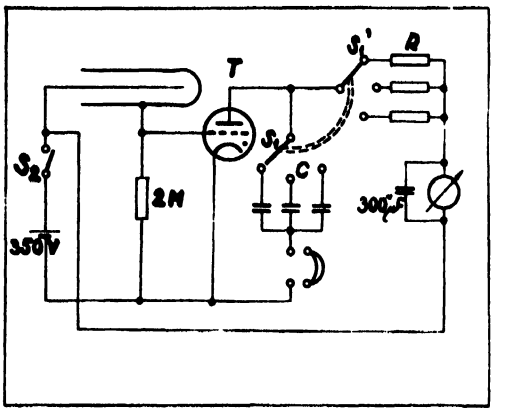


Figure 2. Detector based on halogen self-quenching counter and cold thyratron system. Acoustical, optical and μa instrument indication

ters. All mentioned systems of indication—acoustical, optical or instrumental—can be used and adapted to different purposes. This type of detector showed almost stable characteristics and gave the best results.

The electronic circuit is always a simple one: the pulses from the halogen counters activate the cathode of a cold thyratron, discharging a capacitor C (Fig. 2).

This design has several advantages: (1) the ranges of the counting rate are determined by factors similar to those for the detector of type 2, but greater radiation intensities can be recorded, the time of gas deionisation being smaller for the thyratrons than in the case of neon bulbs; and (2) once the type of thyratron is selected there is no more need for individual adjustment of each detector, as with the type using commercial neon bulbs, so that large-scale production becomes easier.

This type of detector can fully replace any similar devices based on thermionic tubes.

In all the developed types of detectors, halogen self-quenching counters with metal cathode and a working point between 300 and 350 v, were used. The output pulses, on an impedance of 2MΩ, with 50 or more volts and current intensities of some 10μa, have been largely adequate for operating crystal or normal earphones or for the firing of neon bulbs or cold thyratrons.

The cold thyratrons were laboratory made especially for detector type 3. Low power batteries, such as Eveready, were used as power supply, permitting detectors to be in steady operation for several months.

The use of halogen self-quenching counters, in combination with neon bulbs or a cold thyratron, allowed the construction of different simple devices, and their wide application can be expected.

Improvement of the sensitivity of such kinds of instruments can be achieved by developing detectors using scintillation substances in association with a photosensitive Geiger-Müller counter, instead of halogen self-quenching counters, which would yield more effective methods for routine prospecting and radiometric survey. Further improvement in electronics can be expected through further development and application of transistors, instead of ionic valves.

REFERENCES

1. Le Vine, H. D., Nucleonics 12, 62 (1954).

Instruments and Techniques for Measuring Radioactivity in the Field

By F. W. Stead,* USA

The steadily increasing demand for radioactive raw materials has stimulated the rapid development of radiation detection instruments and techniques for measuring radioactivity in the field. A large variety of instruments is now commercially available, ranging from simple Geiger-Müller counter detectors obtainable at low cost to highly precise and sensitive instruments costing many thousands of dollars. The older techniques of measurement have been refined, and newer techniques based on instruments mounted in aircraft and automobiles have been developed.

The radioactivity characteristic of uranium- and thorium-bearing materials offers a unique means of direct detection of significant concentrations of these elements. Unfortunately, even the most penetrating gamma radiation from radioactive materials is effectively absorbed by a few inches of intervening materials. Radioactivity measurements, whether at the outcrop, in drill holes, or in mine openings, will detect only those radioactive materials exposed at a surface or concealed by a small amount of other materials.

It is now commonplace that prospectors, mining engineers, and geologists carry radiation-detection instruments, both those actively engaged in the search for radioactive materials and those searching for other ores. Using sensitive radiation detectors, uranium prospectors need not be able to identify radioactive minerals nor to have more than a cursory knowledge of geology; a marked increase in radioactivity indicates where further work should be done. Many significant uranium deposits in the western United States have been discovered as the direct result of radioactivity surveys.

A detectable change in radioactivity is frequently associated with other raw materials, and it has been clearly demonstrated that radioactivity measurements are valuable in determining the extent and distribution of such materials. The use of radioactivity techniques for other than radioactive raw materials is continually expanding and may ultimately become more important than the direct application to uranium and thorium ores.

INSTRUMENTS

The principal instruments now used to prospect for radioactive raw materials are the Geiger-Müller counter and the more recently developed scintillation counter. From a relatively crude and cumbersome device,[1,2] the portable Geiger-Müller counter has been developed by the health physicists in the atomic energy program into a light-weight, rugged, and highly reliable instrument. Primarily, this instrument was developed and is used for monitoring the radiation intensities in laboratories and manufacturing plants handling high concentrations of radioisotopes. Secondarily, the instrument is widely used to prospect for uranium, and probably more portable Geiger counters are in use today than all other geophysical instruments. The portable scintillation counter, because of its greater sensitivity, is more useful than the Geiger-Müller counter in areas of low radiation intensity, particularly at or near the level of background radiation.

The Geiger-Müller counter tube is fundamentally unchanged since first developed by Geiger and Müller.[3] Excellent reviews of modern Geiger-Müller theory, technique, and application have been published by Curtiss[4] and Friedman.[5] Most counter tubes used in portable instruments have thin-wall glass or aluminum cathodes that will admit the more energetic beta radiation in addition to gamma radiation. Counter tubes with bismuth cathodes or with multiple cathode-anode construction to increase the efficiency of gamma-ray detection are used in some portable instruments.

The present-day scintillation counter is essentially a phosphor viewed by an electron-multiplier phototube. Excellent reviews of current theory and techniques have been prepared by Swank,[6] Linden,[7] and Birks.[8] Almost all portable gamma-ray scintillation instruments use thallium-activated sodium iodide crystals[9] as the phosphor. Semi-portable instruments installed in aircraft and automobiles, occasionally use large plastic phosphors[10,11] and, experimentally, large-volume liquid scintillators.[12]

The portable scintillation counter[13,14] has several advantages over the Geiger-Müller counter: (1) higher efficiency for gamma-ray detection; (2) lower relative cosmic-ray background because of the higher gamma-ray efficiency; and (3) relatively short resolving time, allowing higher counting rates without serious coincidence loss. Comparative disadvantages of the scintillation counter are: (1) present high cost and scarcity of large thallium-activated

* US Geological Survey.

sodium iodide crystals; (2) small pulse output from the photomultiplier requiring a better amplifier circuit than for the Geiger-Müller counter tube; and (3) high-voltage regulation for the photomultiplier is far more critical than regulation for Geiger-Müller counter tube. In small, lightweight portable instruments, adequate high-voltage regulation is difficult to achieve.

Ionization chambers, discussed by Victoreen[15] and Rossi and Staub,[16] are seldom used in portable instruments. Integrating chambers find their greatest use in logging of drill holes,[17] and minor use in detailed surveys of local areas. Pulse-type chambers are used in mobile laboratory installations.[18]

The amplifier circuits used in portable equipment to count the random pulses from radiation detectors are mainly counting-rate meters, and to a very limited extent, scalers. A large variety of counting-rate meters has been used, all involving pulse shaping to uniform size followed by integration into a direct current which is recorded either by a visual or a graphic meter. Initial development of a "total-intensity" rather than a pulse counting-rate meter for scintillation detectors has been completed;[13,19] as yet, insufficient development and testing of this amplifier have been done to determine its applicability in portable instruments. Scaling circuits for portable instruments have been developed from the basic scale-of-two circuit; portable scale-of-eight instruments are electronically limited to low counting-rate applications.

Most portable instruments of the counting-rate meter type are relatively stable and reliable, and do not exhibit marked variations in response because of temperature change, decrease in battery voltage, or shifting detector sensitivity. Simple direct-indicating instruments, in which a pulse is recorded as a click in earphones or as the flash of a neon bulb, are now rarely used because of their limitation to low counting rates. Semiportable instruments, where size and weight are not limiting factors, are designed to use laboratory-type amplifiers and recorders.

TECHNIQUES

Techniques for measuring radioactivity in the field can be roughly grouped as surface, subsurface, and airborne. Reviews of field techniques have been published by Johnson,[20] Wright,[21] Stead,[22] Russell,[23] and Faul.[24] Many of the present techniques of measurements were established prior to and during World War II and, since then, have been modified slightly to utilize improved instrumentation. The development and wide application of the newer techniques such as airborne and carborne surveying reflect the recent advances in radiation instrumentation, particularly the portable scintillation counter.

Essentially all field techniques are based on the detection of gamma radiation. Supplemental detection of beta radiation is useful in picking out the highly radioactive rock and mineral fragments from mineralized outcrops, and many portable Geiger counters are designed to be both beta and gamma sensitive. Because of the short range of alpha radiation, its detection has not proved to be practical in the field.

As commonly used in prospecting for uranium, field techniques of measurement are essentially qualitative. A moderate increase in radioactivity has long been considered sufficient evidence to collect samples or to file a mining claim. This is proved by the thousands of samples sent to Government testing laboratories during the last decade.

To have semi-quantitative significance, field techniques of measurement must be applied with a clear understanding of the many factors involved. Good reviews of the factors affecting the interpretation of radioactivity measurements have been published by Faul,[25] Johnson,[20] Russell,[23] and Wright.[21] These factors include the background component of measurement, the solid-angle or mass effect, the absorption and scattering of radiation by various media, radioactive equilibrium in natural materials, and natural and artificial contamination. Simple relationships can not be established among these factors, and considerable experience is usually necessary for proper interpretation of field measurements.

Valid semi-quantitative interpretation of field measurements requires that the radiation detection instruments should be standardized and calibrated at all times. Standardization involves testing the instrument response with a moderately strong radioactive standard. To be satisfactory for extended use, a portable field instrument should reproduce the measurement of the standard within a stated amount, commonly 10 per cent.

Calibration in absolute units is usually based on first flight, or direct, quanta from a radium source, and is then expressed as milliroentgens per hour.[13] Theoretically, if all portable Geiger and scintillation instruments are correctly calibrated in terms of milliroentgens per hour, measurements made with different instruments should be directly comparable, provided that the spectral energy distribution of the gamma radiation measured is effectively the same as from radium. Practically, several difficulties arise in the large-scale quantitative calibration of instruments. Gamma radiation from natural sources is always much scattered so that the effective energy spectrum is greatly enriched on the low-energy end. Instruments calibrated with first-flight quanta from a point radium source will not show the correct intensity in milliroentgens per hour when the measured radiation is partly scattered. The gross readings will still be comparable from counter to counter of the same energy response, but units such as milliroentgens per hour are essentially meaningless in field practice, where many instruments of different types may be used. Specific difficulties in calibration are: (1) the different response of the Geiger and scintillation counters to various energy levels of gamma radiation, particularly as the scintillation counter has good sensitivity for very low energies

and the Geiger counter does not; (2) the variation in electron-multiplier phototubes, and the consequent variation in sensitivity of scintillation counters; and (3) the non-linearity of the amplifier circuits in portable instruments at high counting rates.

Other units, such as counts per minute or multiples of background radiation, have been used to calibrate instrument response. In most cases, these units indicate a standardization of response, not a calibration in the absolute sense. Measurements expressed in counts per minute are meaningless except for instruments of essentially identical response characteristics and for similar geometry of measurement. Multiples of background are useful for distinguishing significant variations of radioactivity within a limited area, but, as the regional background radiation varies from area to area, multiples of background are not directly comparable unless expressed in absolute units.

The most useful calibration would be in absolute units for the principal element sought, uranium. That is, the calibration would be based on measurements of the radiation intensity from materials containing a known amount of uranium oxide in equilibrium with the disintegration products. The calibration would then be expressed as per cent equivalent uranium oxide, and some individual instruments have been so calibrated. Where adequate consideration has been given to the factors affecting the interpretation of measurement, individual instruments have provided measurements of the uranium content accurate to within a few thousandths of a per cent.[22] The same difficulties in large-scale calibration arise as in the use of microroentgens per hour, and no major effort has been made to calibrate the response of portable instruments in terms of equivalent uranium, equivalent thorium, or equivalent potassium.

Almost all portable instruments now used by Government agencies are calibrated in milli- or microroentgens per hour using gamma radiation from a point radium source. Although such calibration is not entirely satisfactory for field measurements of radioactivity, it is the easiest to use and is the best compromise among other possible means of calibration. Measurements in milliroentgens per hour, made in widely separated areas with different type instruments, can be roughly correlated, particularly where the general nature of divergence in response among the instruments is known.

Because of the large variety of portable instruments now available, instruments can be selected that are statistically adequate over the anticipated range of measurement. Statistical uncertainty introduced by very low counting rates is seldom a factor of importance in present-day measurements.

Surface Techniques

Surface techniques include local surveys or spot examinations, detailed surveys, and regional surveys. The application of surface techniques, when combined with geologic appraisal and evaluation, has been generally described as reconnaissance for radioactive raw materials. Numerous reports describing procedure, techniques, and results of reconnaissance have been issued by the US Geological Survey, the US Atomic Energy Commission, and other groups.[26,27]

Local Surveys

Local surveys, also termed spot examinations or prospecting, are planned either to find localities of anomalously high radioactivity or to evaluate reported occurrences of radioactive raw materials. Such surveys are normally done on foot and are guided by rock types, mineralized zones, and mineral assemblages favorable for the occurrence of radioactive materials.

To indicate possible economic concentrations of radioactive materials, a radioactivity anomaly must show at least a several-fold increase over the local background gamma radiation. The minimum increase is frequently considered to be four-fold for measurements made with a portable Geiger counter and twenty-fold for measurements made with a scintillation counter. Multiples of the background radiation are occasionally used to define geological groupings of anomalies in an area.[28]

In evaluating an outcrop or a new mine development, a beta-gamma sensitive Geiger counter is frequently used to scan the outcrop or mine face and thus to select the most radioactive rock and mineral samples for identification and analysis. Using standardized and calibrated detection instruments such as portable scalers, the equivalent uranium oxide content of rock and mineral samples can be determined in the field within plus or minus 0.002 per cent.[22]

Detailed Surveys

Detailed surveys are made to determine accurately the distribution of radioactivity within an area ranging from a few thousand square feet to many square miles. The objectives may be specific, such as locating and evaluating radioactive ore deposits, or may be general, such as locating fissures, veins, and other structures or determining the variation of radioactivity in and among rock types. In contrast to local surveys where qualitative measurements of radioactivity with simple portable instruments are frequently sufficient, detailed surveys require semiquantitative measurements made with standardized and calibrated instruments.

Detailed surveys, accurately located in respect to topography and geology, are usually made either on a grid pattern or along widely spaced traverse lines. The measurements are shown either as point values[29] or are compiled as isoradioactivity contours.[30] As an aid in geologic mapping, detailed radioactivity surveys have proved useful in tracing fissures, sills, and dikes, particularly where such features are concealed by talus or residual soils.[31]

In general, little if any correlation can be demonstrated between small radioactive ore bodies at shallow depth and the surface distribution of radio-

activity.[32] Occasionally, a closely spaced survey may assist in guiding exploration for concealed deposits. One particular scintillation counter survey in the Black Hills of South Dakota outlined all known uranium deposits within the 10 microroentgen-per-hour contour interval, where the background radiation intensity was 7 microroentgens per hour. The 20 microroentgen contour, roughly three times the regional background radiation, outlined small areas within which additional deposits were later discovered by drilling. These deposits were as much as 60 feet below the surface. Obviously, gamma radiation from the uranium ore could not penetrate 50 or more feet of rock; uranium or some of its disintegration products must have migrated from the ore to the surface. The application of detailed radioactivity surveying to the search for concealed deposits has been demonstrated to be valuable; however, such application is restricted to a few geologic environments where migration of uranium and its disintegration products is either known or likely to occur.

Regional Surveys

Regional surveys, usually covering several thousand square miles, have been successful in locating radioactivity anomalies for more detailed investigations and in providing basic data on the surface distribution of radioactivity. Normally, such surveys are made with car-mounted scintillation counters of the continuously recording type,[13] but occasionally, light portable instruments are used on foot or horseback. The technique of using car-mounted equipment has been described by Nelson.[33] A typical regional survey of several thousand square miles, using primarily car-mounted equipment, has been reported by McKeown.[34] Quantitative differences in radioactivity equivalent to about 0.002 per cent U_3O_8 can be easily determined.[22,33] Instruments mounted in 4-wheel drive vehicles have been successfully used for cross-country traversing in relatively open terrain.

Subsurface Techniques

Subsurface techniques include gamma-ray and neutron logging of exploratory drill holes and measurement of the radon content of gases issuing from soils, springs, and drill holes. The Geiger counter is almost universally used in logging small-diameter drill holes.[35] The scintillation counter[36] and the ionization chamber[17] are widely used where the hole diameter is sufficiently large. Most logging instruments are installed in heavy-duty trucks, but lightweight portable equipment has been developed for logging shallow holes in remote locations.[13] Measurements of radon in gas samples are made with ionization chamber equipment in mobile laboratories.[18]

In exploration for radioactive raw materials, the gamma-ray log of small-diameter drill holes has provided highly valuable information.[37] Gamma-ray logs are used for: (1) correlating stratigraphic horizons; (2) preparing lithologic logs where core recovery is poor or lacking; (3) determining depth and thickness of ore-bearing horizons, and (4) estimating semi-quantitatively the thickness and grade of radioactive ores. Most of these uses have long been well established in the petroleum industry.[38] The significant advances in the application of gamma-ray logging to exploration for radioactive materials are: (1) the direct quantitative assaying of ore in place;[22,35] and (2) the preparation of subsurface isoradioactivity contour maps to guide further exploration at depth.[39] The gamma-ray logging technique has been applied semi-quantitatively in exploration for uranium, thorium, uraniferous phosphates, and potash.

The development of highly sensitive scintillation logging instruments[36,13] offers promise both by distinguishing among uranium, thorium, and potassium by spectrometry in the drill hole, and of improving the lithologic interpretation of the gamma-ray log. One continuing difficulty in semi-quantitative application of gamma-ray logs is the wide range of radioactivity found, from less than 0.001 per cent to more than 10.0 per cent U_3O_8. Thus far, with one particular detector or in a single logging operation, it has not been possible to obtain satisfactory measurements over this wide range of radioactivity.

Neutron logging techniques have been widely applied in the petroleum industry[40] but have not been specifically developed to assist in exploration for radioactive materials. Measurement of the natural neutron flux in drill holes[22] and neutron-gamma and neutron-neutron logging have been considered. As a practical exploration technique, neutron logging does not now seem promising as a direct aid in finding uranium and thorium ores. Combined gamma-ray and neutron logging has proved useful in estimating the grade and thickness of potash salts, and in distinguishing anhydrous from hydrous potash salts.[22]

Migration of radon, a radioactive inert gas, offers a possible long-range method of detecting concealed radioactive materials.[41] Ridland[2] noted a surface concentration of radon in a fissure 60 feet above intersection with a pitchblende vein. In gamma-ray logging of exploratory drill holes on the Colorado Plateau, small sharp anomalies detected several hundred feet down dip from carnotite ores are presumably caused by radon migrating in ground waters along permeable channels. Radon concentration in helium-bearing natural gases is being investigated, both to determine whether abnormally high radon concentration might indicate significant localized concentrations of uranium and radon at depth, and to clarify the relationship between radon and helium.[18] Occasionally, extremely high and variable concentrations of radon are found in mine openings and in drill holes penetrating uranium ores; in rare cases as much as 1×10^{-6} curies of radon per liter (STP) has been found. No clear-cut relationship has been established between the radon concentration in mine openings and drill holes and the uranium content of the country rock. Qualitatively, a high concentration of radon is suggestive of possibly significant uranium concentration nearby, but no quantitative con-

clusions can be drawn based on the radon content of gas samples from drill holes and mine openings.

Airborne Techniques

The development and application of airborne techniques in the search for radioactive raw materials have been made mainly during the last five years.[42,43,44] Since the first systematic airborne radioactivity survey of an area of 1600 square miles was published in 1950, numerous surveys throughout the United States have been made by Government agencies and private companies.[45,46]

Instruments used in airborne surveying must be sufficiently sensitive to measure unambiguously a small change in radioactivity at an air distance governed by aircraft safety. Large volume thallium-activated sodium iodide crystals[44] or plastic scintillators[10] are almost universally used as the radiation detector. High-efficiency Geiger-Müller counter tubes having a multiple-plate cathode structure are occasionally used as the detector. Most instruments are counting-rate meters of the continuously recording type, and are specifically designed for installation in aircraft. In addition to the radiation detection instruments, equipment in multi-engine aircraft usually includes instruments for accurately locating the position of the aircraft in respect to ground.[42,44]

Helicopters, light single-engine aircraft, and long-range multi-engine aircraft have been used for airborne surveys, dependent on the objectives of the particular survey and on the location of the area in respect to the operating base. In regard to objectives, airborne techniques are analogous to surface techniques in that local, detailed, and regional surveys can be distinguished. In selecting an aircraft, it is essential that the aircraft have sufficient range to spend a significant proportion of the total flying time over the area to be surveyed.

The spacing of flight lines for airborne surveys is governed largely by the problems involved. The width of the zone from which anomalous radioactivity can be detected is approximately twice the distance of the aircraft above the ground. As a detector at the 500-foot flight level covers a swath approximately 1000 feet wide, a flight line spacing of one mile results in about twenty per cent of the area being actually surveyed. For detailed surveys the flight level and spacing of flight lines are decreased but for regional surveys the spacing may be increased to give only partial coverage.

The absorption and scattering of gamma radiation at considerable air distances from a natural radioactive source place an effective upper limit on the flight level of airborne surveys. The initial radiation intensity from a natural point source of radiation is decreased to about one one-thousandth at an air distance of 500 feet. Few airborne surveys are made at air distances greater than 500–600 feet, and most surveys are made at air distances of less than 200 feet. Although light, portable instruments can be used effectively in aircraft flying very close to the ground, the rapid attenuation of gamma radiation with distance from the source requires relatively large instruments of the highest possible sensitivity to obtain satisfactory measurements at higher flight levels.

Quantitative interpretation of airborne survey data is not necessary for most applications. The sought-for target is a radioactivity anomaly, a sharp local increase in radiation intensity. The results of the majority of airborne radioactivity surveys are reported without semi-quantitative or quantitative distinction among the anomalies. Anomalies simply indicate localities of more-than-average radioactivity where there is a greater probability of the occurrence of uranium and thorium deposits.

The possibility of quantitative interpretation of airborne survey data has been extensively investigated.[42,43,44,47,48,49] Based on experimental measurements at various air distances over known broad sources of radiation and over a simulated outcrop of uranium ore, considerable progress has been made in establishing the interpretation of airborne radioactivitiy measurements in terms of the equivalent uranium content of the source.[50,51] The radiation from broad sources of semi-infinite extent, such as a sedimentary horizon, can be satisfactorily estimated to within a few thousandths of a per cent equivalent uranium; for example, airborne radioactivity measurements at 500 feet above a shale were interpreted at 1.7×10^{-3} per cent equivalent uranium, and laboratory analyses of representative shale samples showed $1\text{–}2 \times 10^{-3}$ per cent equivalent uranium.[50]

The radiation from a naturally occurring "point" source, such as uranium ore exposed over a few thousand square feet, has proved difficult to interpret in terms of the probable equivalent uranium content and the area of exposure. No simple means of distinguishing between a small outcrop of high-grade ore and a large area of slightly abnormal radioactivity has as yet been developed.[42,44] It is probable that current research on the scattering and absorption of gamma radiation in two media, air and the source proper, will improve the interpretation of airborne survey data.[51]

1. Local Surveys

Local airborne surveys are usually made with light single-engine aircraft flown at 100 feet or less above the ground. A scintillation counting-rate meter of the non-recording type is frequently adequate.[52] An observer, preferably a geologist familiar with the area, records on a suitable base map the localities where a sharp increase in radioactivity is shown on the meter. This application is qualitative and is essentially an extension of prospecting on foot. Although random surveying of outcrops may be done, the usual method is to follow favorable outcrops whether on a cliff face—rim flying—or on a horizontal surface. The most successful application of low-level airborne surveying has been in locating additional deposits in and adjacent to uranium mining districts.

2. Detailed Surveys

Detailed airborne surveys can be made with any type of aircraft, and are applicable to areas ranging from a few square miles to a few hundred square miles. The prime requirement is that the radioactivity measurements must be accurately located in respect to the ground, either by visual recognition, by photographic methods, or by electronic navigation methods (radar, shoran, decca, etc.). The radiation detection instruments are usually of the continuously recording type, and the radioactivity measurements have been reported as spot anomalies, radioactivity profiles, or isoradioactivity contour maps.

Detailed surveys are best applied to areas that might contain extensions of known uranium deposits, or that contain rock types and structures known to be favorable for the occurrence of uranium. Surveys flown on a predetermined grid pattern have been highly successful in many parts of the western United States, and the results of many such surveys have been released as maps showing the spot location of radioactivity anomalies.[45,46]

The results of a few surveys have been released as maps showing relatively large areas of anomalous radioactivity.[53] Isoradioactivity contour maps have been compiled from detailed airborne surveys made by helicopter.[32]

Moxham, Walker, and Baumgardner[30] investigated the relationship between the anomalously high radioactivity recorded during a detailed airborne survey and the surface distribution of radioactive materials. The data both from a detailed ground radioactivity survey and from the airborne survey made at the 500-foot flight level are presented as isoradioactivity contour maps. Comparison of the two contour maps indicates that the airborne isoradioactivity contours conform closely with the ground contours, and that only minor detail is lost at the 500-foot level. Also, comparison between the two isoradioactivity contour maps and the geologic maps indicates that some crystalline rocks of various ages and types can be distinguished by their characteristic radioactivity. The radioactivity measurements made at the 500-foot level could discriminate changes equivalent to 0.001 per cent uranium, and were made far more rapidly and cheaply than were the ground measurements.

3. Regional Surveys

Regional airborne surveys covering from hundreds to thousands of square miles are usually made with multi-engine aircraft flying at a nominal 500-foot altitude and at a flight-line spacing of one-quarter of a mile.[42] Highly sensitive scintillation counting equipment is normally used. Associated instruments are carried for determining continuously the position of the radioactivity measurement in respect to ground.[44] Frequently, aeromagnetic measurements are made in conjunction with the radioactivity measurements, thus providing valuable data at little increase in cost.

Regional airborne surveys differ from detailed surveys partly in the scale of operation and partly in that the objective is to find large and new areas in which radioactive raw materials might occur. Areas for survey are selected largely on geologic inferences as to where uranium and thorium are most likely to occur, rather than being selected on direct evidence such as known favorable rock types and structures or uranium deposits in the area. Regional surveys have proved quite successful in locating new areas not previously known to contain uranium.[54,55]

Under favorable conditions, airborne surveys of large areas offer promise as a rapid and cheap method of reconnaissance geologic mapping. Many rock and residual soil units show a characteristic radioactivity that could be correlated with particular formations by limited ground examination.

Currently, the surface variation in overall radioactivity between and within rock units is being investigated as a means of delimiting large areas favorable for radioactive ores. Recent data suggest that in metamorphic and igneous terranes the uranium deposits may occur in large but localized areas where the radioactivity of the country rock is significantly different from adjacent areas of similar rock types. The target or favorable areas in crystalline rocks might be measurable in square miles rather than in terms of a local concentration of a few hundreds of square yards as is the case in sedimentary terranes. The possible application of regional airborne surveys in locating such large targets is highly attractive, particularly as the survey could be made at wide spacing of flight lines and at high flight level, possibly at the 1000-foot level.

REFERENCES

1. Rajewsky, B., *Das Geiger-Müller-Zählrohr im Dienste des Berghaues / The Geiger-Müller counter applied to mining/*, Zeitschrift für Physik 120: 627–638 (1943).
2. Ridland, G. C., *Use of the Geiger-Müller counter in the search for pitchblende-bearing veins at Great Bear Lake, Canada*, Transactions of American Institute of Mining and Metallurgical Engineers 164: 117–124 (1945).
3. Geiger, H. and Müller, W., *Das Elektronenzählrohr / The electron counter tube/*, Physikalische Zeitschrift 29: 839–841, 30: 489–493 (1928, 1929).
4. Curtiss, L. F., *The Geiger-Müller counter*, National Bureau of Standards (US) Circular 490 (1950).
5. Friedman, Herbert, *Geiger counter tubes*, Proceedings of Institute of Radio Engineers 37: 791–808 (1949).
6. Swank, Robert K., *Recent Advances in theory of Scintillation Phosphors*, Nucleonics 12, no. 3: 14–19 (1954).
7. Linden, B. B., *New Photomultipliers and operating data*, Nucleonics 12, no. 3: 20–23 (1954).
8. Birks, J. B., *Scintillation counters*, McGraw-Hill, New York, and Pergemon Press, London (1953).
9. Harshaw, J. A., Kremers, H. C., Stewart, E. C., Warburton, E. K. and Hay, J. O., *Preparation and performance of some scintillation crystals*, US Atomic Energy Commission Report NYO–1577, Technical Information Service, Oak Ridge (1952).
10. Buck, W. L. and Swank, R. K., *Preparation and performance of efficient plastic scintillators*, Nucleonics 11, no. 11: 48–52 (1953).

11. Wouters, L., *Production of plastic phosphors in quantity,* Nucleonics 12, no. 3: 26 (1954).
12. Harrison, F. B., Cowan, C. L. and Reines, F., *Large-volume liquid scintillators: Their applications,* Nucleonics 12, no. 3: 44–47 (1954).
13. Wilson, E. E., Rhoden, V. C., Vaughn, W. W. and Faul, H., *Portable scintillation counters for geologic use,* US Geological Survey Circular 353 (1954).
14. Davis, Francis J., *Scintillation counters,* in *Nuclear Geology* (edited by H. Faul), John Wiley and Sons, Inc., New York: 31–35 (1954).
15. Victoreen, J. A., *Ionization chambers,* Proceedings of Institute of Radio Engineers 37: 189–199 (1949).
16. Rossi, B. B. and Staub, H. H., *Ionization chambers and counters, Experimental techniques,* McGraw-Hill, New York (1949).
17. Swift, Gilbert, *Simultaneous gamma-ray and neutron well logging,* Geophysics 17: 387–394 (1952).
18. Faul, Henry, Gott, G. B., Manger, G. E., Mytton, J. W. and Sakakura, A. Y., *Radon and helium,* Congress Géologique International, Comptes Rendus, Section IX, 339–348 (1954).
19. LeVine, H. D., *Logarithmic DC ratemeters for scintillation counters,* Nucleonics 12, no. 2: 36–39 (1954).
20. Johnson, D. H., *Radiometric prospecting and assaying,* in *Nuclear Geology* (edited by H. Faul), John Wiley and Sons, New York: 219–241 (1954).
21. Wright, R. J., *Prospecting with a counter,* US Atomic Energy Commission RME–4028, Technical Information Service, Oak Ridge (1953).
22. Stead, F. W., *The Geological Survey's work on development of prospecting tools, instruments, and techniques,* US Geological Survey TEI–211, US Atomic Energy Commission, Technical Information Service, Oak Ridge (1952).
23. Russell, W. L. and Scherbatskoy, S. A., *The use of sensitive gamma ray detectors in prospecting,* Economic Geology 46: 427–446 (1951).
24. Faul, Henry, *Radioactivity exploration with Geiger counters,* Transactions of American Institute of Mining and Metallurgical Engineers 178: 458–478 (1948).
25. Faul, Henry, *Radioactivity methods,* Chapter X in *Exploration Geophysics* (Jakosky), Trija Publishing Co., Los Angeles, California (1949).
26. Nuclear Science Abstracts, issued twice a month by the US Atomic Energy Commission and available from the Government Printing Office (US), Washington, D. C.
27. Wallace, J. H. and Smith, H. B., *Bibliography of US Geological Survey Trace Elements and related reports to June 1, 1954,* US Geological Survey Bulletin 1019–B (1955).
28. Pierson, C. T. and Singewald, Q. D., *Results of reconnaissance for radioactive minerals in parts of the Alma District, Park County, Colorado,* US Geological Survey Circular 294 (1953).
29. Wright, R. J., *Annie Laurie Prospect, Santa Cruz County, Arizona,* US Atomic Energy Commission, RMO–677, Technical Information Service, Oak Ridge (1951).
30. Moxham, R. M., Walker, G. W. and Baumgardner, L. H., *An investigation of airborne radioactivity anomalies in the Rock Corral Area, San Bernardino County, California,* US Geological Survey Bulletin 1021–C (1955).
31. Christman, R. A., Heyman, A. M., Dellwig, L. F. and Gott, G. B., *Thorium investigations, 1950–1952, Wet Mountains, Colorado,* US Geological Survey Circular 290 (1953).
32. Rosenzweig, Abraham, *Evaluation of the Texas Company airborne radioactivity survey at Blanding, Utah,* US Atomic Energy Commission RMO–813, Technical Information Service, Oak Ridge (1952).
33. Nelson, J. M., *Prospecting for uranium with car-mounted equipment,* US Geological Survey Bulletin 988–I: 211–221 (1953).
34. McKeown, F. A., *Reconnaissance for radioactive rocks of Vermont, New Hampshire, Connecticut, Rhode Island, and Southeastern New York,* US Geological Survey TEI–67, US Atomic Energy Commission, Technical Information Service, Oak Ridge (1951).
35. Faul, Henry, *Nuclear logging of drill holes for mineral exploration and soil studies,* in *Nuclear Geology* (edited by H. Faul), John Wiley and Sons, Inc., New York: 250–255 (1954).
36. DiGiovanni, H. J., Graveson, R. T. and Yoli, A. H., *Scintillation unit for drill-hole logging,* Nucleonics 11, no. 4: 34–39 (1953).
37. Cowstock, S. S., *Progress report on gamma-ray logging activities,* US Atomic Energy Commission, RMO–904, Technical Information Service, Oak Ridge (1951).
38. Tittle, C. W., *Gamma-ray and neutron logging in the petroleum industry,* in Nuclear Geology (edited by H. Faul), John Wiley and Sons, Inc., New York: 241–250 (1954).
39. Russell, W. L., *Interpretation of neutron well logs,* American Association of Petroleum Geologists Bulletin 35: 312–341 (1952).
40. Faul, Henry, *Helium, argon, and radon,* in *Nuclear Geology* (edited by H. Faul), John Wiley and Sons, Inc., New York: 133–143 (1954).
41. Stead, F. W., *Airborne radioactivity surveying speeds uranium prospecting,* Engineering and Mining Journal 151, no. 9: 74–77 (1950).
42. Peirson, D. H. and Franklin, E., *Aerial prospecting for radioactive materials,* British Journal of Applied Physics 2: 281–291 (1951).
43. Cowper, G., *Aerial prospecting with scintillation counters,* Nucleonics 12, no. 3: 29–32 (1954).
44. See: *Geology and Mineralogy, location maps,* in *Nuclear Science Abstracts* (reference 29); also monthly releases of *Airborne anomaly location maps,* by US Atomic Energy Commission, obtainable on subscription basis from Government Printing Office (US), Washington, D. C.
45. See: *Airborne radioactivity surveys,* in *US Geological Survey Bulletin 1019–B*: (1955); also *Geology and Mineralogy, Airborne radioactivity surveys,* in *Nuclear Science Abstracts* (reference 29).
46. Cook, J. W., *An analysis of airborne surveying for surface radioactivity,* Geophysics 17: 687–706 (1952).
47. Pedersen, Ole, *Mathematical evaluation of airborne radiological survey data,* US Atomic Energy Commission NYO–4577, Technical Information Service, Oak Ridge (1954).
48. Lundberg, Hans, *Airborne radioactivity surveys,* Oil and Gas Journal 50, no. 49: 165–166 (1952).
49. Sakakura, A. Y., *Absorption and scattering of gamma radiation,* in US Geological Survey TEI–440: 242–243, US Atomic Energy Commission, Technical Information Service, Oak Ridge (1954).
50. Sakakura, A. Y., *Absorption and scattering of gamma radiation,* in US Geological Survey TEI–490: 296–297, US Atomic Energy Commission, Technical Information Service, Oak Ridge (1955).
51. Foote, R. S., *Airborne exploration for uranium,* The Mines Magazine XLIV, no. 10: 31–32 (1954).

52. Moxham, R. M., *Airborne radioactivity surveys for phosphate in Florida,* US Geological Survey Circular 230 (1954).

53. Meuschke, J. L. and Moxham, R. M., *Airborne radioactivity survey of Miller Hill area, Carbon County, Wyoming,* US Geological Survey Trace Elements Memorandum Report TEM-606 (1953).

54. Stead, F. W., Balsley, J. R., Moxham, R. M. and Reinhardt, P. W., *Airborne radioactivity survey of the Pumpkin Buttes area, Campbell and John Counties, Wyoming,* US Geological Survey Trace Elements Memorandum Report TEM-508 (1953).

Scintillation Drill-Hole Logging

By Sherman S. Comstock,* USA

In the search for uranium on the Colorado Plateau, the US Atomic Energy Commission designed[1] a scintillation drill-hole logging unit, TU–5–A, which has been utilized, with minor modifications, since 1952.

This unit includes a probe, a ratemeter, an audio power supply and a strip chart recorder (Figs. 1, 2).

SUBSURFACE UNIT—DETECTING PROBE

Probe Housing

This is a stainless steel waterproof shell, of approximately 29 inches length, and $2\frac{1}{16}$ inches outside diameter, the latter determined by that of a suitable photomultiplier tube. Mild steel shells are unsatisfactory because they tend to become magnetized.

A gain in radial sensitivity over head-in sensitivity of 4 to 1 is achieved by a solid stainless steel nose 3 inches long at the end of the probe. A single conductor double armoured cable 1000 to 1600 feet long connects the probe to the surface unit.

Detector

The detector is a hermetically sealed, thallium activated, sodium iodide crystal, $1\frac{1}{8}$ by $1\frac{1}{2}$ in., packed with an MgO reflector. The crystal is optically coupled to an RCA 6199 photomultiplier using black plastic to exclude light. The effect of magnetic fields is reduced by a mu-metal shield over the tube.

Amplifier

Impulses from the photomultiplier tube are fed to an amplifier which supplies pulses of adequate voltage to a ratemeter adjusted for a minimum detectable energy level of 30 kev.

B-Voltage Supply

A B-voltage supply provides 200 volts to the amplifier stages from a primary source of 60 volts at 400 cycles.

High-Voltage Supply

A regulated supply of 1000 volts from a primary source of 60 volts at 400 cycles is provided for the dynodes of the photomultiplier tube.

Filament Supply

Tube heaters are in series and supplied by a transformer output of 31.6 volts from an input of 60 volts at 400 cycles.

SURFACE UNIT

Ratemeter

Signals pass from the cable, through an impedance matching and frequency discriminating unit, to a diode pulse clipper which cuts off the overshoot pulse formed by the impedance matching transformer. Following the clipping circuit, pulses are fed to a voltage amplifier with a step control of the grid bias, which allows a selection of pulse sizes to be fed to the amplifier and serves the purpose of a pulse-height discriminator.

The voltage amplifier is followed by a conventional univibrator, adjusted to trip at 0.75 volts. "Dead time" is about 40 microseconds; this is the limiting factor in measuring linearly counting rates in excess of 10,000 counts per second. A univibrator feeds an integrating circuit through a cathode follower stage. Time constants in the integration circuit are controlled by varying the value of the integrating resistor.

Figure 1. Scintillation drill-hole logging unit

* US Atomic Energy Commission.

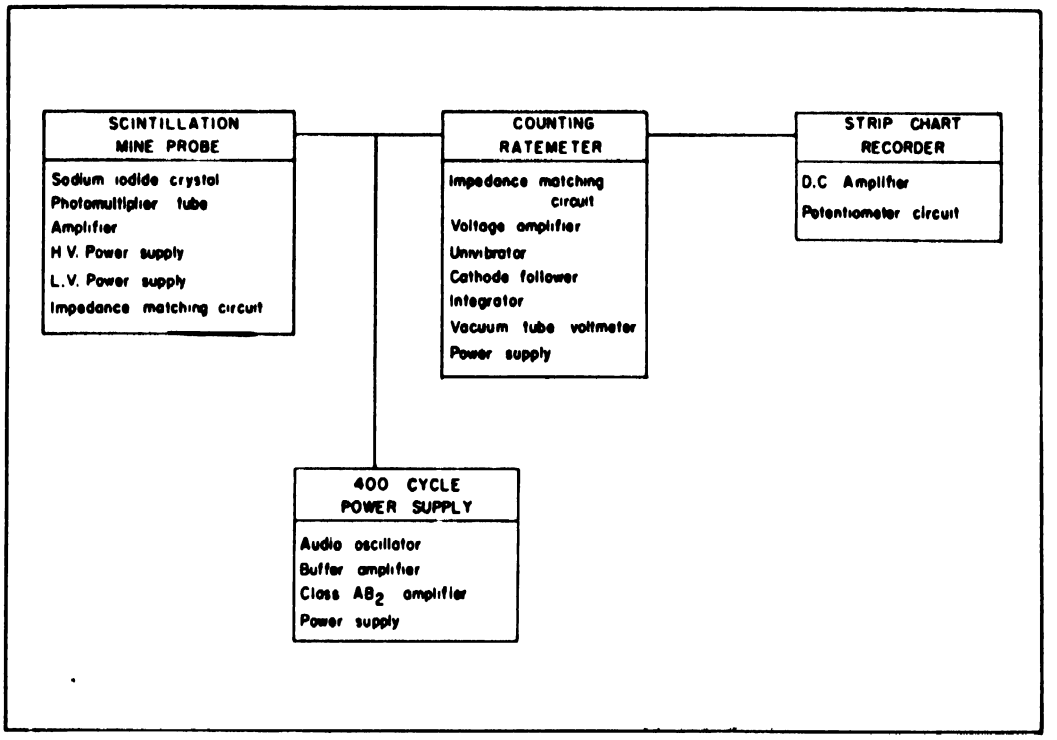


Figure 2. Block diagram of NYOO-type scintillation logging unit

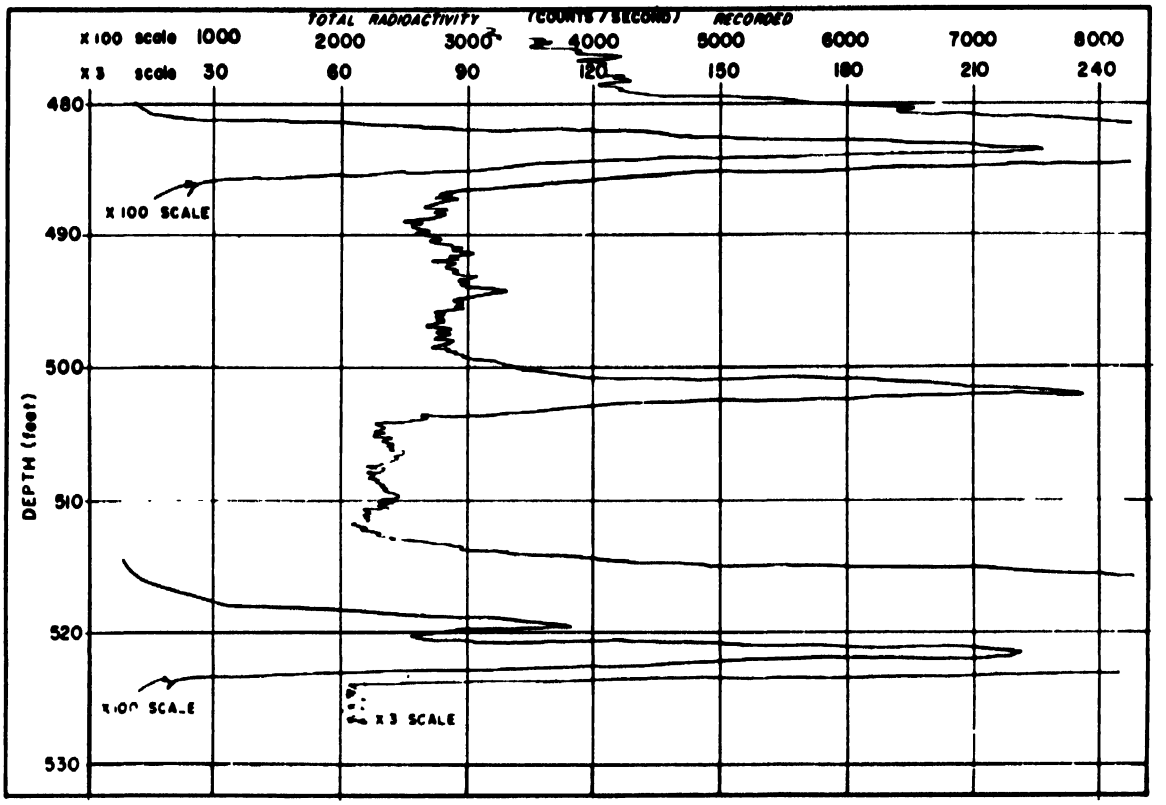


Figure 3. Gamma-ray log of ore zone

Voltage from the integrating circuit is fed to a stable vacuum tube voltmeter designed to provide 10 millivolts across a voltage dropping resistor. This provides drive to a 10-millivolt potentiometer type recorder.

Full scale ranges of 10, 30, 100, 300, 1000, 3000 and 10,000 counts per second are provided. Time constants are ½, 1, 2, 4, 8, and 16 seconds for logging at rates from 5 to 60 feet per minute.

400 Cycle Power Supply

Twelve watts of 400 cycle power are provided from an audio oscillator, buffer and a class AB_2 output stage for the probe power supply.

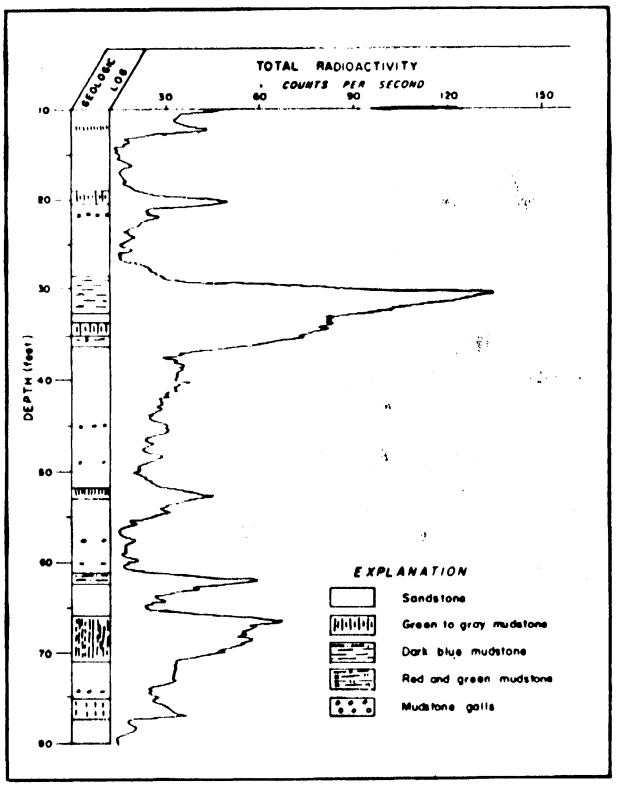


Figure 4. Lithologic interpretation with gamma-ray log

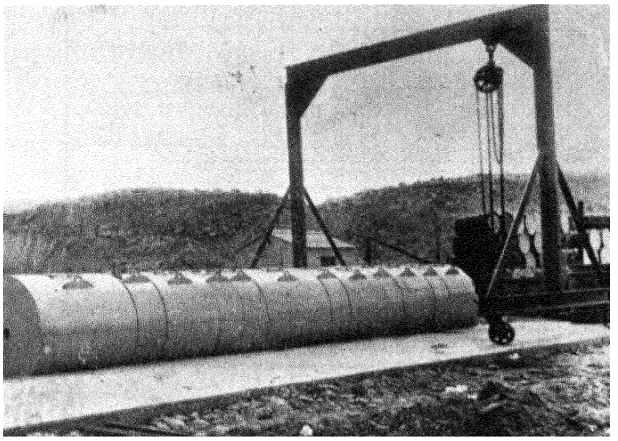


Figure 5. Assay calibration test hole

MECHANICAL EQUIPMENT

A three kva 120/240-volt 60 cycle generator mounted at the front of the vehicle and driven by a power takeoff from the vehicle transmission is the source of primary power (Fig. 1). Vehicle engine speed is controlled by a governor and either a mechanical or electrical throttle adjustment. By more recent modification, the generator is mounted inside the vehicle directly over the transmission.

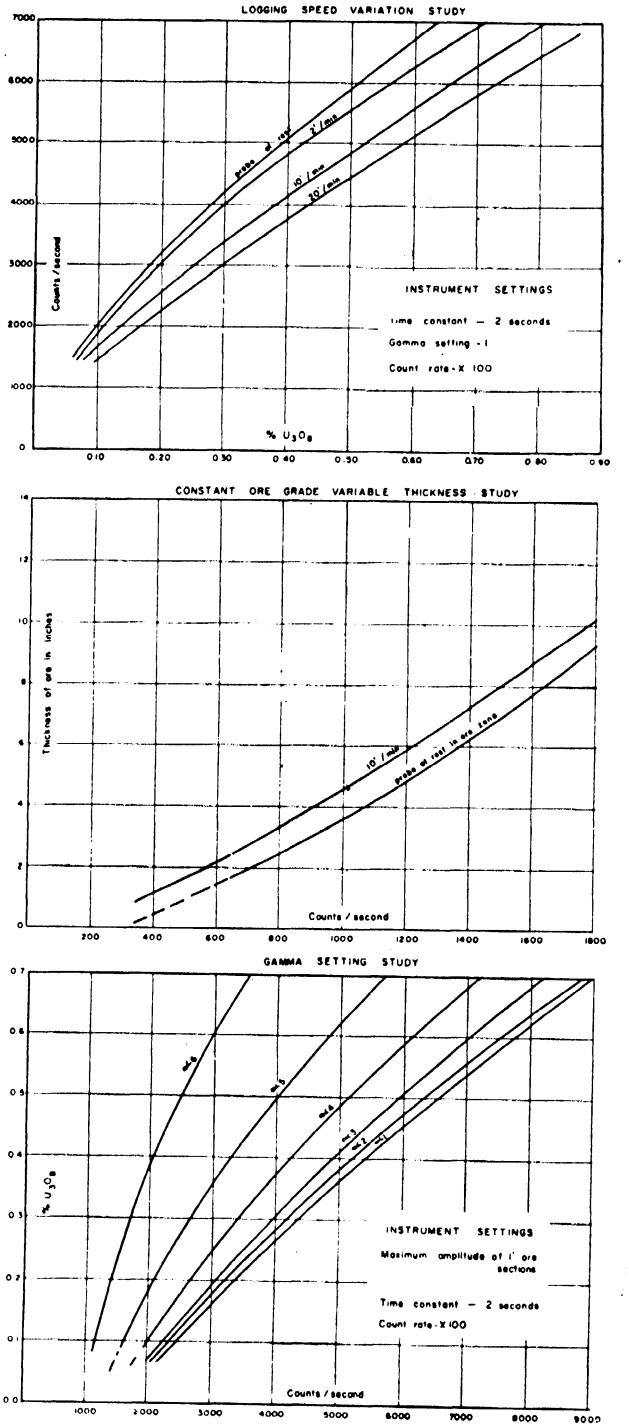


Figure 6. Performance characteristics for TU-5-A logging unit (data from horizontal test hole)

The steel cable is wound on a winch driven by a dc motor which will lift the probe at speeds up to about 65 feet per minute. Servomechanisms drive the odometer and recorder chart drive. The transmitting servomechanism is driven by a measuring wheel.

An underload switch cuts off the winch power when the probe contacts the bottom of the hole or an obstruction, and an overload switch performs the same function when the probe is stuck while raising. These safety switches may be bypassed by a remote control switching unit if desired.

APPLICATION

Objectives in the utilization of gamma ray logs are: to obtain geologic data and to define, for ore reserve calculations, mineralization in terms of thickness and grade.

The extent to which geology may be interpreted from a gamma ray log (Fig. 3) must be determined anew for each area by careful comparison of the core and the gamma ray log of the same hole. Study of core reveals the thickness of sandstone, presence of gray, red and brown mudstone, mudstone flakes in sandstone and similar features which are of aid in exploration drilling. From a gamma ray record, a generalized lithologic log may be constructed in drilling areas where core recovery is poor or where no coring is done (Fig. 4). Isoradioactivity maps, correlation of intraformational units, construction of stratigraphic sections and panel diagrams, structure contour maps, isopach and mudstone-sandstone ratio maps are being used in exploratory drilling, and data for their preparation may be interpreted from radioactivity logs. In specific search for ore bodies, it is essential to know the relative assay of an ore horizon penetrated in order to immediately locate an offset drill hole. Such information, in terms of equivalent per cent of U_3O_8 may be had immediately by a properly calibrated instrument.

Calibration for assay purposes is achieved by use of a standard horizontal test hole which consists of circular sections 36 inches in diameter and 1 foot, 2 feet and 3 feet in length (Fig. 5). Sections are filled with crushed mineralized rock of known U_3O_8 content, or barren sand. Sections can be interchanged by the use of a hoist (Fig. 5).

Figure 6 illustrates the performance characteristics of the TU–5–A logging unit which are fundamental in radiometric log assaying. For a given grade of ore, the count rate is proportional to thickness of ore up to 3 feet.

It is concluded that scintillation drill-hole logging has developed into a practical technique for accurately recording variations in the intensity of radioactivity and should be utilized in exploration for radioactive substances.

REFERENCE

1. DiGiovanni, H. J., Graveson, R. T. and Yoli, A. H., *Scintillation unit for drill-hole logging,* Nucleonics, vol. 11; p. 34–39 (1953).

Air Survey Applied to the Search for Radioactive Minerals in Brazil

By D. A. MacFadyen and Silvio V. Guedes,* Brazil

In this paper, the organization, techniques and results of such surveys are presented. The peculiar features and conditions of the use of aeroscintillometric and aeromagnetometric techniques in prospecting for uranium and thorium in Brazil, are discussed.

INTRODUCTION

Experience has made Brazil exceedingly sensitive to the importance of raw materials in energy production. It is therefore not surprising that, from the very outset of planning for the industrial application of atomic energy, the establishment of uranium and thorium reserves has been a primary concern.

During the past three years, an increasingly active programme of explorations has not only kept the atomic raw materials picture in proper focus, but has demonstrated the probability that Brazil will become a supplier, as well as a user, of radioactive minerals for power production.

In a country of great size, where air transport has reduced the accessibility problem to such a notable extent, it was only natural that airborne radiation detection methods should be applied almost from the start of organized explorations. While the air operation cannot be dissociated from ground work, there is no question that the decisive factor in the subsequent discovery of a large number and variety of radioactive mineral occurrences, has been the employment of the airborne scintillation counter and of air methods generally.

Air survey, as used in the title to this paper, in fact implies the full integration of air photography; photogrammetry; photo-interpretive, field and laboratory geology; radiometry; aeromagnetics; and the whole range of operations which are a part of minerals exploration. This presentation, however, emphasizes the aspects of such integrated operations which are most characteristic of the search for uranium and thorium in Brazil, and most important to it.

BASIC ORGANIZATION OF THE RESEARCH FOR RADIOACTIVE MINERALS

The early aim of organized ground surveys was largely to evaluate and catalogue known occurrences. Out of the successful application of air methods to the discovery of new mineral sources, has evolved a more comprehensive plan and organization for a general atomic raw materials inventory. An accelerating activity which might otherwise have accumulated only loosely-related economic and technical information, clearly warranted co-ordination.

The inventory concept has well known parallels in the planning of forest, land-use and water-resources development, and in almost every form of productive activity. It implies a systematic determination of the quantity and quality of material on hand, kept up-to-date, as a basis for the planning and control of consumption and replacement.

Although many years may be required before the first inventory can be considered complete, much of its information is immediately useable. It is an effective medium for parallel evolution of both short and long-term exploitation programmes.

This paper deals with a radioactive minerals inventory in action, explaining how its basic stages are being carried out; and where procedure is particularly important, revealing why.

THE PRIMARY SEARCH FACILITY—THE AIRBORNE SCINTILLATION COUNTER

An understanding of the organization and techniques of airborne radiation detection described in this paper, demands some familiarity with the primary facility in use. In the simplest terms, this is a specially constructed continuously recording scintillation counter. The instrument incorporates control over sensitivity (the ability to filter out lower-energy radiation), control over the time constant (the ability to vary the period of integration of measurement) and a variable recording scale. The scintillations per minute caused by gamma radiation striking its detecting crystal are counted electronically.

The crystal is mounted in a cylindrical lead shield, in such a manner that an approximate 45 degree downwards cone is "viewed" by the instrument. The viewing axes of a 35-mm positioning camera and of the detector head, are parallel. Each exposure of the positioning camera is registered on a moving recording graph, synchronized with intensity measurements. Flying height above ground, measured by a radio-altimeter, is indicated to the pilot, and similarly recorded.

* PROSPEC, Levantamentos, Prospecções e Aerofotogrametria SA, Rio de Janeiro, Brasil.

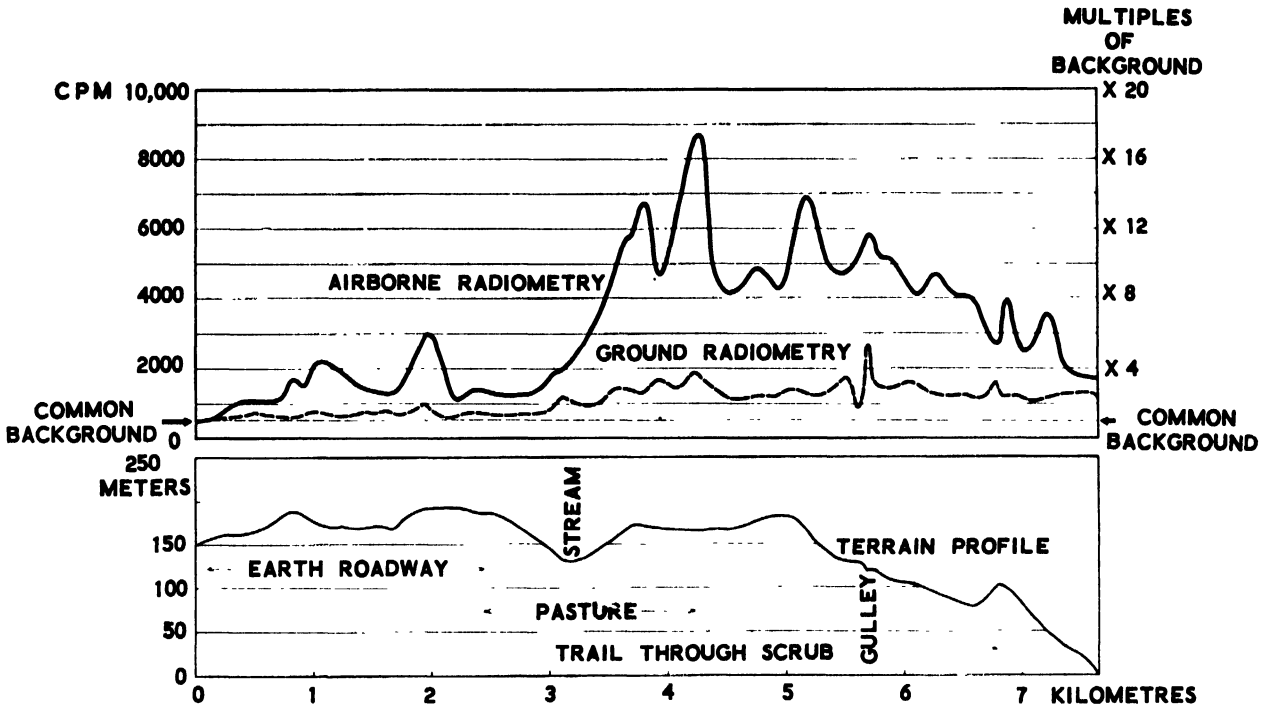


Figure 1. Comparison of airborne and ground radiometric profiles

The radiometric survey's basic product is, therefore, a continuous measurement, in "profile" form, which may be precisely related to the terrain traversed by plotting of the series of 35-mm positioning photographs in normal vertical air survey photography. Reduction of airborne records to map form is a process similar to the compilation of a contour map, by a ground surveyor. Points of equal radiation intensity, from a series of parallel traverses, are joined—the resultant "isorads" presenting radiation anomalies in the area sense.

Airborne radiation detection is usually mapped, for convenience, in cpm (recorded counts per minute) rather than in multiples of background, or roentgen units, as the latter conventions have limited significance in the practical use of air survey results.

FEATURES OF AIR SURVEY WHICH GOVERN PLANNING OF BASIC INVENTORY OPERATIONS

Brazil is a country characterized by deep weathering of surface rocks. This creates problems for the geologist, but its importance to the search for radioactive minerals will be readily seen from the following outline of features which govern the general planning of basic inventory operations.

From practical experience, it has been learned that, conducted under proper conditions of weather, with adequate equipment and procedures, airborne radiation detection is superior to ground radiometry as a means of *locating* significant sources of gamma radiation. The cumulative form of radiation measurement, possible with a moving instrument observing a large surface results in the ability to detect very-low-intensity emanations even at some distance. Quite apart from the obvious advantages of the air method over ground work, having to do with accessibility, speed, volume of information, and cost, the technical superiority of the airborne method in location, is stressed.

In Fig. 1 is depicted an actual comparison of airborne and ground scintillometric profiles, with an indication of relief and surface features. It will be seen that the ratio of anomalous signal to background, in the case of the airborne survey, is four to five times that of the ground survey. It is this much stronger anomalous indication which establishes the superiority of the air method.

The processes of integration which result in higher detectability from the air, place a limitation on discrimination, and as a result, a series of closely spaced veins or outcrops may form a single unit, in a map made from airborne radiometric profiles. Ground scintillation survey has the advantage of very high discrimination, but demands a dense network of traverses for resolution into plan. It has been found definitely advisable to carry airborne operations to their limit of discrimination, and to supplement them with integrated photo-geological and profile interpretation, before commencing the ground radiation detection usually needed even for preliminary surface sampling.

For the high detail needed in the systematic sampling of mineralized areas, and for preparation of drilling plans, ground scintillation surveys are usually required. An interesting feature of the ground scintillation profile shown in Fig. 1 is the exaggeration of intensity resulting from the solid angle effect in passing through a narrow gulley.

It is probable that the most effective means of detailed mapping of the radiation pattern within very large mineralized areas, is by low-flying heli-

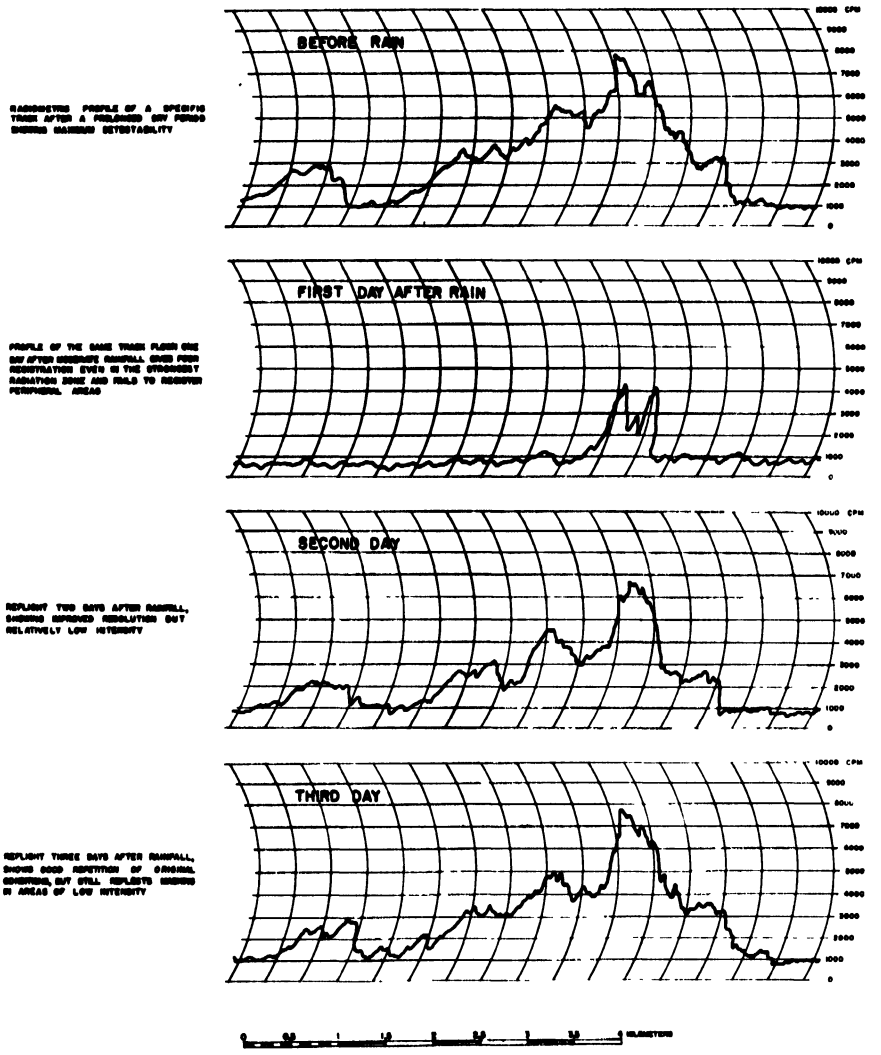


Figure 2. Effect of humidity in airborne radiometry

copter, which comprises between the advantages of "areal" detection and discrimination with proximity.

The weathering of rock and subsequent leaching tend to disseminate radioactive materials over areas much larger than the occurrences themselves, with the result that a *source* of radiation may be indicated from several kilometers away, particularly by the integrated measurements of airborne survey.

Dependent upon the type of occurrence, reconnaissance surveys, to ensure discovery, may require a highly variable density of flights. The single anomaly zone of Fig. 8 has a diameter of about 6 kilometers. The unbroken anomaly partly shown in Fig. 9 has dimensions of roughly 30 km × 8 km. Prior to execution of the project within which the Fig. 11 discovery was made, this anomaly of 30 km length, and two other major radiation zones were detected on a preliminary "character investigation" and calibration flight over a 6000 km² block. Although some definite anomalies have been encountered of less than one kilometer in detectable width, it can be assumed that systematic reconnaissance at 4 to 5 kilometers spacing will detect a high percentage of important radiation zones.

Weather is a most important factor in the conduct of radiation surveys, either airborne or ground. It is known that a good deal of radiometric survey has been attempted under conditions of atmospheric and soil humidity which virtually preclude the registration of any but the very strongest direct radiation. Figure 2 depicts a given track, flown during a prolonged dry period and repeated on the first, second and third day after a moderate rainfall. The drastic loss of registered intensity, and gradual recovery, are clearly shown.

Under the great majority of conditions, relief (proximity) effects can be kept to an insignificant level by exacting flight demands and the use of proper aircraft. Residual effects can be corrected through use of specially obtained calibration data. Figure 5, which demonstrates the effects of flying height on detectability, also indicates the extent to which uncontrolled variation in height above ground may distort the relative intensity measurements of an individual profile.

Airborne magnetometry is an established geophysical tool in structural mapping and rock-type differentiation for regional geological survey. It has

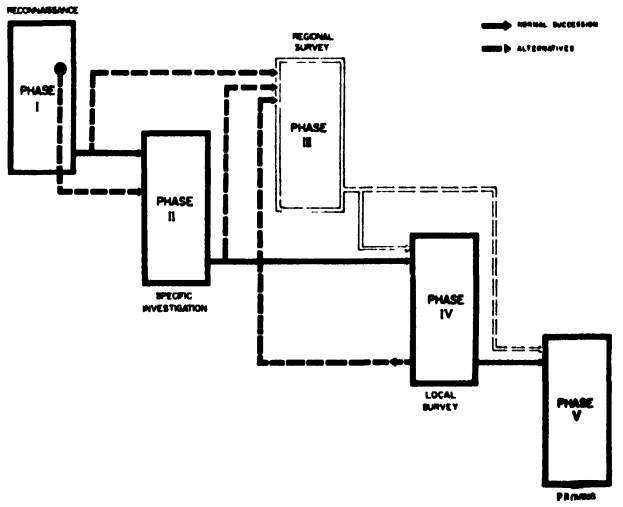


Figure 3. Atomic raw materials inventory; survey phase relations diagram

also proven of great value in locating and delineating radioactive anomalies associated with alkaline type of intrusives. In preliminary investigations, the magnetic pattern is frequently an important guide in assuring the examination of the whole geological unit under consideration.

Vertical air photographs are essential to navigation of dense flight patterns, and to location and mapping of radiation anomalies with the accuracy needed for planning of subsequent ground operations. They are equally important for field orientation of preliminary ground work. The air photographs, interpreted by competent geologists, especially when this work is integrated with aeromagnetic data, are invaluable in establishing structural ambient and continuity of formations.

THE CLASSIFICATION OF INVENTORY ACTIVITY INTO PHASES

It is a long way from the proposal to find a radioactive mineral, to the finalization of a mining plan based on proven quantities. The inventory, whether the intervening operations are conducted as a specific project within it, or are carried out with other primary objectives, must observe and record the complete sequence of events. It is evidently desirable to divide the full process into phases, and five divisions have been found to be the least complex arrangements within which virtually all ground and air activity may be both identified and differentiated.

It is in the nature of mineral explorations that their courses vary greatly, some requiring a deliberate progress through every forseeable operation, and others moving in leaps and bounds towards their conclusion. The five phases of survey described here are not all or always essential, but represent the full range of probable activity:

Phase I—Reconnaissance—An Airborne Operation

This is the broad coverage of the entire country, with priority on its favourable large geological units, by airborne radiation traverses at the widest spacing compatible with the probable detection of all major anomaly zones. Its object is to determine where to concentrate attention.

Phase II—Specific Investigation—An Airborne Operation

This is the specific coverage by systematic radiation profiles of known or suspected occurrences of radioactive minerals, where spacing of traverse will depend upon the nature of the occurrence. It aims at positive delineation as a basis for subsequent operations.

Phase III—Regional Survey—Air and Ground Operations

This is a full-fledged geological/geophysical project applicable to areas of known or probable multiple occurrence where their inter-relationship will be significant. It is a basic geological survey.

Phase IV—Local Survey—Ground and Air Operations

This is the decisive phase of exploration operations, from which the decision to "prove" or to abandon an occurrence will usually be made. It is correctly described as detailed economic geology.

Phase V—Proving—Essentially a Ground Operation

This is the concretization of all factors related to the exploitation of a promising occurrence. Development decision and procedures are its end products. It may be called a mining geological survey.

In the execution of any project, these inventory Phases are not necessarily successive, as will be evident from their description. The phase relations diagram, Table I, depicts the normal succession Phase I, II, IV and V, and the alternatives that experience indicates are most common.

Inventory operations are normally initiated in Phase I, II, or III. For example, a reconnaissance survey, over a very large area, may indicate the presence of several radiation zones. Methods have been evolved for the delineation of prominent anomalies, even during the reconnaissance flights, and the specific investigation of these may actually take place at the earliest stage of discovery. On the other hand successful Phase II investigations have been conducted as a result of bibliographic selection of favourable local situations, or following inconclusive ground indications. Comprehensive regional geological/geophysical surveys, of the Phase III type, justified by general knowledge, or with other geological aims, have resulted in a number of important discoveries.

The confirmation of a positive radiation anomaly, combined with what is known of its circumstance, results in classification of the discovery, and the decision to pursue its possibilities, usually in the "natural" succession shown diagrammatically. However, in some cases, it is found technically or economically advisable to select a different evaluation course, for example, turning back, at some point in a local, Phase IV survey, when it becomes evident that available basic geology is inadequate, or that a series of occurrences should be inter-related.

Table I. Survey Operations Diagram

SURVEY OPERATIONS		PHASE I RECONNAISSANCE	PHASE II SPECIFIC INVESTIGATION	PHASE III REGIONAL SURVEY	PHASE IV LOCAL SURVEY	PHASE V PROVING
BIBLIOGRAPHY		GEOLOGICAL MAPS GENERAL PUBLICATIONS	GEOLOGICAL MAPS PUBLICATIONS REFERENCES	FROM GENERAL GEOLOGY	APPLICABLE REFERENCES	FOR SIMILAR OCCURRENCES
PLANNING		FOR VERY LARGE AREAS	FOR LIMITED AREAS	FOR DEFINED AREAS	LIMITED AREAS SPECIFIC OBJECTIVES	ENGINEER'S PLAN
FLIGHT OPERATIONS	PHOTOGRAPHY	NOT ESSENTIAL	CONVENIENT	SMALL SCALE ± 1:40 000	MEDIUM SCALE ± 1:20 000	LARGE SCALE ± 1:10 000
	RADIOMETRY	WIDE SPACING 2 TO 5 KILOMETERS	MEDIUM SPACING 0.5 TO 2 KILOMETERS	STANDARD SPACING 500 METERS	MINIMUM EFFECTIVE PROFILE SPACING	— — —
	MAGNETOMETRY	NOT ESSENTIAL	USEFUL	USUALLY DESIREABLE	SOMETIMES DESIREABLE	— — —
GROUND OPERATIONS	GEOLOGY			RECONNAISSANCE	OBJECTIVE FROM PRELIMINARY TO DETAILED	MINING GEOLOGY
	RADIOMETRY			— — —	SYSTEMATIC	SPECIAL GEOPHYSICAL APPLICATIONS
	SURFACE SAMPLING			FOR LITHOLOGY	OBJECTIVE FROM PRELIMINARY TO EXTENSIVE	SYSTEMATIC
PHOTOGEOLOGY			USEFUL	RECONNAISSANCE BROAD STRUCTURES	DETAILED INTERPRETATION LOCAL STRUCTURES	— — —
MAPPING	GROUND CONTROL			EXISTING, SUPPLEMENTED	USUALLY TRIANGULATION	TRIANGULATION
	PLANIMETRY			BASE MAPPING 1:20 000 TO 1:50 000	— — —	— — —
	TOPOGRAPHY			— — —	RECONNAISSANCE TOPOGRAPHY 1:5000 – 5M	DETAILED 1:2000 – 2M
GEOPHYSICAL COMPILATION	PRELIMINARY	APPROXIMATE LOCATION OF PROFILES	REASONABLY ACCURATE LOCATION OF ANOMALIES	— — —	— — —	— — —
	FORMAL	— — —	— — —	ACCURATE MAPPING OF RADIOMETRY, MAGNETOMETRY	INTEGRATED AIR AND GROUND DATA	SPECIAL PURPOSE COMPILATIONS
GEOLOGICAL/GEOPHYSICAL INTERPRETATION				FULL INTEGRATION	OBJECTIVE ANALYSIS	SPECIFIC ANALYSIS
GEOLOGICAL MAPPING				"REGIONAL"	DETAILED	THREE – DIMENSIONAL
GEOLOGICAL REPORT				GENERAL	DETAILED – OBJECTIVE	MINING GEOLOGY
DRILLING	PRELIMINARY				FOR PRELIMINARY SAMPLING	— — —
	SYSTEMATIC				— — —	SYSTEMATIC
ANALYSIS	PHYSICAL				PETROGRAPHY	PETROGRAPHY, PETROLOGY SIEVING, CONCENTRATION
	CHEMICAL				ROCK AND CONCENTRATE ANALYSIS	EXTRACTION PROCESSES
ENGINEER'S REPORT		OPERATING DATA ANOMALY DESCRIPTIONS	OPERATING DESCRIPTION RECOMMENDATIONS	ECONOMIC GEOLOGY OF ANOMALOUS ZONES	ECONOMIC ASPECTS RECOMMENDATIONS	PLAN OF EXPLOITATION

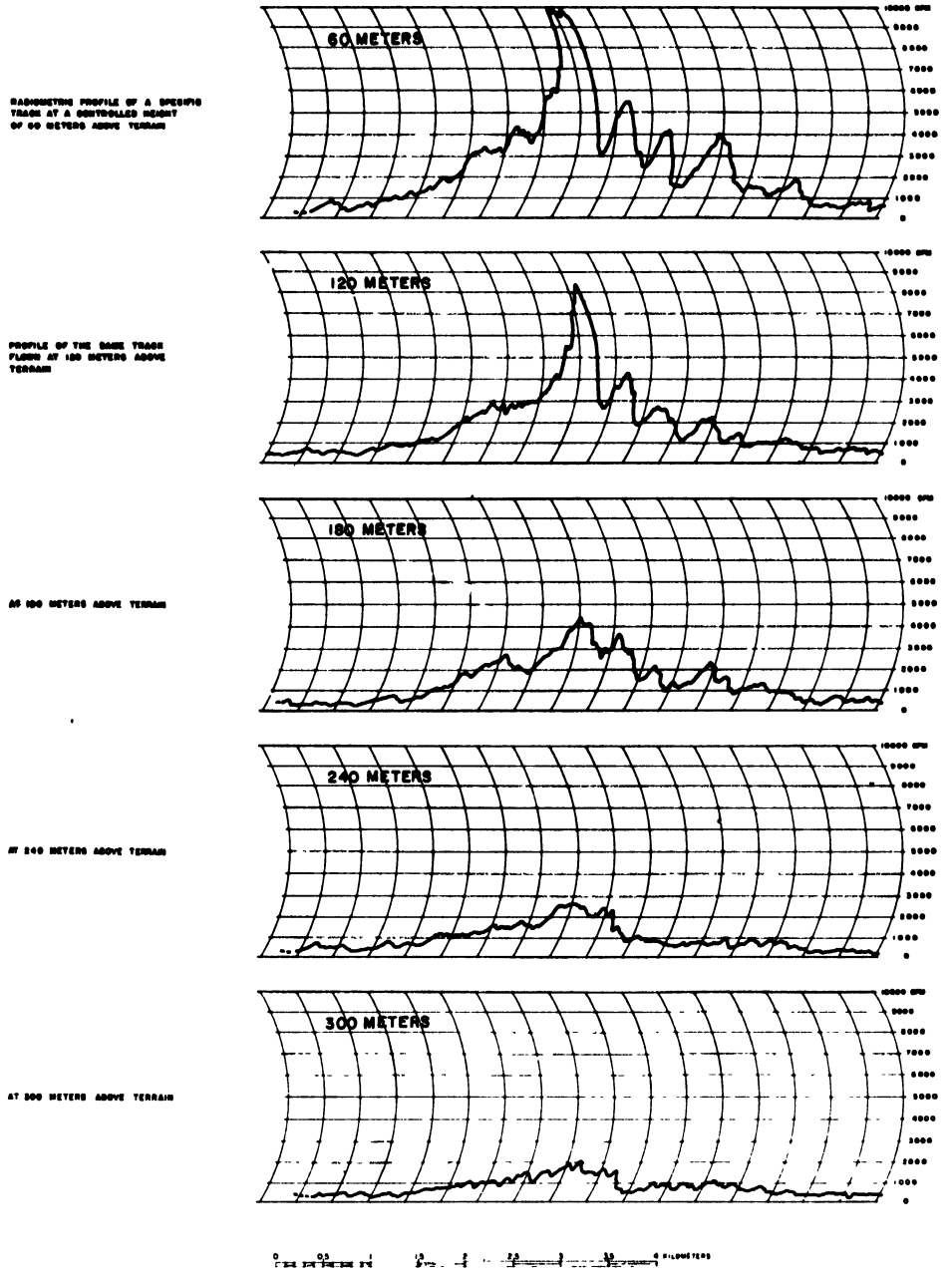


Figure 4. Effect of height in airborne radiometry

The classification of exploration projects into phases is not intended to create technical restrictions, but to act as an essential coordinating facility. The inventory sub-division allows the systematic classification of all past and current operations, with resultant clarification not only of individual situations, but of their inter-relationships. The Phases are the common denominator for a tremendous variety of circumstances and allow the generalization in planning that the long-term aspects of inventory demand.

STANDARD OPERATIONS WITHIN EACH PHASE OF EXPLORATION

The Operations Diagram, Table I, condenses the inventory's operating plan to a descriptive minimum. It depicts the principal activities under each phase, and demonstrates the high degree of continuity of certain types of operation, from one phase to another. It should be recognized that the operations shown are not considered essential, but only normal, to any Phase, and that procedures adopted vary with the situation.

Considerable stress is laid upon bibliographic studies, existing geological data having proven invaluable in the planning of successful radioactive minerals exploration, particularly of Phase II investigations. Planning emphasizes definite technical standards and proper preparation. The use of any available air photographs is another point of importance—quite apart from the direct technical advantages, most important contribution to discoveries has been made by preliminary photo analysis.

Experience has resulted in the adopting of certain specifications as to geophysical flight spacing, photographic and map scales. These specifications are not excessively rigid, their importance being in reducing the extent to which personal opinion may affect the good order and efficiency of work under the broad scheme.

Much attention is given to the necessity and means for adequate compiling of survey data. Accurate mapping, and objective reporting are of paramount importance to the interpretation of survey information, and to subsequent stages of development.

The Operations Diagram greatly oversimplifies the definition of advanced stages of inventory, intending to show the correlation of search and evaluation operations only in the most general way. The real present importance of the inventory administration, is in leading the way through the economically inconclusive stages of exploration, to the point where significance of an occurrence is evident.

SOME FUNDAMENTALS OF AIR SURVEY TECHNIQUE

As this is a rather complicated matter, closely related to the type of detecting instrument in use, no attempt will be made here, to discuss instrumental settings for optimum performance, however other basic procedures of general interest are described.

Flight Altitude and Spacing

Flight altitude must take into account aircraft limitations as well as the advantages of proximity for detection. Heights from 100 to 150 meters above terrain have been found to be feasible from a flying point of view, except under the severest conditions of relief, when 200 meters ground clearance has occasionally been resorted to. From Fig. 3 it may be seen that discrimination drops off rapidly above 200 meters, and that at higher altitudes, the detail of important low intensity radiation may be lost in background variations.

Flight spacing is related to flying height through the detector's "viewing" angle. Interpolation between profiles is minimized with a flight spacing of two-thirds of the ground clearance. Only in the most detailed surveys is this optimum attempted, flight spacings up to about 3 times ground clearance being commonly used. Lateral detection, for reconnaissance surveys with wide flight spacing, can be increased by lowering of the detecting crystal in its shielding cylinder.

Flight Direction

Planning of operations is closely linked with assumed or known geological conditions. It is evident that the Fig. 5 survey would have been considerably less effective if its flight direction were parallel to the shore line. A systematic survey of a series of parallel pegmatite dykes would logically be conducted at right angles to their trend, and later intensification flights might follow anomalous indications. It is perhaps sufficient to state that operations planning is very much a geologist's job.

The Platform

The carrying aircraft may be of almost any type, but few are truly adaptable to the wide range of flight conditions encountered. For certain local, detailed survey, a light aircraft has been found suitable, but the broader inventory type operations call for a large, stable aircraft, with long range, low speed, stability in turbulence, and high manoeuvering performance.

The importance of the carrying aircraft is realized best, indirectly, on examination of the Fig. 4 profiles, which show the effect of height on detectability of radiation. Flying is normally at 150 meters above terrain, and this height must be maintained to close tolerances, regardless of relief and aircraft attitude. Continuous 200–300 meter terrain variations are frequently met, and for systematic surveying, the heavy aircraft, with an excess of power and wide permissible speed range becomes essential.

Navigation

For surveys of the Phase III and IV types, it is necessary to have vertical photographs for flight navigation. The Phase I reconnaissance profiles may be flown on existing maps and the Phase II investigations carried out by timed runs and systematic turns, which form a network, but these latter flights will later require air photographs for accurate plotting of profiles.

Calibration

Particularly during major operations which involve the integration of a large number of flights, it is exceedingly important that detecting equipment be properly calibrated, and that for every flight a conclusive airborne test-run be carried out to confirm that instrument operation, atmospheric, and ground conditions are consistent with the standards set for the particular project. The practice of periodic repetition of flights over a positive radiation anomaly has been adopted, wherever feasible, as a supplement to the more difficult and critical routine checks of background over a test line.

Coordination with Magnetic Survey

For Phase II investigations and for regional surveys, magnetic and radiation detection may often be simultaneous. Fortunately, the flight techniques of radiometry are almost entirely compatible with magnetic requirements, which therefore place no important restriction on the principal operation. A relatively heavy aircraft is essential as a platform for the magnetometer.

RESULTS OF TYPICAL AIRBORNE RADIOMETRIC SURVEYS

It is not the purpose of this paper to present the details of photogrammetric and data reduction processes between the airborne survey and the final radiometric map. Nor does it extend into the mineralogical field beyond the limited identification of certain minerals with radiation anomalies. For each of the following survey demonstrations, a minimal

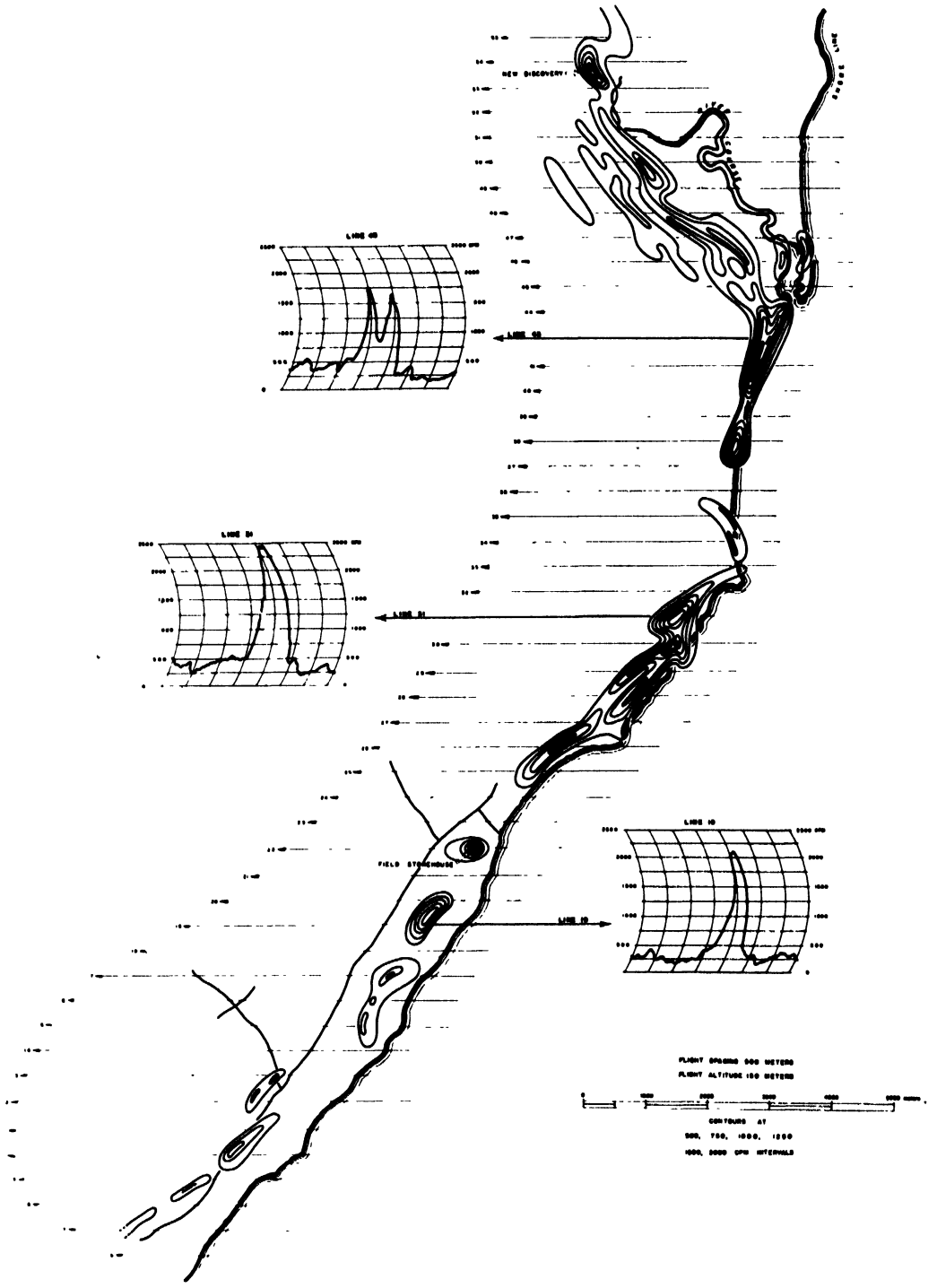


Figure 5. Airborne radiometry of coastal monazite deposits

geological background is given, with the operating data necessary for method assessment. It should be noted that radiation profile cpm scale varies in the examples that are shown.

Figure 5 is the radiometric mapping of a well known monazite-bearing coastal strip. A scintillation survey at 500 meter spacing, at right angles to deposit trends, located and outlined all known occurrences, registered intensities in surprisingly accurate proportion to the known quantities of monazite lying about one meter below surface, and effected a completely new discovery within a short distance of previous intensive ground prospecting. The survey is somewhat unique in having precisely indicated the presence of some bags of concentrate in a field storehouse.

This was an experimental Phase II Specific Investigation, flown and compiled using existing air photographs. The new discovery, in this relatively simple situation, passed rapidly through both Phases IV and V, adding importantly to established reserves of the area.

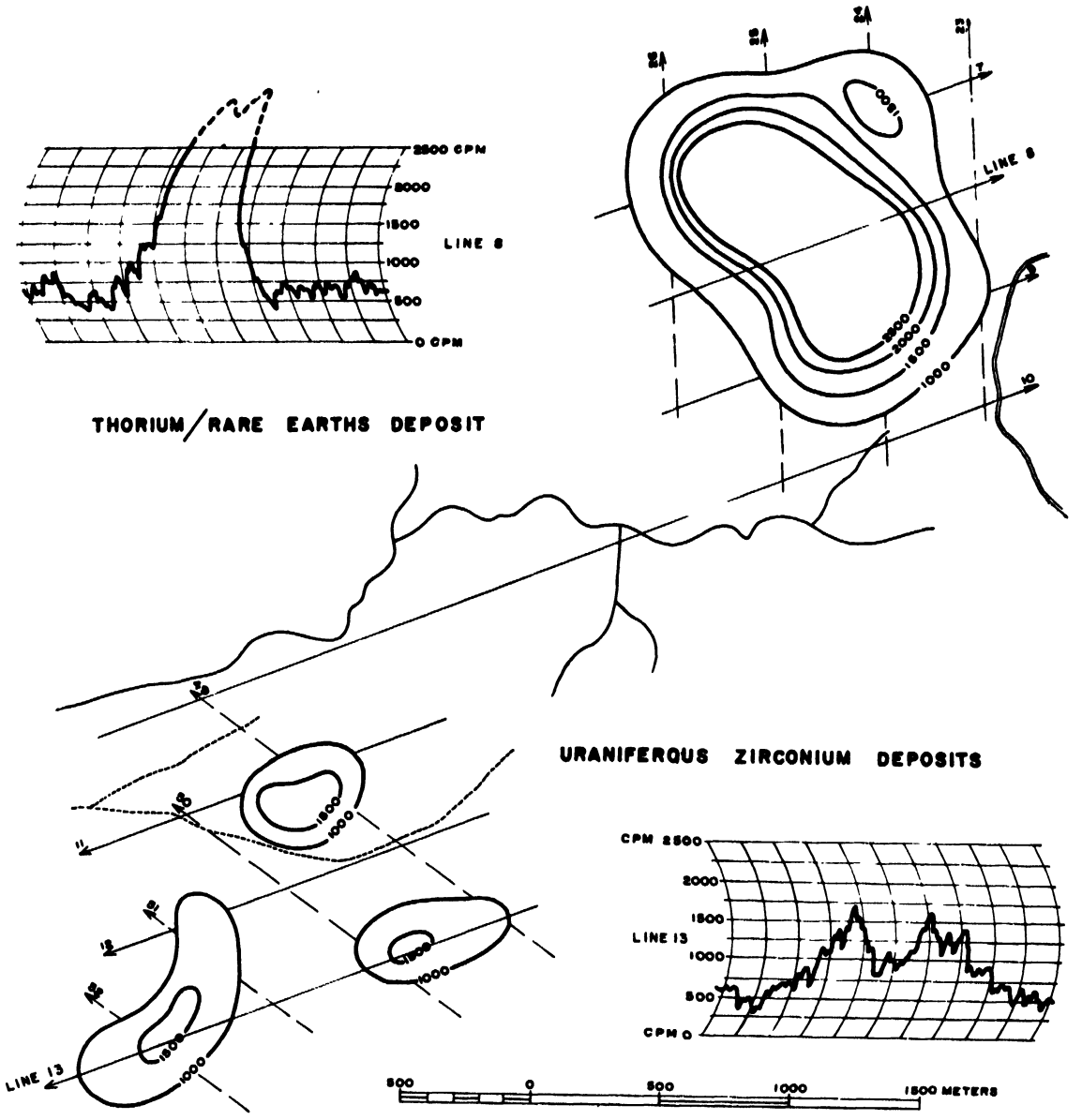


Figure 6. Airborne radiometry in an alkaline province

Figure 6 is the radiometric mapping of an occurrence of uraniferous zirconium and a nearby thorium/rare earth deposit in an alkaline province. An interesting contrast of radiation intensity is shown, the alluvial zirconium/uranium producing relatively weak, scattered anomalies. This Phase II investigation was initiated with limited knowledge of the radioactive character of the zirconium deposits, and sensitivity and recording scale were adapted to the weak radiation encountered over a known occurrence. As a result, two thorium/rare earth deposits, within a few kilometers, and exhibiting much stronger radiation, were recorded "off scale" as seen in Fig. 6.

This investigation was followed by a regional magnetic radiation survey aimed at correlation of the numerous anomalies encountered.

Figure 7 is the radiometric mapping of a highly concentrated occurrence of columbium-pyrochlore. Flights at 250 meter spacing, integrated with crossing flights at 500 meter spacing, have discriminated in considerable detail, the surface exposure of the pyrochlore, and numerous peripheral anomalies. This survey is especially noteworthy, in that the presence of the thorium/uranium/rare earth-rich mineralization, was discovered during a specific investigation of a known radioactive apatite formation about 2 kilometers distant. Both occurrences are within the same major anomaly. Radiation is relatively weak over the apatite zone, but reaches 23 times background over the pyrochlore, with normal instrument settings.

This Phase II project subsequently passed through Phases III and IV, having now advanced well into the proving stage.

Figure 8 is the radiometric mapping of half of a large anomaly caused by multiple veins of a thorium/rare earth-bearing mineral in a gneissic

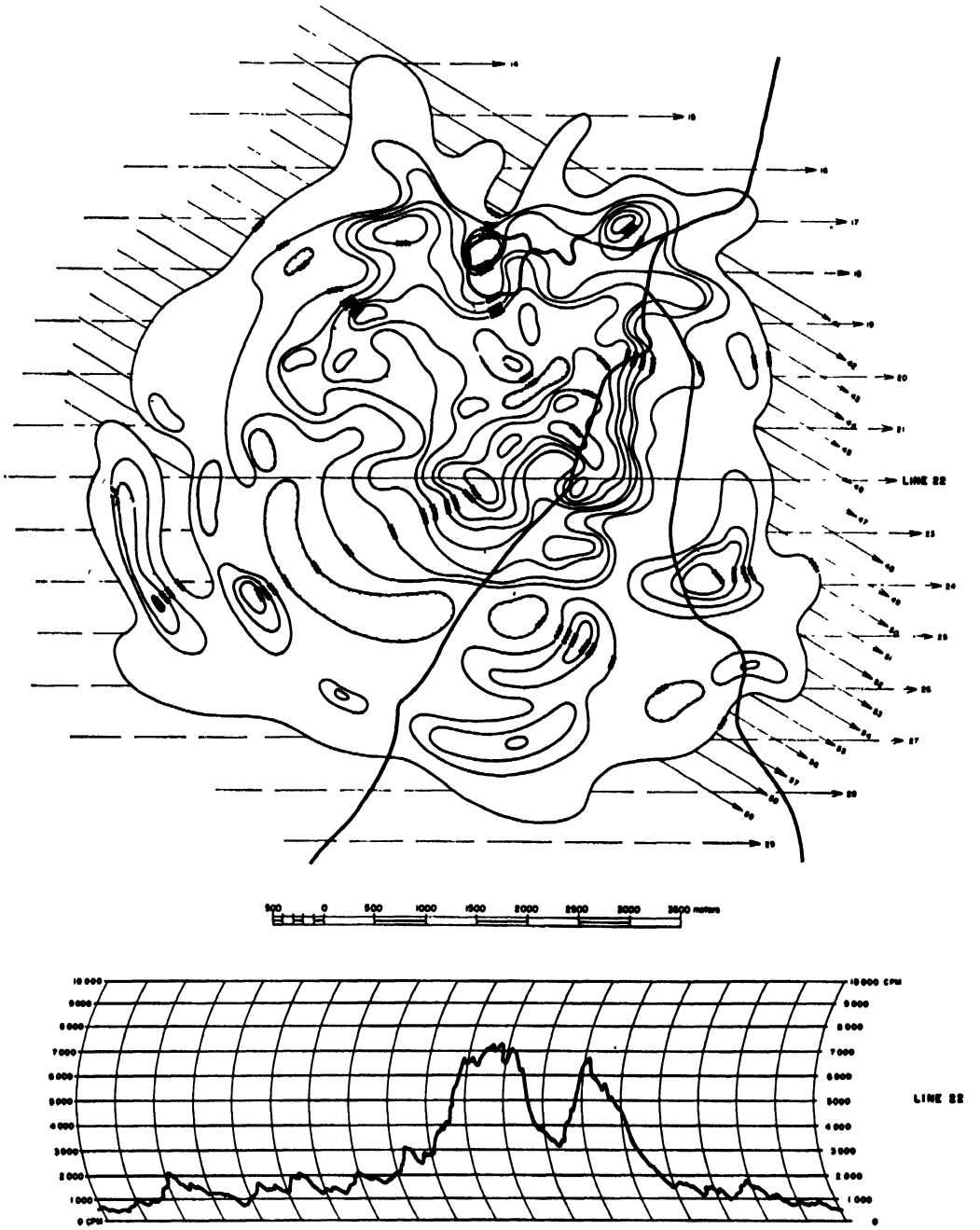


Figure 7. Airborne radiometry of an alkaline intrusive with pyrochlore mineralization

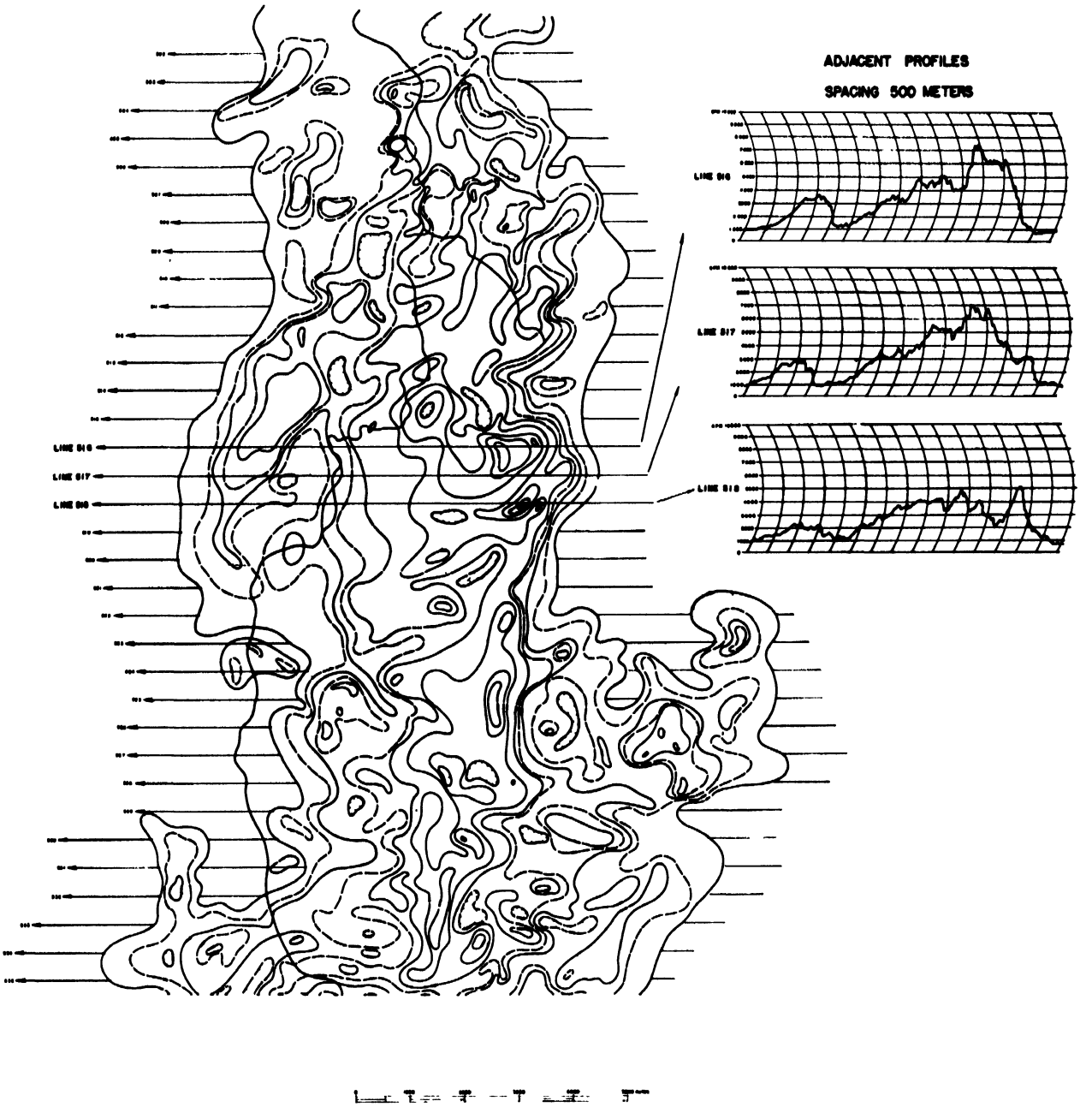


Figure 8. Airborne radiometry of a thorium-bearing gneiss

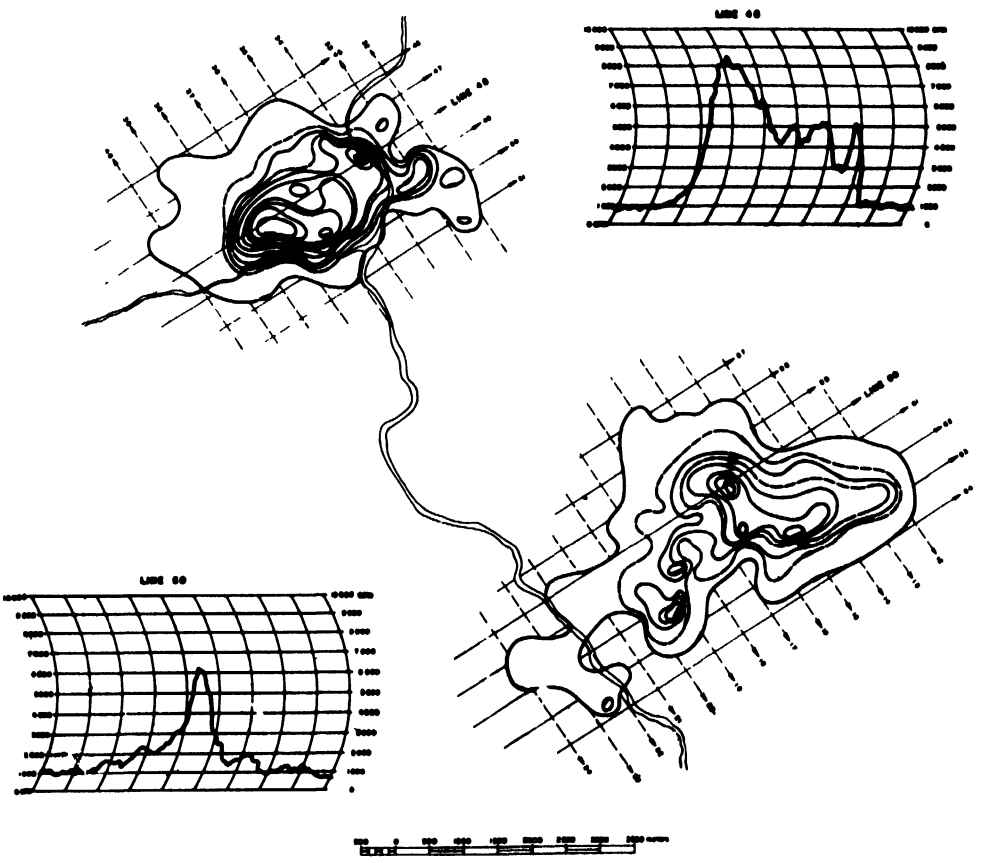


Figure 9. Airborne radiometry of syenite intrusives

rock. This anomaly, continuous over 240 km², was mapped during a Phase III regional survey of an area considered favourable geologically to radioactive mineral occurrence. The project is now in the Phase IV classification, with preliminary drilling about to commence.

Figure 9 is the radiation mapping of two syenite intrusives encountered during a Phase III type of survey with general geological purpose. The radioactive mineral has not yet been identified.

Figure 10 is the radiation mapping of what is believed to be an alluvial deposit, encountered during the same Regional Survey as the Fig. 8 anomaly. Even in profile, the radiometry lacks prominent peaks, indicating probable wide dissemination of radioactive material.

Figure 11 is the aeromagnetic mapping of the columbium-pyrochlore-bearing intrusive of Fig. 8, demonstrating an association which has proven common to several other similar occurrences and aided not only in their discovery but in structural determinations of great value in later operations. The limit of significant radiation is shown by a heavy broken line.

The pattern of magnetite concentration in the intrusive was determined from second derivative mapping of the total field magnetic measurements illustrated. An evident relationship between magnetite distribution and radiation intensity led to the establishment, by sample analysis, of a quantitative correlation between magnetite and pyrochlore in the rock. As a result, both types of air survey data have been most useful in the planning of drilling and other proving operations.

Radiometric maps of the types shown are the principal product of their respective airborne surveys. Whether they are rough indications such as the Fig. 6 investigation, or detailed and precise, as in the Fig. 7 project, these maps, and the topographic and geological data with which they are closely integrated, are highly significant steps in the sequence of location, identification and evaluation.

CONCLUSIONS

When it is realized that the discoveries of radioactive minerals discussed in this paper represent less than one-half of the successful search carried out by a single geophysical flying unit, operating intermittently during an eighteen month period, the significance of air survey to the "atomic" future of Brazil may be assessed. Not only is this country most generously provided with major radioactive mineral occurrences, but air methods appear to be most effective in locating them.

The exploitability of discoveries made up to the present is a matter beyond the scope of this paper, however it is appropriate to consider a particular aspect of the economic question here—the occurrence of uranium and thorium in association with other important minerals, which may be discovered in the radiometric search. In many instances, the

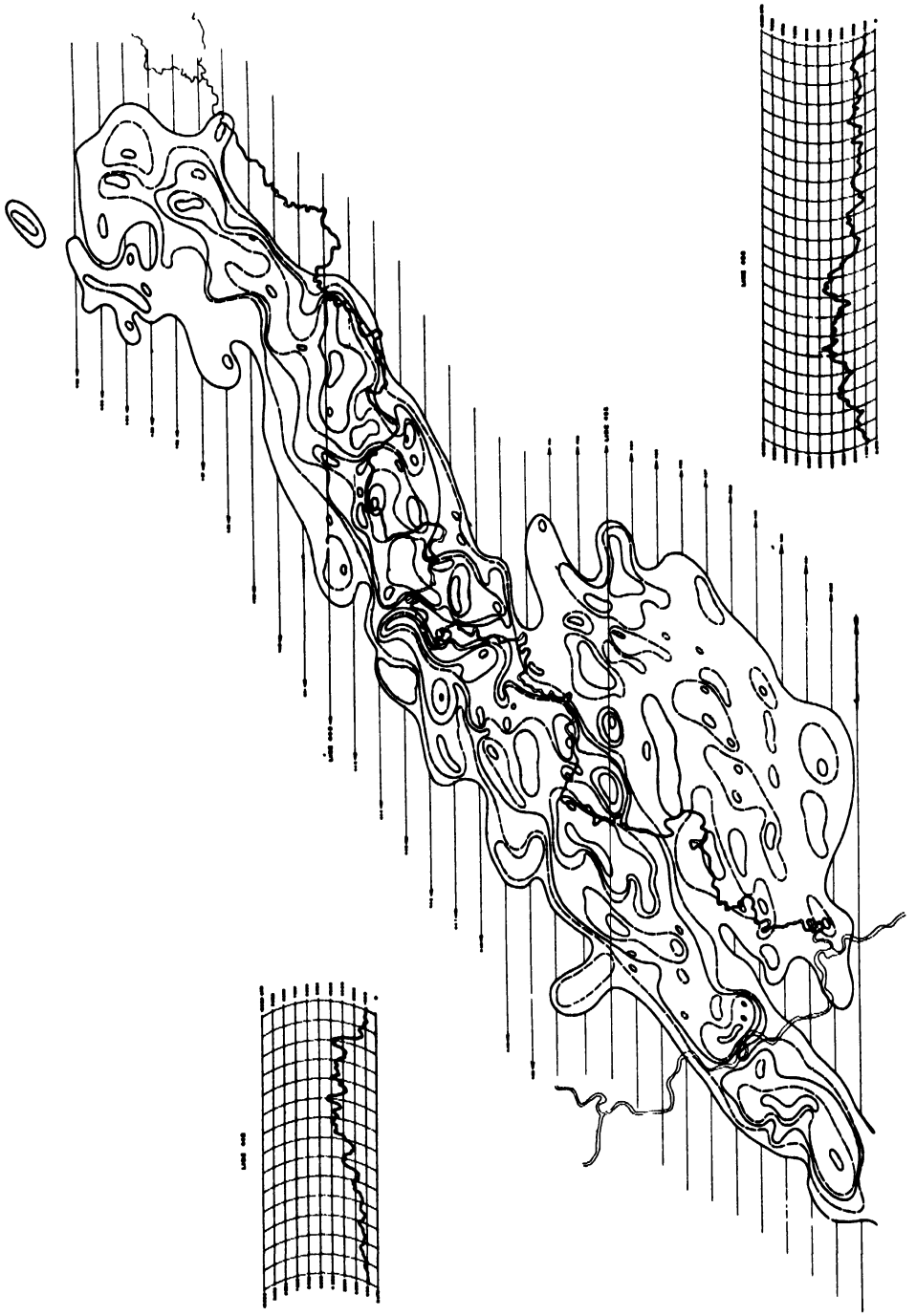


Figure 10. Airborne radiometry of a broad alluvial deposit

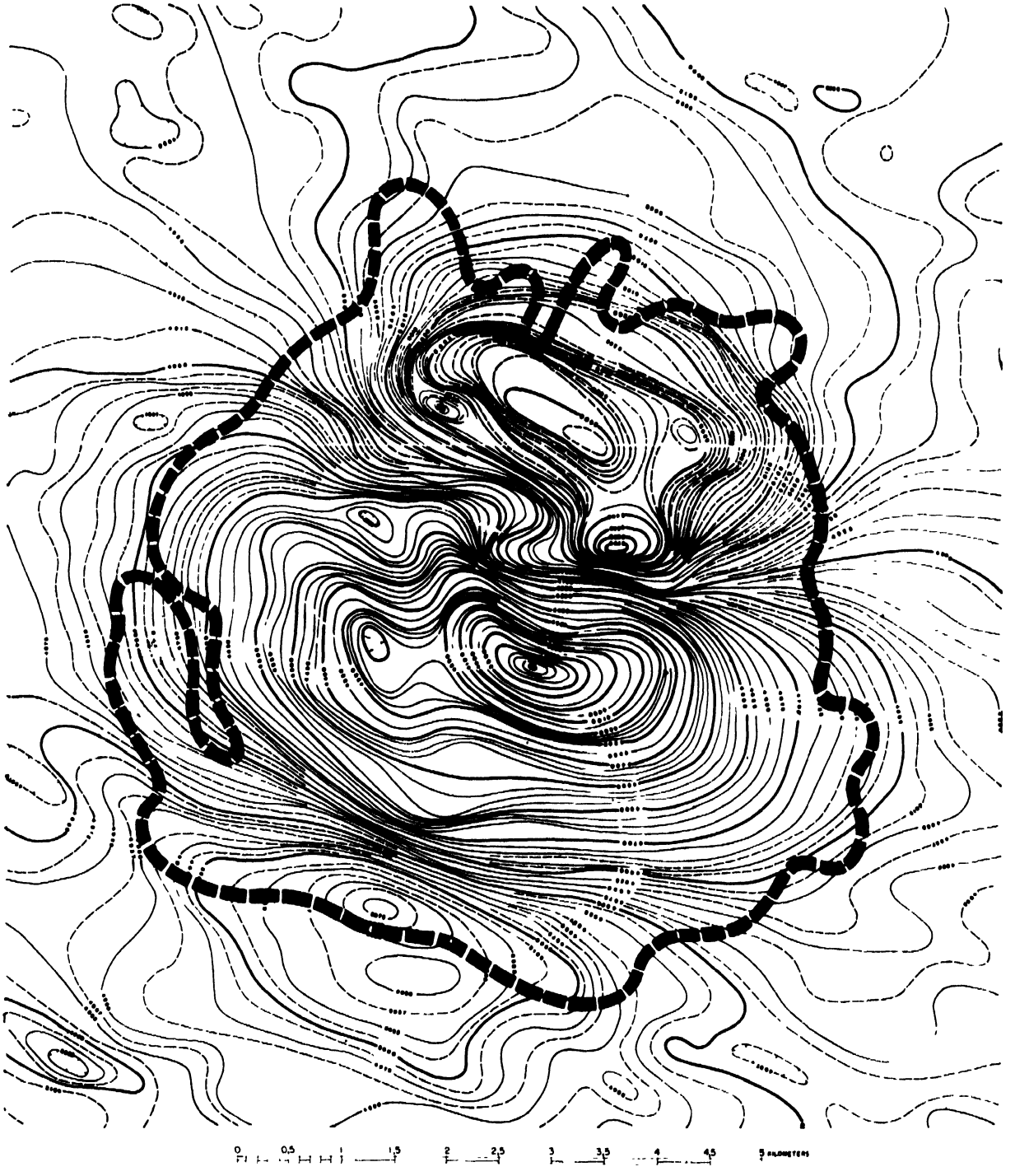


Figure 11. Airborne magnetometry of a syenite plug showing relationship with Fig. 7 radioactive anomaly

mining and extraction of atomic minerals may not be economic, for themselves alone, but quite feasible as a by-product or in conjunction with other minerals. This is a point of considerable importance in the justification of a broad exploration programme of the inventory type.

The current market value of the already proven reserves of an associated mineral discovered by one of the surveys demonstrated here, amounts to five thousand times the whole cost of all operations, air and ground, of the surveying organization, during the eighteen month period of the explorations. By implication, an inventory of raw materials for atomic energy production, in Brazil, will finance itself.

Such optimistic views are tempered by the hope that world distribution of atomic energy raw materials may be fortuitous for those countries which do not themselves possess the technical and economic means for peaceful exploitation of the atom.

Aeroradiometric Prospecting for Uranium and Thorium Deposits and the Interpretation of Gamma Anomalies

By V. I. Baranov,* USSR

Aviation is extensively employed in prospecting for deposits of uranium and thorium in the immense territory of the Soviet Union. Several deposits of industrial significance were discovered with its help. The search for radioactive ores by aviation is conducted under the USSR Ministry for Geology and Preservation of Mineral Wealth, in accordance with a single state plan.

The purpose of aeroradiometric prospecting is to determine the radioactivity of mineral rock from the air, using geophysical instruments and subsequently to give geological and geophysical interpretations of the anomalies discovered.

Together with the development and improvement of the technique and methods of measuring radioactive geophysical parameters from the air, methods of choosing regions and air routes for survey, and of interpreting the results obtained, were also worked out.

A characteristic feature of prospecting for deposits of radioactive ores by aviation is the closely linked correlation between geological and geophysical methods of investigation which makes it possible for the whole work—from the choosing of the route to the evaluation of the discoveries—to be done by a single air-prospecting party.

THE GEOPHYSICAL BASIS OF PROSPECTING BY AIR FOR RADIOACTIVE ORE DEPOSITS

It is known that the radioactive elements in rock emit penetrating gamma radiation, and in addition, discharge into the surrounding atmosphere the gaseous emanations radon and thoron.

In the USSR, two methods of searching for radioactive ore deposits by air were tested, the aero-ionization and aero-gamma methods.

The physical basis for the first method is the fact that the radiation of radioactive elements is of primary significance in evaluating the ionizing factors in atmospheric air. The total ionization of the air at the surface of the earth is made up of the following:

$$\Sigma q = q_{\alpha+\beta} + q_{\gamma} + q_{Rn} + q_{Tn} + q_k + q_a$$

where $q_{\alpha+\beta}$ stands for the ion formation by α- and β-rays of radioelements present in the soil, q_{γ} is ion formation at the expense of γ radiation of rocks, q_{Rn} and q_{Tn} is ion formation by Rn and Tn radiations and their disintegration products present in the air, q_k is ion formation by cosmic rays, and q_a is the ion formation by radiations of the radioactive sediment on the ground.

Only three ionizing factors, q_k, q_{γ}, and q_{Rn}, have noticeable significance at flying height.

Thus, in one mountain district of the Soviet Union the following averages were obtained, characterizing relative values of different ionizing factors on the earth's surface at a height of 150 m.

Ionizing components	q_k	q_{γ}	q_{Rn}	q_{Tn} *and others*
On the earth's surface	3.9%	30.8%	42.3%	23%
At 150 m altitude	6.5%	24%	69.5%	–

Thus, with increasing height, q_{Rn} comes to the fore among the ionizing factors, so that alterations in the ionization of the air at flight altitude must reflect changes in the concentration of radon. Consequently, the air ionization method is a simple way of determining the aerial radioactivity.

Taking into consideration the mechanism of diffusive and quasi-diffusive distribution of radon in the air layer near the earth's surface and in the atmosphere, it may be calculated that a doubling of the ionization in the lower layers of the atmosphere over a wide area should be observed where there is the following concentration of uranium in rocks covered with friable deposits of diverse width:

Width of deposit in meters	2	5	8	10	11.5
Concentration of uranium, in %, causing doubling of atmosphere ionization	1.5×10^{-3}	1×10^{-2}	0.1	0.3	1.0

The method of ionization, as distinct from the gamma method, registers not only the radioactivity of uranium-bearing rocks, but their emanating quality as well.

A condenser, operating by producing a conduction current, serves as the instrument for measuring the ionization of the atmosphere. The conduction current, after proper amplification, is automatically recorded.

Tests of the aerial ionizing method showed that clearly defined anomalies appear over known ore deposits. This method gives a large number of pseudo anomalies due to foreign sources of ionization and

Original language: Russian.

space charges in the atmosphere. Further, as a result of the transfer of radon and its disintegration products by air streams, determination of the exact relations of the anomalies is complicated. The application of the ionization method is limited at present; the chief industrial aeroradiometric method is the gamma method.

The subject of investigations by the aerial gamma method is the gamma radiation in the atmosphere from rock near the surface of the earth. The direct relation between this radiation and the concentration of radioactive elements in the upper layer of rock (to a depth of the first few dozen centimeters) is the basis for the method of prospecting by air. The aerial gamma method has been most widely developed, both as concerns the availability of apparatus and the scope of application of the method. In gamma surveying both on the earth's surface and underground, a quantitative interpretation of the results is possible, that is, a direct determination of the content of radioactive elements in rocks from the readings of the geophysical instruments. In surveying by airplane, a difficulty in geophysical interpretation arises due to absorption and scattering of gamma radiation in the air, and to specific interferences.

In actual conditions, with widespread layers of matter and a complex composition of primary gamma photons, it is advisable to make use of the generalized laws of distribution of gamma radiation in evaluating the effect registered by the radiometer from the air.

The most important one concerns the law of change in intensity and the deformation of the spectral composition of the point source of radiation in an extensive geological medium. In many cases the exponential law proves satisfactory for practical purposes, with a certain effective absorption coefficient, depending on the spectral composition of the primary gamma radiation.

In the case of flat extended media—sections of rock formations—the effect on the aeroradiometer receiver can be determined according to the basic formula

$$I = K \epsilon a^{-1} \int_{\Omega} e^{-\frac{aF(z_0, \varphi\theta)}{\cos\theta}} d\Omega \qquad (1)$$

where I stands for the intensity of the gamma radiation, ϵ for the weight concentration of the radioactive matter, and z_0, φ, θ are the cylindrical coordinates.

$$F(z_0\varphi\theta) = \int_0^{z_0} \rho(z, \theta\, \varphi) dz$$

where ρ stands for the density of the medium, μ is the effective absorption coefficient, $a = \mu/\rho$, K is the constant depending on the character of the primary gamma radiation and the unit of measure, and $d\Omega$ stands for an element of the solid angle.

When the anomaly of the gamma field intensity at the surface of the earth is I_0, we have

$$K \epsilon a^{-1} = \frac{I_0}{2\pi} \qquad (2)$$

and for calculating the intensity at points of the absorbing medium, air, according to the given distribution of I_0 on a plane surface of separation, it is sufficient to know this distribution and the density of the absorbing medium.

An analytical computation of the intensity of gamma radiation at the altitude of airplane flight according to Equation 1 is possible in many cases, but the results are quite inconvenient for practical use.

Computing the integral (Equation 1), using (Equation 2) for the gamma field anomaly on the surface of the earth, an arbitrary configuration can be made conveniently and simply with the aid of a nomogram.

In important practical cases of linear anomalies, the relation between the integrated influencing effect on the instrument and the total quantity of radioactive matter per unit of length of the anomaly is significant. It can be shown that

$$\int_{-\infty}^{+\infty} I(x)dx = \alpha\, q\, \Phi(\mu h)\, [\sin\varphi]^{-1} \qquad (3)$$

where $I(x)$ represents the intensity of gamma radiation or the impulse counting rate of the Geiger or scintillating radiation receiver at the flying height h, $\Phi(\mu h)$ is the change function of the value $I(h)$ for a homogeneous flat extended section, φ is the angle between the line of flight of the airplane and the direction of the linear anomaly, and α is the coefficient, depending on choice of unit.

The useful effect is registered by the aeroradiometer against a background of numerous interferences, such as cosmic radiation, gamma radiation of radioactive emanations in the air, and others. For eliminating these, it is important to know the so-called altitude curve.

If $N = N(h)$ is known, where N represents the total gamma radiation counting rate at the altitude h, then using known data on the variation of cosmic radiation with altitude, it is possible to obtain $n = n(h)$, where n stands for the counting rate due to the gamma radiation of the rock strata alone.

The presence of serious interferences essentially lowers the accuracy in measuring the rock's gamma radiation itself. The relative mean quadratic error ϵ in measuring gamma radiation of the rock is expressed thus:

$$\epsilon = \frac{\sqrt{(I_\gamma + I_{airplane} + I_{Rn})\bar{q} + N_{cosmic} + N_{impurity}}}{\sqrt{2RCI_\gamma q}} \qquad (4)$$

q being the sensitivity of the gamma radiation detector, and RC the time constant of the device.

The lessening of the inaccuracy of investigations is achieved in different ways. To weaken the influence of cosmic radiation, the method of coincidences, involving the alignment of a group of Geiger counters is used.

As evident from Equation 4, it is more advantageous when the sensitivity of the receiver increases strongly towards the useful radiation than towards the "interfering" radiations. This is achieved by the

use of scintillation counters and gaseous counters with heavy metal cathodes.

Knowing $n = n(h)$, it is easy to determine the corrections necessary for the altitude of flight.

In practical aerial gamma prospecting, the flight altitude is measured by a radioaltimeter with continuous recording of its indications. Corrections due to flight altitude are made in two ways: (1) by calculation (or by nomogram) based on the flight altitude curve; and (2) by automatically correcting during the flight, using special electronic circuits which take into account both the altitude with respect to the topography, and the height of the airplane above sea level.

Scintillation counters do not produce a single altitude curve, but a series of curves, each of which corresponds to a given discrimination of the scintillation counter. The methods of determining the useful radiation, correcting errors due to the flying altitude and eliminating interferences, are analogous to those described above.

The process of registering the impulses arising in the gamma radiation receiver of the aeroradiometer (the Geiger counter, scintillating crystal) depends, as a matter of fact, on the time constant of the aeroradiometers, which is especially important in registering rapidly changing gamma fields.

For standard aeroradiometers, the average counting rate of the impulses is determined by integrating them into the RC mesh. In this case corrections based on the time constant of the instrument are made with the aid of special nomograms, constructed from the equation

$$KN = i_R + RC\frac{di_R}{dt} \qquad (5)$$

in which N is the average counting rate of the impulses, i_R is the mean current through the resistance R, and K is the coefficient, depending on the constant of the instrument and also the choice of unit.

In some experimental aeroradiometers, in order to lessen the influence of the time constant of the instrument, automatic changing of the time constant of the RC instrument is used. In this case, with a certain $di_R/dt \geqslant d$, a circuit with a small RC is automatically switched in, assuring a more dependable separation of the local anomaly (d is the given value).

In exploration by air in mountain districts a serious distortion of the gamma field is caused by the relief. It can be shown that minor depressions and hillocks (up to 10 to 20 meters) only insignificantly deform the gamma field at a flight altitude of 100 meters. Thus, over a conical rise, the increase of the gamma field ΔI would be approximately:

$$\Delta I = I_0\left\{\Phi(\mu h_1) - \Phi(\mu h) - \cos\theta \times\left[\Phi\left(\frac{\mu h_1}{\cos\theta}\right) - \Phi\left(\frac{\mu h}{\cos\theta}\right)\right]\right\} \qquad (6)$$

Φ representing the *King* function; and at a height h_1 of 100 m, the height of the rising h 50 m, and with an angle θ of 45° at the crest, the approximate increase would be 6 or 7%.

All approximate calculations of the influence of the relief are made with the aid of special nomograms.

In case the diagrams for the direction of the aeroradiometer and the aeroradioaltimeter come close, the calculation of the influence of the relief is made by one of the above mentioned ways of correcting for the altitude. For altimeters used in modern Soviet airplanes and helicopters, the influence of the relief is determined satisfactorily enough in cases where the relief slopes are not more than 45 or 50 deg. In complex mountain districts determining the influence of the relief is definitely more difficult. In such cases a special flight method is used, depending on the form of the relief.

An important problem in the search for radioactive ores is the separation of uranium and thorium anomalies directly from the airplane. Work along this line is conducted with Geiger counters of various spectral sensitivity characteristics, or with scintillating counters serving as spectrometers.

The kind of ore content is determined with confidence when the objects under exploration create a sufficiently intense gamma field at the flying altitude.

THE ORGANIZATION OF AERORADIOMETRIC PROSPECTING

The choice of districts for prospecting for radioactive ores by airplane is based on structural-metallogenic and paleogeographical analyses.

The work of prospecting is conducted by groups of qualified geologists and geophysicists of the aeroprospecting expedition in three closely bound stages; the search for anomalies, the search for the deposits based on the anomalies, and the evaluation of the deposits.

The aeroexploration expedition is headed by a geologist, and is composed of air and land groups. The number of the latter is so determined that all the anomalies disclosed can be evaluated by the group during the trip.

The aeroprospecting expedition is equipped with light boring machinery and compressors mounted on automobiles.

Prospecting by air is preceded by aerial scouting surveys for the purpose of making geologico-geomorphological observations and determining the degree of radioactivity (background) of different rocks characteristic for the district. The selection of the exploration depends on the trend or strike of the geological elements and the position of the reference points in the locality and on the maps.

The main type of prospecting network in level regions consists of a system of parallel routes, 250 m apart on an average, 20 to 40 km long, at an altitude of about 50 m. In mountainous regions, the form of the relief often complicates the directing airplanes along routes desirable from the geological standpoint,

and in planning the routes the first consideration must be the peculiarities of the relief and the necessity of maintaining the operating flight altitude. Under these conditions helicopters are used. Aerial photography is used for more precise association of the anomalous sections with the locality.

The recordings made during the flight are worked over by the operator, a geophysicist. In going over the material, the necessary corrections are made, considering the flight altitude, the relief of the district, and the time-constant of the instruments. The final geophysical data is then fixed on the geological map.

In cases of significant anomalies, detailed surveyings are made from the air, and geophysical (gamma surveyings, emanation surveyings) and geological and drilling work are started on the ground.

INTERPRETATION OF AEROGAMMA ANOMALIES

The intensity and size of the anomalous gamma field registered by the instruments over the radioactive section depends on the following factors: (1) the surface intensity of the gamma radiation and its distribution over the section; (2) the size and configuration of the sections; and (3) the nature of the radioactive source.

In practice, aeroradiometrical work has shown that a large part of the disclosed anomalies are not connected with deposits of industrial value. Therefore the checking of all aerogamma anomalies on the ground causes unproductive expense in labor and material.

The primary problem in interpreting anomalies is the rejecting of anomalies without prospects, obvious from both the geophysical and geological data, and hence having no need of checking or of studying on the ground.

This problem is solved to suit the concrete conditions of each district, based on a series of local indications, determined by experiment.

For example, in some cases anomalies caused by varied structure and texture of identical materials, for instance, large and fine grained granites, and anomalies caused by a diversity in the composition of rocks (a dike of felsiteporphyry in lime) and others may prove to offer no prospects.

It is much easier to point out the indications of anomalies worthy of immediate notice.

A sign of possible promise of anomalies is their localized character on a background of rocks of the same type. All sections associated with uranium of intensified radioactivity may offer possibilities.

In level or slightly hilly districts, with a development of thick superficial layers, where outcrops of ore bodies and country rocks take up quite a small area, wide deposits of uranium may be found with medium or even lowered radioactivity.

In districts where the country rock is hidden beneath friable formations, water springs marked by intensified radioactivity are worth noting. Anomalies which are adopted to zones of tectonic disturbances and to zones of mineralizations, especially in rock of the carbonate and basic type, as well as in intrusives and effusives of acid composition, are worth investigating. Of especial interest are the districts with altered coloring of the rock, for instance, districts which indicate a process of hydrothermal leaching and districts of iron oxide enrichment with a red and brownish-red colouring.

Anomalies in the sustained stratigraphic levels of sedimentary rocks, even in the case of insignificant gamma field intensity, are prospective.

In evaluating the prospects of anomalies, the possibility of intensified radioactivity caused by other mineral deposits must also be considered.

In order to determine those anomalies whose lack of prospective worth cannot be established with sufficient accuracy on the basis of the geophysical data of the air survey and geological indications, preliminary check-ups are made on the ground; and first of all, geophysically.

The final conclusion as to the interpretation of aeroradiometric data can be made after the local indications of connection between individual anomalies and evidence of ores have been established.

From experience in prospecting for uranium and thorium deposits by airplane and the interpretation of their results, we conclude that deposits do not always accompany intensified radioactivity of the rock and that intensified radioactivity of the rock cannot serve as the main criterion in prospecting. Wide fields of any activity may turn out to have equal prospects.

Likewise, the evaluation of individual anomalies by their form and intensity alone, without comparing all the geophysical and geological data and local signs, is impossible.

Investigations in improving methods of interpreting the data obtained in aeroradiometric surveying continue.

The following methods of work have been evolved in practice for assuring the determination of all sections of practical interest, irrespective of the intensity of radiation on the ground.

1. Detailed study of the anomalous section during the process of aeroradiometrical surveying, with repeated flights, at low altitudes, and comparison of the routes from different directions.
2. Geological surveying and interpretation of anomalous recordings.
3. Surface checking of anomalies, including radiometric recording and a sufficient amount of mining and mechanical boring.

Since zones of breaks and contacts of different rocks, and areas where intrusive conglomerations are spread, as well as other data, show up clearly in aeroradiometrical recordings, geologists extensively utilize these data for greater accuracy in defining geological structure of a given territory.

In several districts work on applying combined aerogamma and aeromagnetic recordings is being conducted.

Airborne Radiometric Surveying

By Thomas L. Boyle,* USA

PERSONNEL

The search for anomalous radioactivity by airborne equipment is exacting work, replete with hazards for the inexperienced. A complete crew, selected with care for outstanding qualifications, consists of four: geologist-observer, pilot, geologist and his assistant.

The foremost of these, chief of the airborne crew, should have, in addition to adequate knowledge of geology, a comprehension of operation of radiation detection equipment, experience in interpretation of aerial photographs, and must be familiar with the rudiments of surveying and the principles of sampling

The pilot, on whose quick judgment and instantaneous reaction depend the lives of two men, must hold a commercial pilot license and have not less than 500 hours flying time in the aircraft of the type, class and power he will be required to operate. Moreover, in order that the unit may be independent of repair depots, he must have a mechanic's aircraft-and-engine rating.

The geologist, whose responsibility is to examine each anomaly discovered, must be as well qualified as the geologist-observer and since airborne prospecting may be carried out both near to and distant from civilization, the more qualifications his assistant may have, the better.

EQUIPMENT

Pioneers in the field of airborne radiometric surveying, the Canadian Atomic Energy Commission and the United States Geological Survey (Trace Elements Branch) the latter acting for the Atomic Energy Commission, favored in early work, the use of multi-engine aircraft equipped with scintillation counters coupled to aerial cameras, radar altimeters and various recording instruments. Applying knowledge gained from this complex equipment, the United States Atomic Energy Commission began the practice of low-level flying with a light two-place fixed-wing plane carrying a scintillation counter. Choice of aircraft was guided by specifications of: exceptional performance and dependability, high maneuverability, low initial and operational cost, ease of maintenance, capability of safe minimum cruising and low landing speeds, and high wing construction for ground visibility and obstruction clearance on rough landing fields.

* US Atomic Energy Commission.

Aircraft

A plane (Fig. 1) meeting these standards is powered with a 135 horsepower engine, has exceptional performance and maneuverability up to 15,000 feet; its purchase price, which includes two wing tanks of capacity allowing five hours cruising, navigation and landing lights, two-way radio and shoulder harness for both pilot and geologist-observer, is $6000. Operational costs—gas, oil and maintenance—do not exceed, under normal flight conditions, $7 per hour.

In choice of aircraft for airborne radiometric survey, helicopters merit consideration. Their high initial cost is a deterrent to their use despite the fact that they may fly and maneuver readily in winds up to 60 miles an hour, and can operate safely at low speeds. Moreover, they traverse readily and at close range, much topography which is inaccessible to fixed-wing-craft.

Instrumentation

The development in the last few years of scintillation counters rendered remarkably sensitive by the use of large sodium iodide or plastic phosphor crystals scanned by a photomultiplier tube, resulted in an excellent instrument for the detection of radioactivity from the air. The detector unit of such an instrument should be mounted in a sponge rubber lined aluminum cylinder (Fig. 2) to avoid shock and to eliminate vibration as much as possible. Installation in the rear compartment of the aircraft will reduce to a minimum the radiation effect of luminous dials on flying instruments.

The various parts comprising this instrument are: (1) detector head containing a crystal (3½ in. diam. × 2 in. long), photomultiplier tube and electronic circuitry (Fig. 2, *A*); (2) control unit with audio alarm system (Fig. 3); (3) power unit (Fig. 2, *B*) consisting of dynamotor (12 volts, 2.5 amperes), stabilizing circuit and fuses; and (4) aircraft 12 volt battery (mounted in fuselage at rear of cockpit).

Use of such an instrument in aircraft flying under ideal conditions at various altitudes, at 100 miles an hour (time constant 1.6) has shown that gamma rays emanating from a point source follows the inverse square law which applies in the case of light, (Fig. 4).

Figures 5 and 6 incorporate the results obtained in the use of a 3½ inch sodium iodide crystal in flights over a 40 ton point source of 0.3 per cent

U_3O_8. Curves obtained where the plane traversed the source at various altitudes are almost identical to that on Fig. 4.

Ground Equipment

For ground investigation of anomalous radioactivity the geologist and his assistant need a four-wheel drive vehicle, camping equipment and a portable Geiger or scintillation counter.

OPERATIONAL TECHNIQUE

Whatever the area to be flown, the operation begins with the recommendation of a geologist familiar with the regional geology and with specific outcrops of the various potential host rocks. Aided, if available, by a geologic map of the region and aerial photographs, the geologist-observer familiarizes himself with the topography, ground obstructions dangerous

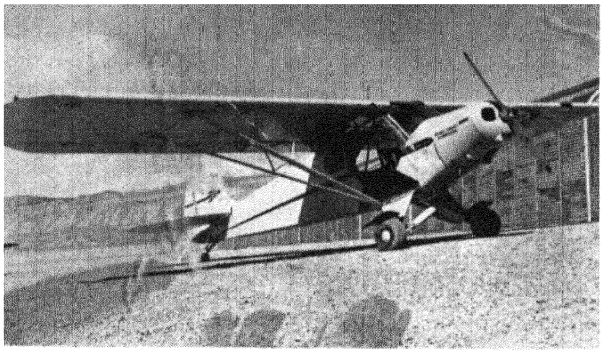


Figure 1. Light aircraft used for airborne radiometric surveying

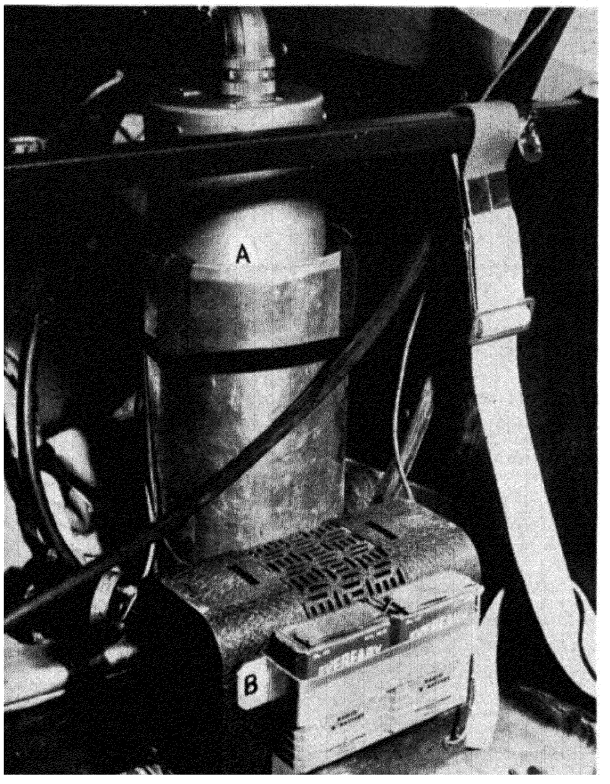


Figure 2. Detector head assembly (A), and power unit (B)

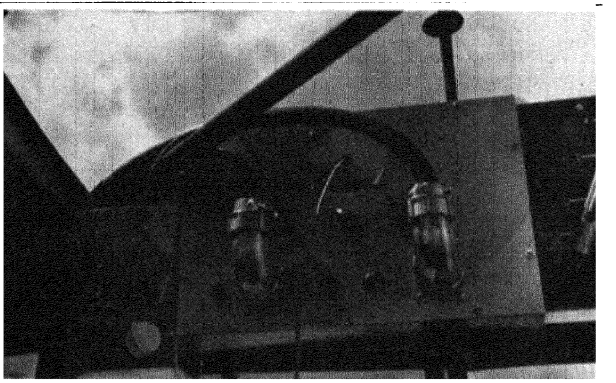


Figure 3. Scintillation-cou[illegible] unit

to low-level flight, the outcrop belt of formations to be flown and such access roads as there may be to the remote corners of the region.

Low-level flight is hazardous and a reasonable margin of safety demands that it be undertaken only during those early morning hours (dawn to perhaps 9 or 10 A.M.) when the air is calm and at maximum density. During later hours, thermals rising from rough terrain and agitated by winds greater than 15 miles an hour preclude safe flying.

The area to be prospected each morning by low-level flight is first examined at an altitude of 500 feet. Distinctive topographic features marking the boundaries are noted and a careful search is made for hazards to low-level flight. These vary with the region but even in remote areas may include telephone and power lines and mine cables extending from valley floor to valley rims. With all hazards carefully noted, the survey may begin with the use of either of two standard procedures which, although as thorough as conditions permit, are judged to give a flight coverage of not more than 50 per cent.

Rim (Contour) Flying

In regions of youthful topography—deep narrow canyons separated by wide to narrow divides—formations particularly favorable for the occurrence of uranium may outcrop at any level from valley floor to rim. Among such topography it is then necessary to fly the contour of outcrop of the preferred formation at distances 50 feet to 100 feet from it, and at a speed of approximately 75 miles per hour.

If the formation under survey is thin, flight along its contour is as continuous as topography will allow; irregular topography may necessitate circling and successive traverses over relatively short outcrop lengths. Should the selected formation be thick—200–300 feet—then several passes which will bring the plane within 100 feet of all portions are necessary.

Variations in topography have a great proportional influence on instrument readings when flying close to the ground. This becomes more apparent when flying over rough and deeply dissected terrain. With practice the geologist-observer learns to interpret the variable differences registered on instrument between true anomalies and anomalies caused by mass effects or by igneous intrusions.

Grid Flying

Where a favorable horizon outcrops in a wide belt of relatively smooth topography it is most economical to fly as closely as is possible on a grid and at altitudes of 100–200 ft. Such altitudes allow coverage of 100–200 ft. on each side of the aircraft.

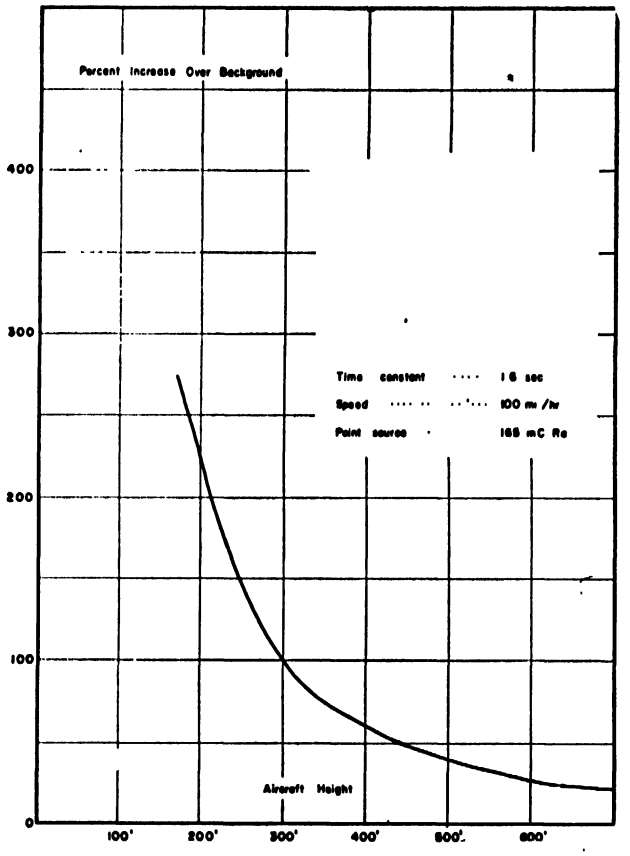


Figure 4. Per cent increase over background as a function of aircraft height

Ground Examination

Once anomalous radioactivity is discovered from the air, several passes check the intensity, and the spot is plotted on an aerial photograph or geologic map. It is then the responsibility of the geologist to complete a reconnaissance map of the site and to collect representative samples for assay.

It has been the practice of the Atomic Energy Commission to post on the 15th of each month, for public examination in 22 cities scattered throughout the United States, maps showing the location of all anomalies on Public Domain discovered during the preceding month.

Flight Precautions

In one year of representative operation, approximately 10,000 square miles of grid flying and 10,000 miles of rim flying was completed by 7 air crews.

In a total of approximately 8400 hours (about 60,000 miles of actual prospecting) of rim and grid flight there were only two accidents, neither of which resulted in serious injury to flight personnel. Neither mishap was the result of personnel incompetence and in both, the aircraft was a total loss.

One accident was caused by unforseeable downdraft, the second a result of collision with a power line spanning a narrow valley, unmarked by right-of-way clearing and rendered invisible by poor post-dawn visibility.

There is, of course, no limit to precautions which must be taken in airborne reconnaissance. Pilots should receive dual flight instruction in the technique of low-level prospecting, they should comprehend the significance of "density altitude." Canyon rims should be flown only on the up-wind side of escarpments and in all cases air conditions must be tested at successively lower altitudes over the area to be flown. Safety harness and "hard hats" should be standard equipment and the more sensitive the

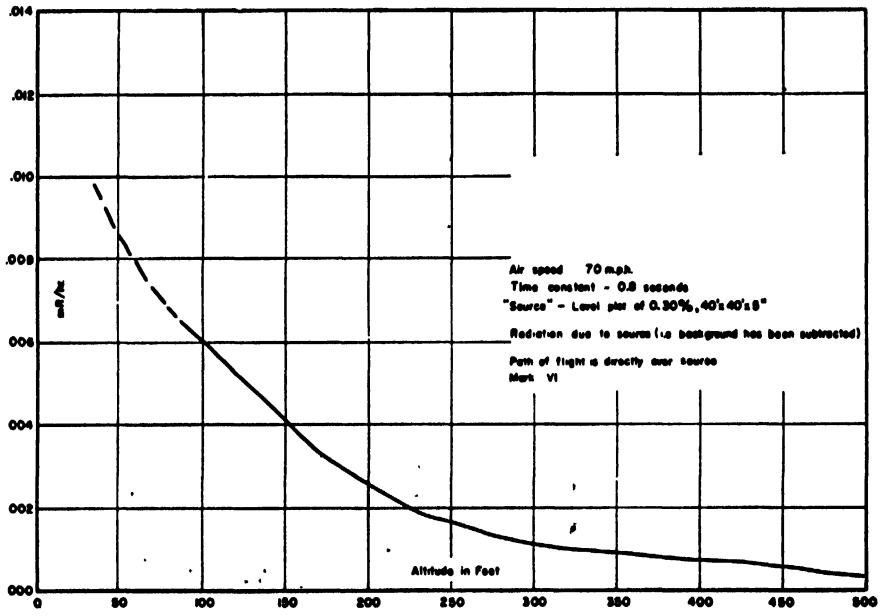


Figure 5. Relation between instrument reading and flight-path elevation

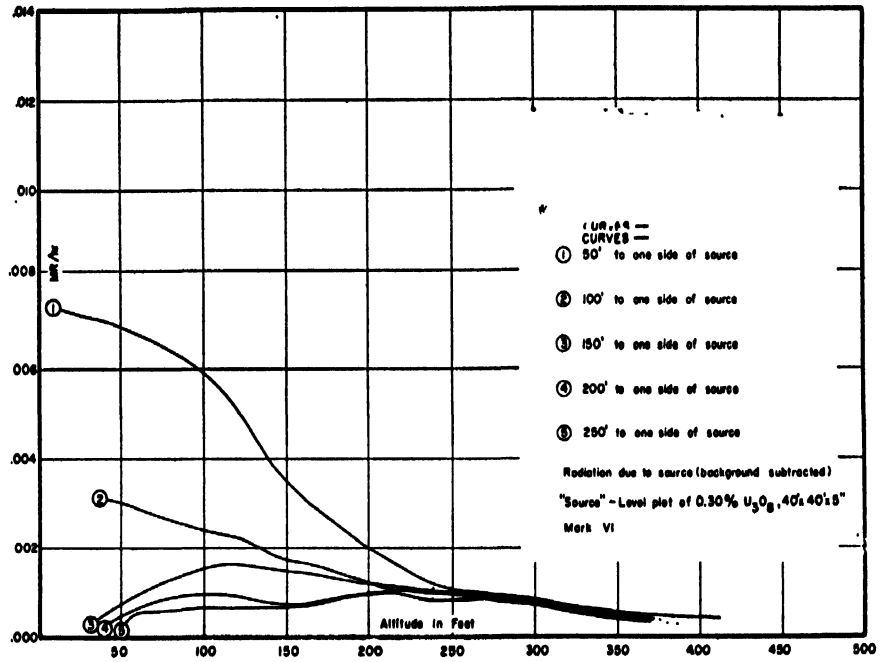


Figure 6. Relation between instrument reading and flight-path elevation

detection apparatus, the higher the flight may be made.

Canyons in which a 180° turn cannot be executed should not be flown and in flying vertical canyon walls, the pilot should check his perspective by successively circling and closing his flight path with the cliff face.

RESULTS

Utah

Approximately 620 hours of rim and grid flying over outcrops of Jurassic Morrison, Triassic Chinle and Shinarump outcrops located 95 localities of anomalous radioactivity, the most productive of these was that one in the Shinarump conglomerate on the southwest portion of the San Rafael Swell which evolved into the Delta Mine.

Arizona

Twenty anomalies were located in the Dripping Springs quartzite (pre-Cambrian) north of Globe as a result of approximately 220 hours of rim flying. It is estimated half contain material of ore grade.

South Dakota

About 455 hours of low-level flying over the outcrop of the Inyan Kara (Cretaceous) in the Black Hills located 36 anomalies from which come about 75 per cent of production of that region.

In the Slim Buttes region, ten hours of low-level flight located 10 anomalies in lignites.

Wyoming

Airborne prospecting of Tertiary sediments along various portions of the Big Horn Basin, east flank of the Big Horn Mountains, Hartville Uplift, Old Woman and Lance Creek anticlines revealed 355 anomalies during 545 hours of flight. About 40 discoveries have produced ore.

New Mexico

Flying along the flanks of the Sangre de Cristo and Chuska Mountains, and in the Schoole, Magdalena and Carizozo districts for 425 hours located 40 anomalies. The number of producing mines developed on these is not known.

Other Areas

Airborne prospecting in other portions of the United States has been remunerative in terms of number of radiometric anomalies discovered but not in terms of tons of ore produced from the many prospects developed at those sites. This record should not be interpreted as condemnation of those areas: airborne prospecting is not a substitute for prospecting on the ground, rather it is an adjunct to it which cannot be counted as more than 50% effective.

Gamma-ray penetration of rock is less than one foot, hence even a large uranium deposit beneath such a cover may escape detection from the air or ground. Moreover, each foot of snowfall reduces the intensity of radiation which may be detected. In addition, aside from the large scale criteria of favorability—discoloration; structural features, etc.—which can be noted from the air, airborne prospecting does not allow examination of small features such as carbonaceous debris, suitable lithology and smaller structural phenomena which together may indicate local areas favorable to uranium mineralization.

Air Scattering of Gamma Rays from Thick Uranium Sources

By A. Y. Sakakura,* USA

A knowledge of the air scattering of gamma rays from naturally occurring thick uranium sources is necessary to interpret radioactivity measurements made at considerable air distances from sources. As currently applied, airborne radioactivity surveying is essentially a qualitative technique, that is, anomalously high radioactivity relative to the immediate surroundings is used to guide ground investigations to localities where radioactive deposits of economic importance might occur. The interpretation of measurements should be placed on a quantitative basis if the technique of airborne radioactivity surveying is to be further developed as a geophysical tool. For satisfactory interpretation, the various observable quantities recorded by a counting-rate meter, such as the peak intensity (counts per second), total number of counts (the area under the curve), and the shape of the curve must be correlated with the principal characteristics of a natural source, namely, the grade in terms of the equivalent uranium oxide content and the configuration in terms of the surface dimensions.

As the fundamental properties of gamma radiation are well known for the energy range from natural sources, the ideal method of interpretation would be based on the theoretical computation of the radiation intensity emanating from sources of various configurations. The advantage of the computational approach is that the results do not have to be resolved in terms of the response characteristics of a particular detector. Where the radiation source is distributed in one medium, rocks and soils, and is measured at considerable distances from the source in another medium, air, the intensity of scattered radiation predominates over that of primary radiation; thus, a numerical solution of the Boltzmann equation for the gamma-ray transport in two media is necessary. The solution of this equation is, in general, a function of three space variables (coordinates of the point at which the radiation intensity is computed), two angular variables (scattering), and an energy variable for any given source configuration. Once such a solution is obtained, the response of any detector, knowing its spectral and angular characteristics, could be computed.

Unfortunately, no satisfactory general solutions to two media problems have been published, although the US Geological Survey with the cooperation of the Computing Facility of the US Atomic Energy Commission at New York University is now engaged in solving the two-media problem with plane symmetry. However, analytical approximations and a vast quantity of numerical solutions to one-media problems in various geometries exist,[1] from which one can predict trends of solutions in two media. Moreover, for high energy radiation traveling in a forward direction, the presence of the boundary is immaterial. The general procedure in solving the Boltzmann equation was developed by Spencer and Fano[2,3,4] at the National Bureau of Standards. A topical summary and pertinent bibliography are given in recent articles by Fano,[2,3] the former containing mathematical details. Many of the physical arguments that follow are based on his discussions. A further source of difficulty in detail, if not in principle, in solving the Boltzmann equation is that the uranium source spectrum is very complex, necessitating the solution of many problems with different primary source energies and the superposition of these individual solutions. An alternative approach to the approximate solution of the two-media Boltzmann equation consists of using the existing solutions computed for simple geometries and the knowledge of the gamma-ray spectrum of uranium. Then these solutions are combined according to educated guesses as to what the two-media solutions should be from a previous knowledge of simple geometric solutions and analytical behavior of the solutions.

However, the simplest approach is a semi-empirical one, wherein an experimental or assumed form of radiation intensity law for an elementary source is integrated over a suitable geometric configuration to obtain the intensities from various sources. Peirson and Franklin[5] made such an integration assuming an inverse-square exponential law, which not only neglects the effect of scattering but also the many lines of the uranium spectrum. Carmichael and others[6] used the inverse-square law but considered air scattering by experimentally determining the "effective absorption coefficient" from measurements of the radiation from radium sources. Cook[7] assumed an "effective" energy and used effective computed cross-section and the inverse-square law. There is no *a priori* reason why an effective cross section measured or calculated in one source-to-medium orientation should be applicable to others.

To avoid this conceptual difficulty, measurements were made on infinitely thick, "point" and broad

* US Geological Survey.

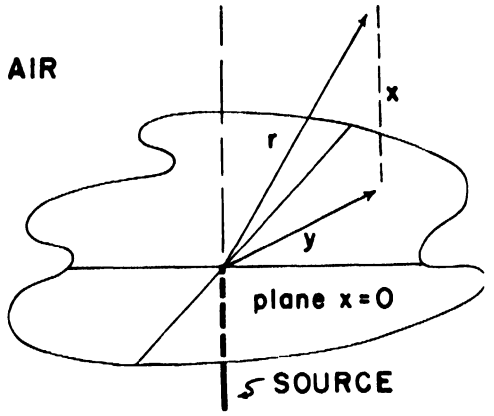


Figure 1. Elementary point source geometry

sources. In this way the integration in depth has already been performed. An effective point source can be obtained when the areal extent of the source is small compared to the air distances at which measurements are made. Other sources are synthesized from the point source data through integration over a surface.

Although a semi-empirical approach is adopted it is convenient to retain the structure of the theory, especially for extrapolating the data to areas not covered by the experimental measurements. Thus, the intensity is represented by the product of the unscattered contribution of the most penetrating component and a build-up factor for the scattered radiation, which for moderate penetration is a polynomial in the distance variable.[2,3,4]

More detailed treatment, especially of the mathematical aspects, of what follows is described elsewhere.[8]

INTENSITY FROM VARIOUS SOURCES

The two fundamental sources are: (1) elementary point source, the line depicted in Fig. 1; and (2) infinite broad source, the region $x \leq 0$ filled uniformly with radioactive material, shown in Fig. 2. Obviously, in this case, the source is an infinite superposition of the elementary sources. Thus, a functional form dictated by theory is chosen for the elementary source, and the constants are selected so that the expression fits the elementary source experimental data, and the result of integrating this expression over an infinite surface fits the infinite-source experimental data.

The intermediate source types are:

1. Line source, an infinitely long source of breadth, "a" much less than the diameter of the elementary point source. The intensity $I\ (x,y,a)$ is a function of altitude x, and, y, the distance from the point of observation to the axis of the source, projected onto the plane of the source.

2. Slab source, intermediate source between the line source and the infinite broad source. Its length is assumed to be infinite. The intensity $I_s(x,y,a)$ is a function of altitude x, the ground projection, y, of the distance from the observation point to the center axis of the source, and breadth, "a".

3. Finite source, a circular source of diameter greater than an elementary source and less than an infinite source. The intensity $I_f(x,y,a)$ is a function of the altitude x, the ground projection, y, of the distance between the detector and the center of the source, and the diameter "a".

All the solutions can be expressed in closed form except for the last source. Numerical computations show that, for a detector at an altitude of 500 feet, the following conclusions can be drawn:

1. Finite sources of diameter greater than 1700 feet and slab sources greater than 1200 feet in breadth are infinite sources.

2. Finite sources less than 550 feet in diameter are point sources.

3. Slab sources less than 800 feet in breadth are line sources.

4. Line and slab sources must be 1700 feet in length to be considered infinitely long.

AREA UNDER COUNTING-RATE-METER CURVE

Knowing the response of the instrument and the velocity of the detector, the areas under the curves can be computed for various source configurations and grade. These areas are:

1. Elementary point source. The area $H_p\ (v,x,\xi,a)$ is a function of the altitude x, ground projection, ξ, of the distance of closest approach between the detector and the center of the source, velocity v, of the detector, and diameter "a".

2. Finite source. The area $H_f(v,x,\xi,a)$ is a function of the same variables as above.

3. Line source. The area $H_e(v,x,\theta,a)$ is a function of altitude x, velocity v, breadth "a", and θ, the acute angle between the normal to the axis of the source and the ground projection of the flight line.

4. Slab source. The area $H_s(v,x,\theta,a)$ is a function of the same variables as above.

Cases (2) and (4) have been evaluated numerically for a 500-foot altitude. The others can be expressed in closed form.

INTERPRETATION OF ANOMALIES

The unknown factors that enter into the interpretation of an anomaly are the source position relative to the detector, its size and its grade. As the

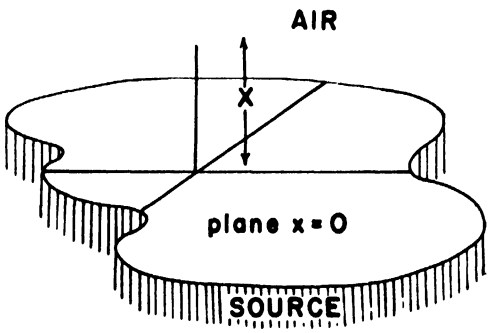


Figure 2. Infinite broad source geometry

usual practice is to make continuously recorded measurements along equally spaced, constant-altitude flight lines, the location of the anomaly along the direction of flight can be determined approximately. The source would be located along a line which passes through the peak position of the anomaly and which is at right angles to the flight path. Assuming the source symmetries described above, the shape of the source is reduced to one variable (breadth of line or slab source or radius of a point or finite source). Thus, there are three unknowns to relate to the observable quantities. The most obvious one is the peak intensity reading, another the area under the curve. The third is the shape of the anomaly, such as its slope and its half-maximum value. However, examination of the computed values shows that the slope varies slightly as the grade-area of the source is increased. Moveover, if one were not flying directly over the source, the anomaly would broaden considerably. An objection to analysis of shape is the fact that the shape would be most susceptible to the variation in position of an airborne detector. Thus, on a given line of observation, one has two observables and three unknowns on one line, or four observables and three unknowns on two lines. Consequently, there are two categories of anomalies: those that are visible on two or more adjacent lines and those that are visible only on one. On the latter, the information is necessarily incomplete.

Computations reveal that at a nominal 500-foot flight altitude and at a line spacing of ¼ mile, an ore-grade body (0.1 per cent U_3O_8) with a minimum raduis of 60 feet located midway between the two flight lines is detectable. As any finite source under 275 feet in radius can be considered a point source, which really has only two observables, the grade-area and the distance from the detector, any ore-grade body visible on only one flight line is completely specified. In this case, the grade-area can be mathematically expressed in terms of the two observables, that is, the peak intensity and the area under the curve.

If the anomaly were visible on two adjacent lines, there are four observables on hand: $H_f(x,\xi)$, $I_f(x,\xi)$, $H_f(x,d-\xi)$ and $I_f(x,d-\xi)$ where d is the spacing of the lines. As the grade of deposits ranges widely, one requires grade-independent quantities. Two of these are:

$$\frac{H_f(x,d-\xi)}{I_f(x,d-\xi)} = R_f(x,d-\xi)$$

$$\frac{H_f(x,\xi)}{I_f(x,\xi)} = R_f(x,\xi)$$

If one were to use the computed quantities and plot $R_f(x,\ d-\xi)$ vs $R_f(x,\ \xi)$, a series of curves for different values of "a" would be obtained. With the use of observed quantities, "a" can be determined from this plot. Moreover, it is found that when the point-source formulas relating grade-area to I_p and H_p are applied to finite source values at $d-\xi$ and ξ and the resulting grade-area values are then averaged, the averages are constant for all values of ξ at fixed "a". These averages can be corrected with true grade-areas by multiplication with a conversion factor. The procedure is then:

1. Compute

$$\frac{H(x,\xi)}{I(x,\xi)}$$

and

$$\frac{H(x,d-\xi)}{I(x,d-\xi)}$$

to determine "a" from a precalculated plot of $R_f(x,\ d-\xi)$ vs $R_f(x,\ \xi)$.

2. Compute grade-area at ξ and $d-\xi$ using the point-source formula and take the average of the two values.

3. Multiply the average by a precalculated factor for a given "a".

This procedure gives the grade-area of the finite source, and from the grade-area and "a", the grade.

The preceding discussion refers only to finite sources. Line and slab sources, by definition, will yield the same peak reading and area on two adjacent lines. The ratio

$$\frac{H_s(x,\theta)}{I_s(x,\theta)}\cos\theta = \frac{H_s(x,0)}{I_s(x,0)}$$

yields the value of "a" for line and slab sources. The factor θ is determined from the relative position of the anomaly on two adjacent flight lines. Then the application of the expression for the slab-source area under the curve yields the grade-breadth and, consequently, the grade.

If the anomalies show decided flattening at the peak, application of the expression for an infinite source evidently will yield the grade. Moreover the breadth at one-half peak intensity denotes the breadth of the source. This aspect of the calculations has been amply confirmed by ground investigations.

In the case of a compound anomaly reflecting two or more separate point sources, the separation into individual sources and the determination of the respective H_s' and I_s' presents some difficulties.

SUMMARY

Certain general concepts underlying the semi-empirical approach to the interpretation of airborne radioactivity measurements warrant attention, although the particular method presented here is not entirely satisfactory for all aspects of interpretation. These concepts are:

1. Use of an elementary point source of infinite thickness. This eliminates the necessity of assumptions that scattering and absorption of gamma radiation are not influenced by the presence of a boundary between media and that the scattering effect of a medium is dependent only on the electronic density.

2. Use of point and infinite broad source behavior to fix the analytical form of the elementary function.

3. The investigation, numerically and analytically, of relationships among observables and source characteristics.

The combination of observables selected for analysis is not uniquely valid to an adequate interpretation. Other combinations yielding an equal or greater amount of information would also be valid. For example, after identifying the source type, the grade could be computed as though the source were either directly under the detector or at the point midway between two adjacent flight lines, thus obtaining values for the two extremes of grade.

It must be stressed that there are many approaches to this problem. The interpretation of anomalies presented here has been sufficiently confirmed by ground investigation and sampling of the natural sources to make it seem that this method as now developed is reasonably useful.

ACKNOWLEDGEMENT

The author is grateful to L. V. Spencer of the National Bureau of Standards for an illuminating discussion on this subject.

REFERENCES

1. Goldstein, H. and Wilkins, J. E., *Calculations of the penetration of gamma rays, final report,* US Atomic Energy Commission, Report NYO-3075 (1954).
2. Fano, W., *Penetration of X- and gamma rays to extremely great depths,* Journal of Research of National Bureau of Standards (US): no. 2, 95–121 (1953).
3. Fano, W., *Gamma ray attenuation,* Nucleonics 11: no. 8, 8–12; no. 9, 55–61 (1953).
4. Spencer, L. V. and Fano, W., *Penetration and diffusion of X-rays. Calculation of spatial distribution by polynomial expansion,* Journal of Research of National Bureau of Standards (US): no. 46, 446–456 (1951).
5. Peirson, D. H. and Franklin, E., *Aerial prospecting for radioactive minerals,* British Journal of Applied Physics 2: 281–291 (1951).
6. Godby, C. A., Connack, S. H. G., Steljer, J. F., Cowper, G. and Carmichael, H., *Aerial prospecting for radioactive materials,* National Research Council of Canada, Report no. CRR-495 (1952).
7. Cook, J. C., *An analysis of airborne surveying for surface radioactivity,* Geophysics 17: no. 4, 687–706 (1952).
8. Sakakura, A. Y., *On the air scattering of gamma-rays from thick uranium sources,* US Geological Survey report in preparation.

Techniques for Prospecting for Uranium and Thorium

By staffs of the United States Atomic Energy Commission and the Geological Survey

Ten years ago, when the potential of atomic power became public knowledge, prospecting for radioactive minerals in the United States represented only a very minor effort of government and industry. Consequently, the techniques employed then were, by today's standards, exceedingly crude. Since then the efforts of thousands of workers have perfected many new instruments and techniques for finding uranium and thorium.

The reports submitted by some of these men to this Conference describe the most important advances in the techniques of prospecting by a large number of geologists, geochemists, botanists, and geophysicists. It is not possible in this summary of these papers to make specific reference to the authors in the text, but it is a pleasure to acknowledge their fine work and also that of their colleagues who have done so much to advance the arts of prospecting and exploring for uranium and thorium.

Successful prospecting and physical exploration for uranium and thorium require the application of many geological, geochemical, and geophysical techniques. Each of these has its place in the difficult task of finding, exploring, and developing these deposits; commonly several techniques must be used in combination. Fortunately, these two elements have one unusual property in common—radioactivity—that makes possible techniques not applicable to the prospecting for other minerals. Radiation detection devices consequently have played a major role in the finding and developing of uranium and thorium deposits.

The application of geologic knowledge in the search for uranium and thorium deposits has greatly increased the rate of discovery of new districts and of ore deposits within new and old districts. Many deposits have been found in environments previously believed to be unfavorable for the occurrence of these metals. This emphasizes the fact that good prospecting requires that all theories and hypotheses—not just the one in favor at the moment—be considered carefully.

The favorability of each distinct geologic unit within large areas not previously known to contain uranium and thorium deposits can be evaluated, with a reasonable degree of assurance, on the basis of existing knowledge. This is in a large part due to the large number of man-years of experience that have been put into the search for uranium.

Prospecting for epigenetic deposits of uranium should emphasize, on the basis of existing knowledge, areas of deep-seated tectonic structures, particularly those related to (1) near-surface intrusions, and associated extrusives, (2) depositional basins containing terrestrial sediments, and (3) granite batholiths. Ultra-mafic and plateau basalt igneous terranes appear unfavorable. Low-grade syngenetic deposits should be sought in (1) marine, continental shelf sediments of the black shale and phosphorite types, (2) terrestrial and marine places, (3) alkalic igneous stocks, sills, and dikes, and (4) granitic pegmatites. Marine sandstones, conglomerates, mudstones, and carbonate rocks rarely contain syngenetic concentrations of uranium. Epigenetic deposits of thorium are largely restricted to metamorphic and igneous terranes where they are associated with alkalic igneous rocks and carbonatite masses, that in themselves may contain syngenetic concentrations.

Within these favorable terranes the ore deposits commonly occur in clusters or districts; the individual ore bodies are of various sizes and grades. The guides to concealed deposits are largely structural, lithologic, mineralogic, and chemical. Within any ore district or region specific stratigraphic horizons, or specific types of lithology, mineralogy, or structure may be the most important guides to ore. These phenomena are amenable to mapping and have served as extremely useful aids in planning exploration; such maps as yet, however, have been used only to a limited extent in surface prospecting. In some areas, such as the Black Hills of South Dakota and Wyoming, where the favorable host rock is caped by impermeable beds, structure contour maps of the upper surface of the porous host rock delimit areas of irregular structure, such as anticlines, structural terraces, and zones of interfingering that appear to have localized the ore deposits. In the Colorado Plateau area similar maps of the lower surface of the host rock point out the channels and swales that are favorable structures for localizing ore.

Isopachous maps indicate the thicker, more favorable parts of sandstone host rocks in the Colorado Plateau and of uraniferous parts of the lignites of the Great Plains region and other areas. Similar maps of alteration zones in the siltstones below sandstone host rocks and of color zones within them have also proved their worth. Contour maps of the upper surface of ground water and of abundance of critical

elements, such as fluorine, in the water, are useful in areas of caliche-type deposits such as the schroeckingerite of the Red Desert region, Wyoming.

Maps have also been made of the direction of flow in paleostream channels, using crossbedding, linearity of grains, logs, scours and channels, current ripples, and other sedimentary structures that control in detail the shape and distribution of ore bodies in sandstones. Iso-abundance maps of pebbles, grain sizes, heavy minerals, metals, and rock types have been used both in prospecting and as guides to exploration. Maps showing similar rates of change in facies together with mudstone frequency have been useful in guiding exploration on the Colorado Plateau. Mapping of alteration zones, both of clay and hematitic impregnated materials associated with veins in igneous and metamorphic rocks, as at Marysville, Utah or sandstones as at Temple Mountains, Utah, aids in prediction of ore shoots and deposits.

A system of geologic prospecting for monazite based on studies of the distribution of detrital heavy minerals has been developed to show regional relations of monazite to other heavy minerals. It is especially suited to regions of intense weathering and deep residual soil, but it might be used wherever there is adequate stream density and no interference from glacial deposits.

Heavy-mineral concentrates are taken by panning riffle gravel from the beds of small streams whose distributive provinces, above the sites of the samples, do not exceed 2 square miles. Equal volumes of sediment of reasonably similar mechanical composition are used for all samples. The mineralogical composition of each concentrate obtained by grain count, converted by nomogram to 100 per cent on a quartz-free basis, is plotted on a group of maps showing sample localities. The abundance of each mineral is contoured at suitable intervals of weight per cent on the map. The "grain" of the information obtained from the contours is generally coarse, thus samples should be taken over a minimum of several thousand square miles. Highs formed by monazite or "indicator minerals" become the loci of normal geologic search for monazite deposits.

Sampling of known uranium ore bodies and the surrounding materials has been undertaken in an attempt to delineate the primary geochemical halo which theoretically surrounds every ore body to some degree. The three dimensional distribution of trace elements related to an ore body is a function of differential ion mobilities of the chemical elements related to the ore emplacement. Primary geochemical halos have been of great assistance in locating blind ore bodies of non-ferrous metals and the same criteria may apply in uranium exploration.

Most geochemical studies have been directed toward delineating secondary geochemical halos. This is considered a most fruitful line of investigation because many areas of interest are covered by soil. During weathering and erosion, capillary attraction and plant growth and decay have an additive effect, tending to concentrate metals in soils from this ore deposit and primary geochemical halos in country rock. Soil analysis is a valuable tool, both in areas where soils are in place and also where they have been transported. Water sampling of both ground water and surface streams shows that favorable uranium formations and districts can be outlined by this method.

The application of geochemical techniques to exploration is not materially different from geophysical methods, in that all related geological factors must be evaluated in relation to the geochemical technique used. To be effective it must be rapid and relatively cheap. Trace amounts of uranium can be measured directly and the results can be related to potential concealed ore bodies or favorable areas. The amount of leachable uranium in sedimentary rocks has been measured by paper chromatographic and fluorimetric methods. These methods can discriminate 0.5 ppm at a background of 10 ppm. The direct measurement of uranium in conjunction with radioactivity measurements have been valuable in separating uranium from its highly radioactive daughter products. The mobility of the uranyl ion is very high and hence its direct detection holds promise for locating ore deposits.

The indirect approach involving the measurement of concentrations of other elements associated with uranium has been applied in several areas in the United States. This method assumes that at some stage during ore emplacement, solutions carrying metallic ions other than uranium may have travelled further and enlarged the target for geochemical exploration. The well known lead dithizone analytical methods are used for determination of base metals and new methods have been developed for measuring trace concentrations of V, Mo, Se, Ca, and Nb.

The sampling of ground water and measurement of its uranium content has resulted in the indication of areas favorable for uranium that have subsequently been found to contain commercial deposits. Most ground water contains less than 2 parts per 10^9 (ppb) uranium and water from volcanic and tuffaceous sediments considered favorable for uranium deposits may contain 10 to 250 ppb. In many areas sampling indicates that leaching of uranium is taking place at the present time. Variations in the uranium content of ground waters vary with the transmissivity of the host rock which, in turn, effects the availability of uranium.

The measurement of surface water in streams indicates that the uranium concentration decreases down stream by dilution and that nearly all large streams traversing uraniferous areas commonly contain 1 to 10 ppb. The threshold of significance is 3 to 10 times background, depending upon geological factors. In the Florida phosphate area, the background is 0.1 ppb and the threshold of significance is approximately 0.3 ppb. Here a uranium content of 1 to 3.5 ppb is regarded as a strong indication of the presence of uraniferous phosphate. In the Colorado Plateau, surface streams have a back-

ground of about 0.5 to 3.0 ppb and a threshold of significance of about 4 ppb in the major streams. Anomalies in or near uraniferous areas range from 5 to 12 ppb for streams free of contamination.

Botanical methods of prospecting are based on the premise that concealed mineral deposits may be reflected chemically in surface vegetation. Results suggest that ore bodies under a cover of barren sandstone as much as 25 meters thick may be detected by testing plants growing above them for uranium and associated elements.

One botanical method in use is based upon the presence of uranium in all plants in small but measurable amounts. The uranium content of plants rooted in ore, however, is detectably greater than the uranium content of plants rooted in barren ground. The uranium content of the ash of plants rooted in unmineralized sandstone is generally less than 1 ppb. A content of several parts per million is common in the ash of plants rooted in ore. Plant ash is analyzed for uranium by the fluorimetric method.

Another botanical method of prospecting, that of mapping the distribution of indicator plants, has been used in ecologically favorable areas. A plant may be used as an indicator plant in prospecting if its distribution is controlled by any factor related to the chemistry of the deposit. Carnotite ore and other oxidized uranium ores contain appreciable amounts of available selenium and sulfur. The distribution patterns of plants requiring one of these elements in quantity may indicate favorable ground.

Botanical prospecting in advance of drilling for shallow ore deposits may substantially reduce the number of holes required and can be used in unprospected country to suggest areas worthy of intensive geologic study.

The development of highly sensitive radiation detection equipment, especially the scintillation counter, has made possible the airborne detection of radiation from exposed or near-surface uranium deposits. Light single-engine aircraft equipped with scintillation counters, flying at 50 to 100 feet above the grounds and at ground speeds of approximately 60 miles per hour has been effective in discovery of commercial uranium deposits. The technique is most effective in areas of well exposed formations known to be favorable for uranium or thorium; its especially effective where favorable formations are horizontal and exposed in vertical cliffs. The greatest success has been in rapid prospecting known mineralized formations. The aircraft is flown within 100 feet of the vertical exposure, following the contour of the outcrop. In areas of low relief and poor exposure, a rectangular grid pattern is flown at low altitude and the positions of radiation anomalies are plotted on aerial photographs.

Airborne surveying at altitudes of 500 feet with multi-engine aircraft is used to delineate radioactivity in broad areas not previously known to contain uranium or thorium deposits, thus indicating the favorability of these areas for more detailed prospecting and exploration. Crystalline rocks of different ages and types also can be easily distinguished by their characteristic radioactivity as recorded by this method. Five hundred feet of air distance is an effective upper limit to the application of airborne radiation prospecting, and 200 feet is probably the most efficient altitude considering the attenuation of radiation with air distance and the width of the zone from which anomalous radioactivity can be detected. This zone of effective detection is approximately twice the distance of the aircraft above the ground.

Quantitative interpretation of airborne radiation data has been shown possible for broad sources and the equivalent uranium of these sources can be estimated to within a few thousandths of one per cent. The quantitative relationships between the peak intensity and area under the curve as recorded by a counting ratemeter and the source strength and size have been empirically established as a function of the velocity and distance of a detector from the source. Excellent equipment and instruments are available commercially for detailed airborne radiation surveys for both high-level and low-level flying and the technique is finding wide application in private uranium exploration.

The application of gamma-ray detection in subsurface exploration has become increasingly important in the past several years. Radiation detection in drill holes supplies valuable information on the position and character of uranium mineralization. Gamma-ray radiation is measured with highly sensitive scintillation detectors raised through drill holes on cables which transmit data to the mechanical surface recorder. Geologic units can be correlated between drill holes; thickness and general type of geologic members can be determined, and the approximate grade of ore can be obtained by correlating core assays from a number of holes with radiation data. One field procedure involves the recording of the maximum gamma-ray log deflection recorder in a favorable geologic member and plotting this as a function of depth for each drill hole. A map is drawn showing lines of equal radioactive intensity and effective placing of drill holes is based on the results. Scintillation gamma-ray logging instruments in use at the present time are limited to holes with a nominal diameter of greater than 2 inches. Geiger tube logging instruments are used for holes smaller than 2 inches. Quantitative assay results based on scintillation gamma-ray logging techniques are limited by disequilibrium and thickness variables, and are not generally reliable for reporting ore reserves. Electric logging equipment is being used in conjunction with gamma-ray logging instruments to provide more detailed lithologic and other geologic information. Effective single-point electrode design makes in-hole electric logging of dry holes possible in conjunction with gamma-ray logs and expands the usefulness of the combination logging

procedure. Evidence indicates that the single-point electric log data can be used for quantitative interpretation of resistivity parameters.

Detailed radiation surveys at the ground surface are most effectively made by a geologist using scintillation or a Geiger counter and are usually made on a rectangular grid pattern from which maps are drawn showing lines of equal radiation. Reconnaissance surveys on outcropping ore bodies known to be favorable are made by walking the outcrops. Regional reconnaissance radiation surveys are commonly made with car-mounted scintillation instruments of the continuously recording type, which provide the location of radioactivity anomalies leading to more detailed ground studies and provide data on the surface distribution of radioactivity in large areas.

Unexposed uranium deposits have not proved susceptible to direct detection by geophysical methods because of the lack of contrast in physical properties between ore-bearing material and host rock. This is true because of the low concentration of uranium ore. Some geophysical methods have proved to be of value, however, in the detection and delineation of indirect geologic guides to ore.

Electrical resistivity methods indicate that uranium mineralization is accompanied by variations in the resistivity of the containing sediments which are detectable by electrical means. Surface and in-hole logging results indicate that there is no known difference in electrical properties attributable to the uranium mineralization. One set of data, however, shows high resistivity values near deposits in South Dakota; another set of data shows low resistivity values associated with deposits in Wyoming, where ore minerals are of a completely different type. Electric resistivity measurements on surface, made with direct current equipment and non-polarizable electrodes, delineate thicker parts of the Salt Wash sandstone member of the Morrison formation in Colorado as areas of anomalous high resistivity. These thick parts of sandstones are considered favorable for ore in some areas. The Shinarump conglomerate filling paleo-channels cut in the less indurated Moenkopi formation in the Colorado Plateau have been successfully outlined using seismic refraction surveys with standard equipment. Continuous profiling with reversed shots has resulted in location of previously unknown mineralized channels. Channels filled with Shinarump conglomerate have also been located by a combination of vertical and horizontal resistivity profiling.

Extensive experimental investigations have been made of the application of reflection seismic methods, surface-inhole electrical methods, and natural potential methods without conclusive results. Further research is planned to evaluate the shallow seismic reflection method using continuous velocity logging equipment, in conjunction with the high resolution seismic equipment. Work is also planned to test the application of induced polarization, radio frequency, and electromagnetic induction methods to uranium exploration problems.

Specialized drilling techniques have been developed to fit unique problems in uranium exploration on the Colorado Plateau. Paleostream channels in the Shinarump conglomerate, in which many ore deposits of the Colorado Plateau occur, may be from hundreds to thousands of feet wide and from tens to hundreds of feet deep with depths of scours as much as fifty to sixty feet. One drilling technique developed to outline such channels involves drilling a fence of holes a short distance behind the cliff exposure of the channel and perpendicular to the projected trend of the channel. The axis of the channel is then determined by alignment of the structurally lowest hole drilled with the lowest point of the channel in the Shinarump on the exposure. A line of holes is then drilled on the projected axis and if the axis orientation changes as noted by drill data, a new perpendicular fence is drilled for reorientation of axis and drill pattern.

Grid patterns are used for drill hole guidance where little is known regarding the geology or the trend of favorable ground. Hole spacing is contingent on the target size for the particular formation being drilled or on the purpose of the drilling if other than to intersect ore (that is, for geologic information). Preliminary drilling is usually done on wide spacing with secondary drilling in the search for ore bodies much closer, offsets commonly being from approximately 25 to 60 feet. Nearly all of the common type of drilling rigs are used on the Colorado Plateau; there is a trend to use more mobile heavy duty drills and accessories, improved sampling in dry drilling, and increased use of air as a circulating medium. Drilling costs have decreased markedly since the beginning of the program due to increased efficiency and competition.

A unique method has been developed to extend favorable zones for uranium mineralization in the Salt Wash member of the Morrison formation in the Colorado Plateau. Data are collected from wide-spaced drill holes from which is plotted a lithofacies map employing the ratio of mudstone to sandstone content of a depositional unit. In this type of subsurface map, there is more than a random coincidence displayed between the location of the mineral deposits and the position of facies or environment change. This information is available to the geologist from data supplied by drill holes spaced from 500 to 1000 feet apart.

Radiohydrogeological Method in Prospecting for Uranium Deposits

By A. A. Saukoff, USSR

The radiohydrogeological (hydrogeochemical) method of prospecting for uranium deposits is based on the ability of this element and its disintegration products—radium and radon—to dissolve in natural waters and migrate with them. The development of this method became possible as a result of theoretical conclusions on the migration of elements drawn chiefly by Vernadsky and Fersman; these conclusions have since been further defined and concretized by a number of researchers in hydrogeology; an important part was played also by chemists, who developed sufficiently sensitive and accurate methods for analysing natural waters for their radioactive element content.

Studies of the radiochemical composition of natural waters began soon after the discovery of radioactivity, but for a long time they were devoted only to medicinal problems, because the beneficent influence of waters containing radon on the human organism had been established. For this reason, during the first period only radon was determined in the water; somewhat later scientists learned to determine the presence of radium, and began to analyse waters for the content of this element also.

It was much harder with the determination of uranium in natural waters; satisfactory methods for its determination were suggested only in recent years.

At present a large number of facts have been accumulated on the occurrence of radioactive elements in natural waters, and these facts have formed a basis for the development in the USSR of the hydrogeochemical method of prospecting for uranium deposits. It was proved that in prospecting for uranium ore deposits the best and most easily interpreted results are usually obtained by studies of the water halos of the uranium dissemination; as for radium and radon, they also play an important part, but their properties differ from those of uranium, and consequently, their migration is often also different.

It has been proved that all natural waters contain uranium, though its concentration varies over a wide range, from $n \times 10^{-8}$ gm/l to $n \times 10^{-2}$ gm/l. The uranium content of sea water is 2×10^{-6} gm/l; in river waters it varies from $n \times 10^{-8}$ gm/l to $n \times 10^{-5}$ gm/l; in some undrained basins it runs as high as $n \times 10^{-5}$ gm/l.

The uranium content in underground waters varies very widely; thus, in the spring waters from barren rocks it sometimes drops as low as $n \times 10^{-8}$ gm/l; in the mine waters of uranium deposits it reaches as high as several hundredths of a gram per liter. High contents of uranium (and often of radium and radon as well) are observed in underground waters which have passed through uranium deposits; the concentration range in water, enriched with uranium by flowing through mineral deposits is usually between $n \times 10^{-5}$ and $n \times 10^{-3}$ gm/l, and sometimes rises as high as $n \times 10^{-2}$ gm/l.

Uranium enters natural waters from various rocks through which these waters migrate, as well as from deposits in which it usually occurs as an independent mineral. This is proved both by observations in nature and by special experimental studies of the solubility of uranium minerals and of the leaching of uranium from rocks by various reagents, including reagents approaching natural waters by their properties. The amount of uranium that passes into solution depends on many factors, among others, on its concentration and forms of occurrence in the rocks and deposits, on the chemical composition of the solutions, including the gases dissolved in them, especially oxygen, on the rate of flow of the solutions, etc.

Proceeding from the high concentrations of uranium in its deposits, compared to rocks, and taking into account the relatively high solubility of its ore minerals it is evident that solutions washing the uranium deposits should, as a rule, be enriched in uranium, as well as in other radioactive elements, in comparison to the solutions which migrate in ordinary rocks. This, indeed, is often the case with waters that have passed through deposits. Waters that circulate under conditions strongly promoting reductions are an exception: they do not become enriched in uranium, but contain high concentrations of Ra and Rn. The enrichment of water halos, connected with deposits, in uranium or other radioactive elements makes it possible to solve the reverse problem, viz., to prospect for uranium deposits by studing the content of radioactive elements in underground and surface waters.

Given favourable conditions, waters enriched in

Original language: Russian.

radioactive elements may come out on the surface in lower parts of the relief as springs, or may be encountered by mine workings, drill holes, wells, etc. The content of radioactive elements in them will depend on the length and nature of the path by which the waters came from the deposit; they are richest in the vicinity of the deposit; at various distances from it they may mix with poor waters from barren rocks, and the concentration of radioactive elements in them will decrease, but still will remain anomalously high compared to ordinary waters circulating among rocks.

These general conclusions form the basis of the hydrogeochemical method of prospecting for uranium deposits.

Hydrogeochemical investigations consist of three main kinds of work: sampling the waters, determining the content of radioactive elements in them and interpreting the results.

In order to reveal waters anomalously rich in radioactive elements, samples are taken from all the springs, streams (at various points), wells, drill holes and other sources of water in the region being prospected for new deposits or orebodies; samples of water are taken also at all places of its exposures in mine workings at new sites (from cracks, drill holes, etc.).

In some regions, where there are few water sources, special pits of not very great depth or drill holes are sunk for the purpose of sampling underground waters.

In view of the seasonal changes in the content of radioactive elements which take place in underground waters during the year, hydrogeochemical investigations are carried out with a veiw to taking the water samples from each small section in the course of a comparatively small time interval of the same seasons. Besides, in the regions where work is carried out on typical water sources systematic observation is organized on the content of uranium or other radioactive elements in the water during the entire period of field work. This data facilitates a more correct analysis of the large amount of data collected over large areas as a result of water sampling at various seasons.

When sampling natural waters attention is directed mainly to determining the uranium content; a large proportion of the samples are analyzed also for radon; radium is determined only in a few selected samples, as well as in all cases where the water samples show high uranium or radon content.

At sections where reduction conditions develop in the waters, for instance, in waters circulating in highly bituminous rocks, determination of radium and radon in all the samples is necessary. The reason for this is that under such conditions uranium ores do not dissolve perceptibly in the waters, so that the latter, though they may have passed through ores, will be anything but high in uranium, though in this case they will always be anomalously rich in radium and radon (however, the latter disintegrates quickly, so that several hundred meters away from the ore its content will not be extraordinarily high).

In those cases where the waters of springs, streams or other water sources are found to be anomalously high in uranium and other radioactive elements, a more detailed hydrogeochemical investigation is carried out over the area watershed from which these waters take their source, supplemented by geophysical prospecting and other methods. A complete chemical analysis is made of all the anomalous waters, the composition of the dissolved and spontaneous gases determined when necessary, and regular observation of the behaviour of the radioelements and other dissolved components organized in time.

Methods, based on the adsorption of uranium from natural waters by an adsorbent are used for the determination of small uranium amounts in natural waters. The uranium sample, thus adsorbed is determined by means of fluorimetric or colorimetric analysis.

The content of the element in the waters can be determined quite accurately, quickly and easily, so that properly equipped field laboratories serve well enough for the mass water sampling done by field and prospecting parties. The necessary determinations of radium and radon are made by usual geophysical methods.

The most complicated part of a hydrogeochemical investigation is the interpretation of the data obtained by the sampling of the water sources. In the scientific development of the hydrogeochemical method this problem drew the greatest attention. For this purpose a number of conformities with the migration laws of radioactive elements in various underground waters had to be ascertained.

The interpretation of facts is based on the principle of anomaly, the essence of which consists in the following. The mass sampling of the water sources gives sufficient ground to establish the normal, usual content of uranium and other radioelements in the waters, i.e., of the so called natural hydrogeochemical background.

The natural hydrogeochemical background is not established as a set of universally applicable values of the radioelement content in underground waters, but is determined separately for each definite type of rock, and for each district. When rocks of the same kind occur under substantially differing climatic conditions a separate natural background is established for each climatic zone. This is especially important in mountain regions, where the vertical climatic zones often rapidly change.

When establishing the background uranium content in the underground waters of any given rocks, the hydrogeochemical conditions under which those rocks occur are always taken into consideration—whether these conditions promote oxidation with free oxygen occurring in underground waters, well below their level, whether they are bituminous and promote reduction, or whether they otherwise promote the solution of the ores and the migration of

uranium in the underground waters, or interfere with them. The natural background itself varies over a wide range, from $n \times 10^{-8}$ to 5×10^{-4} gm/l of uranium, and thus, what is a natural hydrogeochemical background in some districts will be a strongly anomalous phenomenon in others, if differences in the water-bearing rocks, climatic and other conditions are not taken into consideration. Thus, for instance, in regions with a dry climate, the underground waters in the zone of intensive water exchange often contain $n \times 10^{-5}$ gm/l uranium, as a result of their passage through barren rocks substantially enriched with uranium. In anomalous waters, which have passed through ores, the uranium content increases to $n \times 10^{-3}$ gm/l and more. In adjacent districts the waters of the same rocks, but under climatic conditions of high altitudes, usually contain $n \times 10^{-7}$–$n \times 10^{-8}$ gm/l of uranium, while anomalous waters formed by passing through a uranium mineralization often contain only $n \times 10^{-5}$–5×10^{-4} gm/l.

Thus, the hydrogeochemical background is established individually for the underground waters of each kind of rock, for different climatic zones, for definite seasons of the year, for different hydrogeochemical conditions, taking into account the geomorphological and other differences between districts.

When the usual background contents of uranium or other radioactive elements in the underground waters is known, there is no difficulty in revealing the anomalous water sources, in which the content of these elements in the water exceeds by a factor of 10 or more the natural background (for the same season): for instance, 5×10^{-5} gm/l of uranium or more with the usual uranium content in the water of these rocks averaging 5×10^{-6} gm/l. The same refers also to radium. Waters are considered anomalous in radon if its content exceeds the natural background by 20 me or more.

An estimation of the research significance of the revealed water anomalies is made by careful analysis of the possible causes and conditions for their occurrence. In each case an individual assessment is made of the geological structure, the hydrogeological conditions, and the geomorphological and other peculiarities of the watershed area from which the anomalous source draws its waters.

The first thing that has to be established is whether the watershed area contains any foreign rock massifs of minor area, but with high uranium content, which could raise the natural background for the mixed waters without any anomaly in uranium content really existing.

Knowledge of the geomorphology of the district is important because it is possible to establish the time of opening of the geostructure of the area, thus making it also possible to determine the difference of intensity and depth effect on rocks and ores of active water exchange. On areas with well developed weathering crusts, where the deposits are intensively oxidized and washed by underground waters to a depth of several tens of meters, the uranium content anomalies are, as a rule, not so pronounced. Therefore, in some cases, in well washed structures water anomalies with an excess of only half an order (over the natural background) are significant from a prospecting standpoint. For instance, a uranium content in waters of shallow circulation (springs, wells, etc.) amounting to 6×10^{-6}–5×10^{-5} gm/l with a background of $n \times 10^{-7}$ gm/l may serve as an indication of a deposit which has survived erosion by underground waters at some depth or other.

In districts with already known deposits the peculiarities of the ores, their composition, permeability and other factors influencing the ore solution by underground waters should be taken into account. Thus, for instance, compact pitchblende or amorphous oxide ores enrich the underground waters in radioelements less than loose amorphous oxide ores. Water anomalies arising from the solution of compact ores are less sailent, so that the uranium content in anomalous waters exceeding the natural background by a factor of only 5 to 10 times may indicate commercial ore occurrences.

In interpretating water anomalies a more complete character of given anomalous waters and the surrounding hydrogeochemical background must be available (in Ra and Rn content, chemical composition, etc.).

High concentrations of radium in anomalous waters are also good indications for prospecting, while a high radon content is indicative of an uranium mineralization which caused the water anomaly, being comparatively near the water source in which this content was observed.

In some cases a more correct analysis of the causes of a water anomaly can be made by using the data on the chemical and gaseous composition of the anomalous waters, inasmuch as anomalous waters sometimes differ in this respect from the surrounding waters. Thus, for instance, in some districts waters anomalous in uranium are distinguished by a high sulphate content, since uranium ores are usually associated with sulphides.

In interpretating water anomalies it is especially important to take into consideration the hydrogeological conditions over the area supplying these waters (the direction of flow of the anomalous waters, etc.). If the anomalous waters are considerably diluted, especially when they join streams, in some cases an excess of uranium content of from one half to one order, i.e., from 5 to 10 times, compared to the natural background, may be considered a favourable sign in prospecting.

In deciding upon the research significance of water anomalies climatic peculiarities of the district should be taken into consideration. Thus, for instance, in a district with a dry climate an anomalously high uranium content may occur in the waters due to the evaporation of soil waters; this leads to the formation of false anomalies.

Establishing the research significance of data on the radium and radon content in waters is based on similar principles.

In some cases, to establish the research significance of water anomalies, especially in districts with highly developed loose formations covering the outcrops of the lode rocks, special work is done with a view to delineating the halos of anomalous waters in order to find their sources and determine the location and extent of possible uranium mineralization. For this purpose pits or drill holes are sunk to strike the underground waters.

The final decision as to the prospecting significance of water anomalies is made after all the data on the geology, mineralogy and geochemistry of the districts under consideration have been taken into account. After this, the necessary geophysical, hydrogeological and other kinds of geological and prospecting investigations are started in the promising districts.

The use of the hydrogeochemical method has led to the discovery of new ore-bearing districts and deposits, as well as new orebodies in deposits already being mined or prospected.

In recent years the Geological Survey of the USSR has begun to make use of scientific principles underlying the hydrochemical method for prospecting deposits of other commercial metalliferous minerals (base metals, molybdenum, etc.).

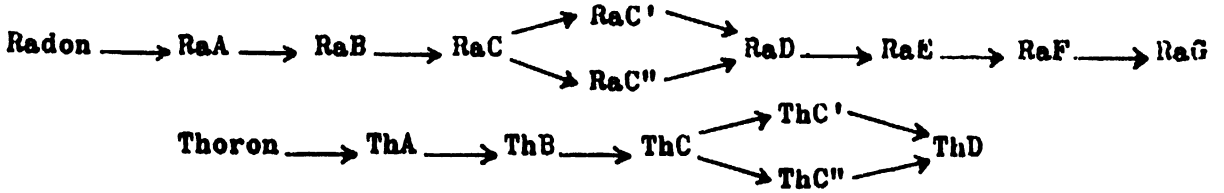
The hydrogeochemical method is a result of the joint efforts of hydrogeologists, geochemists and chemists. Its scientific development and practical initiation in prospecting was carried out by the Academy of Sciences of the USSR, the Ministry of Geology and Protection of the Mineral Resources of the USSR, and a number of other organizations.

Remote Location of Uranium and Thorium Deposits

By K. G. Vohra,* India

Investigations on radon and thoron and their decay products in the atmospheric air have suggested new techniques of prospecting for uranium and thorium mineral deposits. It is found that a correlation of the measurements of radon and thoron decay products in an air mass with wind and other meteorological data can give information about the surface deposits of uranium and thorium over which the air has blown. This study can be made at remote distances from the mineral deposits and useless scanning of vast areas can be avoided.

Uranium and thorium minerals are widely distributed in the earth's crust. Their decay products radon and thoron, which are gases, are constantly produced in all rocks and soil. They are discharged into the atmospheric air owing to daily variations in the atmospheric pressure and subsequent diffusion. Thus the normal atmospheric air becomes contaminated with radon and thoron. This contamination is higher in areas having higher concentrations of uranium and thorium minerals. Measurements of radon and thoron contents of the air have been made at many places since the discovery of radioactivity[1,2,3] and large variations have been observed. These variations are partly caused by meteorological factors and partly by the variable uranium and thorium contents of different rocks and soil. After the radon and thoron emanations are acquired by the air by exhalation from the rocks and soil, mixing takes place rapidly, since the wind flow near the surface is almost always turbulent. Vertical transport of the emanations is caused by the convection currents of the air. The emanations decay in the air and during mixing and movement the air contains varying proportions of the decay products of radon and thoron. The decay schemes of radon and thoron are shown below:



The winds carry the radioactive matter great distances horizontally. At any remote place the radioactive composition of the air can be determined, from which the time of origin of a particular emanation in the air can be deduced. The time elapsed since the air picked up the emanation has been called the "age" of the air. Knowing the "age" of the air, the trajectories of the winds and velocity of the air, information about uranium and thorium mineral deposits can be obtained.

Collection of Deposits from the Air

As the emanation decays in the air, the recoil atoms of the decay products resulting in the processes of alpha and beta decay are ionised. They behave in the air just as normal atmospheric ions. The radioactive ions are neutralised by recombination with normal ions and probably get attached to atmospheric aerosols in the process. These radioactive ions can be collected on negatively charged electrodes exposed in the air. The present experiments are based on the collection of radioactive ions. The ions are collected with high efficiency in an ion collector shown in Fig. 1. The wind tunnel is 80 cm long and 8 cm in diameter. The collecting rod is a steel rod placed axially to the wind tunnel and is 8 cm long and 1.5 mm in diameter. An exponential horn is coupled at the inlet to get a streamlined flow of air. The air is drawn through the wind tunnel by means of a fan. A potential of −2000 volts is applied to the collecting rod. Alpha activity of the deposits collected on the rods is measured with a proportional counter. The decay curves are followed for several hours. A theory has been developed for the analysis of decay curves of the deposits obtained by ion collection. The theory is outlined below.

Development of Theory

The radioactive ions disappear by recombination as well as by radioactive decay. The value of the recombination constant depends on several factors.[4] If we consider the decay constant λ' for the transition: Positive ion → neutral atom, the half value period ln $2/\lambda'$ or the average life $1/\lambda'$ may be associated with an ion by analogy with radioactive

* Atomic Energy Establishment, Trombay.

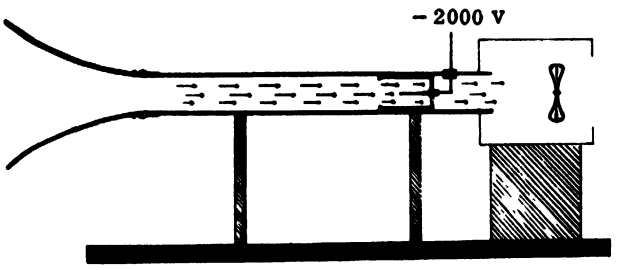


Figure 1. The ion collector

decay. The average life will vary greatly according to circumstances, but there is a fair agreement in literature regarding its order of magnitude.[5] The value is found over land areas to lie between 10 and 60 seconds, and is higher over the oceans. In the present theory two values of λ' have been considered.

Let us first consider the case of radon and its decay products in the air. Suppose N_0 atoms of radon are introduced into a volume of air at time $\tau = 0$. The numbers I_1, I_2, I_3 of ions of RaA, RaB and RaC respectively in this volume of air at a subsequent time τ are given by the following general equations.

$$\frac{dI_1}{dt} = \lambda_0 N_0 - (\lambda_1 + \lambda') I_1$$

$$\frac{dI_2}{dt} = \lambda_1 N_1 - (\lambda_2 + \lambda') I_2$$

$$\frac{dI_3}{dt} = \lambda_2 N_2 - (\lambda_3 + \lambda') I_3$$

where λ_0, λ_1, λ_2, and λ_3 are the decay constants of radon, RaA, RaB and RaC respectively and λ' is the recombination constant. N_1 and N_2 are the numbers of atoms of RaA and RaB respectively, in the air at time τ. The first term in each of these equations gives the rate of production of ions by the decay of the parent, and the second term gives the loss of ions by recombination as well as by radioactive decay. On integration, these equations give the values of I_1, I_2, and I_3. These values have been calculated for different values of τ, the "age" of the air and are shown in Table I. This table has been calculated for $N_0 = 10^6$ atoms, and $\lambda' = 0.693$ and 0.30 corresponding to the half lives of 1 minute and 2.31 minutes respectively for the ions.

Table I. Growth of Ions in the Air

τ=(age of the air)	5 min	10 min	20 min	60 min	150 min
		$\lambda'=0.693$			
I_1 (RaA)	135.2	136.5	136.4		
I_2 (RaB)	95.1	148.7	171.7	173.8	
I_3 (RaC)	5.4	19.9	52.7	129.4	160.7
		$\lambda'=0.30$			
I_1 (RaA)	221.4	237.1	238.0		
I_2 (RaB)	151.0	288.5	371.7	383.3	
I_3 (RaC)	7.7	34.1	103.1	277.1	361.3

If we now assume that a volume of air which contained 10^6 atoms of radon at $\tau = 0$ passes the ion-collector per minute, the values in Table I will give the rates of collection of the different ions for different values of the "age" of the air. After a sufficiently long time the collection of RaA ions will give an equilibrium deposit of Ra(A+B+C). Similarly collection of RaB ions will give an equilibrium deposit of Ra(B+C). RaC is produced in both of the above processes and is also collected directly as RaC. At equilibrium the rates of collection of ions in the above series will be the same as the rates of decay of atoms on the collector. From rates of collection from Table I for $\tau = 10$ minutes, the following equations can be written at equilibrium.

$$\lambda_1 N'_1 = \lambda_2 N'_2 = \lambda_3 N'_3 = 136.5 \ldots.$$
rate of collection of RaA ions

$$\lambda_2 N'_2 = \lambda_3 N'_3 = 148.7 \ldots.$$
rate of collection of RaB ions

$$\lambda_3 N'_3 = 19.9 \ldots.$$
rate of collection of RaC ions

where N'_1, N'_2, and N'_3 are the numbers of atoms of RaA, RaB, and RaC respectively on the collector. The total number of atoms of RaA, RaB, and RaC on the collector for $\tau = 10$ minutes can be calculated from these equations. This is done in Table II for different values of τ.

Table II. Deposit on the Collector

τ=(age of the air)	5 min	10 min	20 min	60 min	150 min
		$\lambda'=0.693$			
N'_1 (RaA)	594.7	600.5	600.0	598.0	585.0
N'_2 (RaB)	8906	11,028	11,915	11,980	11,833
N'_3 (RaC)	6698	8674	8908	12,484	13,418
		$\lambda'=0.30$			
N'_1 (RaA)	973.9	1043	1047	1048	1021
N'_2 (RaB)	14,401	20,325	23,577	24,033	23,743
N'_3 (RaC)	10,805	15,909	17,624	25,543	27,714

The total alpha activity of a sample will be the sum of activities due to the initial deposits of RaA, RaB, and RaC. Table II shows that the total deposits on the collector increase with the "age" of the air. The growth of total alpha activity with the "age" of the air has been evaluated and is shown in Figure 2*A*. Figure 2*B* shows the normalised decay curves of the deposits for two extreme cases in Table II for $\lambda' = 0.693$. The remaining curves fall between these two extremes. The decay curves for $\lambda' = 0.30$ are similar to these curves. The decay curves show the following features:

1. All the curves have a closely similar trend which is not sensitive to the "age" of the air.
2. Between $t = 20$ min and $t = 60$ min the decay curve is almost linear (t is the time after removal of the collector).
3. The activity at $t = 60$ min is very closely one half of the activity at $t = 20$ min.

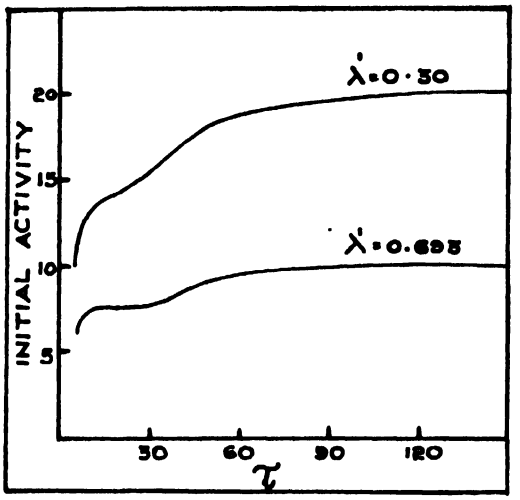


Figure 2A. Activity on the collector at $t = 0$ as a function of τ for two values of recombination constant

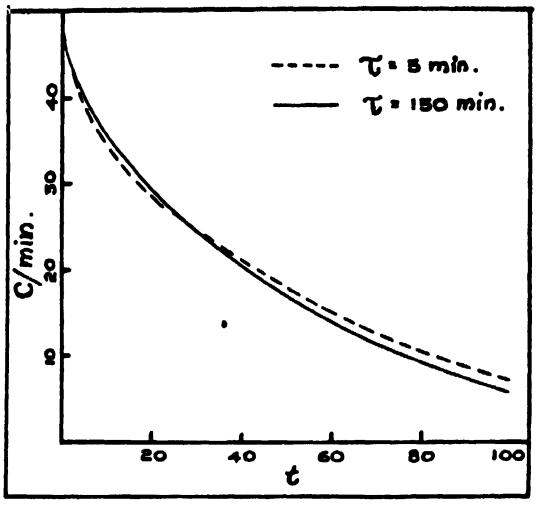


Figure 2B. Normalized decay curves of the deposits on the collector for $\tau = 5$ min and $\tau = 150$ min

4. In the range studied, a variation of the decay constant for the recombination does not significantly affect the nature of the curves.

THE CASE OF THORON CONTAMINATION

Most of the thoron picked up by the air from the rocks and soil containing thorium-bearing minerals breaks up into its decay products within a few minutes. Its next decay product ThA is highly unstable (half life 0.14 sec) and may be excluded from the present analysis. ThB is, however, fairly stable and can remain in the air for a long time. In order to collect the ions of ThB from the air, thoron should have recently decayed to give the ions of ThB. The ions disappear by recombination much more rapidly than by radioactive decay. Consequently, old ThB which will be in a neutral state cannot be collected in an ion collector—though it will give rise to ThC ions. If a sufficient number of ThB ions is collected, it is a definite indication that the source of thoron is nearby. The fresher the thoron contamination, the higher is the ratio of ThB to ThC ions in the air. The following treatment gives ThB/ThC ratio for different values of τ where τ is again the "age" of the air which picked up thoron at $\tau = 0$.

Proceeding in the same way as in the case of radon contamination, let us again assume that a volume of air picks up N_0 atoms of thoron at $\tau = 0$. The number of ions of ThB and ThC in this volume at a subsequent time τ have been evaluated in the same way as in the case of radon and are shown in Table III.

If we assume that a volume of air containing 10^5 atoms of thoron at $\tau = 0$ passes the collector per minute, the values in Table III give the rates of collection of each type of ions for different values of the "age" of the air. Let these rates be denoted by R_1 and R_2 for ThB and ThC respectively. Total amount of ThB on the collector for a collection time T is given by

$$N_B = \frac{R_1}{\lambda_1}(1 - e^{-\lambda_1 T})$$

where λ_1 is the decay constant of ThB. ThC is produced on the collector by the decay of ThB during collection and is also collected directly as ThC. Total ThC collection at the end of time T is given by

$$N_C = \frac{R_1}{\lambda_2}\left[1 - \frac{\lambda_1 e^{-\lambda_2 T} - \lambda_2 e^{-\lambda_1 T}}{\lambda_1 - \lambda_2}\right] + \frac{R_2}{\lambda_2}(1 - e^{-\lambda_2 T})$$

where λ_2 is the decay constant of ThC. For a collection time of 8 hours, a value often used in the experiments, the number of atoms of ThB and ThC on the collector and ThB/ThC ratios for different values of air "age" are given in Table IV.

ThB/ThC ratio shows a rapid decline with the "age" of the air. Using this ratio as a convenient parameter, theoretical decay curves showing the activity of the collecter as a function of time after removal for three different values of ThB/ThC ratio are shown in Fig. 3*A*. The slopes of the logarithmic plots give ThB/ThC ratios. Knowing

Table III. Number of Ions of ThB and ThC in the Air for $N_0 = 10^5$

τ=(age of the air)	2.5 min	5 min	7.5 min	10 min	15 min	20 min
I_1 (ThB)	30,945	10,061	2463	534	22	1
I_2 (ThC)	84.5	135.8	149.8	152.6	152.6	151.8

Table IV. Deposits of ThB and ThC on the Collector for a Collection Time of 8 hours; and ThB/ThC Ratios for Different Values of T

τ=(age of the air)	2.5 min	5 min	7.5 min	10 min	15 min
N_B	1,156,538	376,020	92,053	19,958	822
N_C	94,033	31,514	8728	2936	1392
N_B/N_C	12.3	11.9	10.5	6.8	0.59

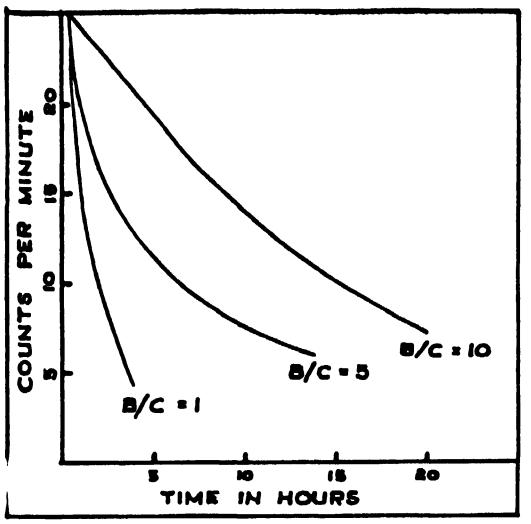


Figure 3A. Theoretical decay curves for three values of N_B/N_C (marked B/C on the diagram)

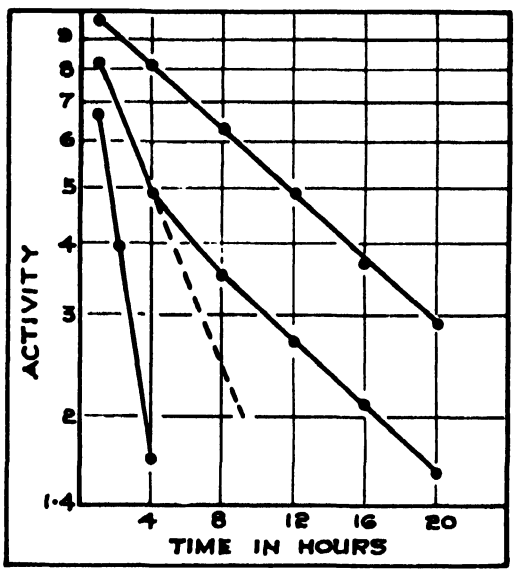


Figure 3B. Theoretical decay curves of Fig. 3A with the activity plotted on a log scale

ThB/ThC ratio, the "age" of the air can be found with the help of the data of Table IV. The collections made nearer to the areas of thorium mineral deposits will give large ThB/ThC ratios. At greater distances from the deposits the activity will correspond to ThC decay and the activity curves will not show tails, i.e., an appreciable number of counts even after many hours. It follows that when the "tail" is found, the air must have picked up thoron very recently—not earlier than 15 minutes before it passes the collector.

EXPERIMENTS

The experiments have been carried out in Bombay, India. These initial experiments were not intended for locating any radioactive mineral deposits, but were designed to study the seasonal variations of the radioactive content of the air.

The collections were made at heights of 60 to 70 ft above ground to avoid the effects of excessive radon and thoron near the soil. The ion collector was placed in the open air at the top of a tower and was orientated to face the incoming winds. The collections were made from two different locations in the City separated by a distance of 4 miles. The air was drawn at an average rate of 8 litres per second. The instruments for the mesaurement of wind direction and velocity, and temperature were also set up near the ion-collector. The collection time ranged from 4 to 40 hours though most of the collections were made for 4 to 8 hours. Collections were made during the day time and especially during the hot hours of the day when the effects of convection and turbulence may be expected to give good mixing in the lower levels of the air. This would tend to make the measurements less dependent on the precise location of the collector.

A total of 40 collections were made during the years 1952 and 1953. Most of the collections were made during the prevalence of summer and winter monsoon winds. These are two major winds affecting Bombay and the same type of air mass persists for a period of about 3 months during each season.[6]

The alpha activity of the deposits was studied by mounting the collecting rods inside a proportional counter. The proportional counter has an alpha background of 30 counts per hour. The decay curves were followed for several hours.

ANALYSIS AND RESULTS

The decay curves fall in two distinctly different groups, one corresponding to the summer monsoon winds and the other to winter monsoon winds. The experimental curves of January, February and March are very closely similar to theoretical radon decay curves. These curves do show a linear trend between $t = 20$ min and $t = 60$ min and the activity drops to about half in this interval. The experimental points of a typical decay curve are shown in Fig. 4. Best fitting straight line has been calculated for the points lying between, and just close to, $t = 20$ min and $t = 60$ min and is shown in the graph. The actual points included in the calculation of the straight line by the method of least squares are shown solid in the figure. The deviations of the points from the straight line are within the normal statistical limits. This shows that the hypothesis of radon contamination during the months of the winter monsoon is correct. The calculated value of radon content is 128 atoms per litre. Calculation shows that if 10% of the atoms of radon in the uppermost 1 cm^3 of soil with an average uranium content of 10^{-6} gm per gm^7, are injected in the air per day, and if this is mixed in a vertical column of 1 km thickness, the observed value of radon content is fully accounted for. Since the winds during these months blow over large areas of land in the north and north-east of Bombay, the air will have the normal radon content. Thus one may infer that the land areas to the north and north-east of Bombay

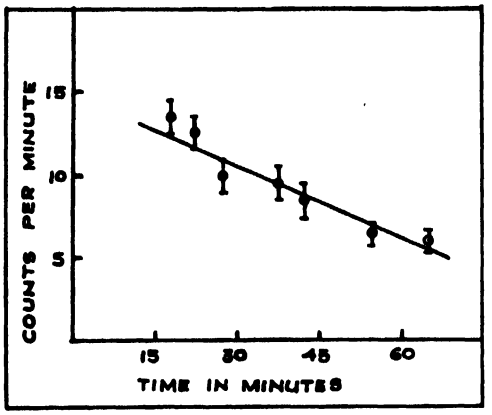


Figure 4. Experimental data of a typical collection made during the winter monsoon months

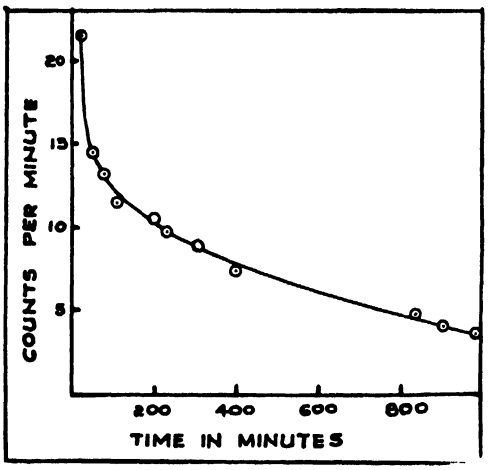


Figure 5. A typical experimental decay curve of collections made during the summer monsoon months

do not contain any extensive surface deposits of uranium over a distance of a few hundred miles. Much higher concentrations will be expected if the air had blown over any rich deposits of uranium. For example, the atmosphere of a normal uranium mine contains up to 10^8 atoms of radon per litre.[8] If the winds are consistently blowing in one direction, even after large dilutions, the concentration at a distance of several miles along the wind pattern may be expected to be higher than the observed value.

No attempt has been made to estimate the "age" of the air in the above experiments. The "age" of the air in the case of radon contamination has to be estimated by obtaining data from several stations simultaneously and correlating the results with Fig. 2*A*.

The second group of decay curves falls in the months of July, August and September—the months of strong summer monsoon activity. These decay curves show long "tails" corresponding to ThB. A typical decay curve of these months is shown in Fig. 5. The air "age" has been estimated for these collections and is found to lie in the range of 5 to 10 minutes. The small value of the air "age" shows that the winds must be picking up thoron on their way to the collector from a distance of a mile or two. This indicates the presence of traces of thorium-bearing minerals along the coastline in Bombay since the west and southwest monsoon winds must blow over this coast. This has been established by blowing air over a bed of sand from the local coast in a long box and collecting deposits from this air. These deposits gave stronger collections of ThB and large ThB/ThC ratios.

ION COLLECTION ON GEIGER COUNTER

In the experiments so far mentioned a proportional counter has been used for the study of decay curves. This counter has to be evacuated and filled every time a deposit is obtained and the process takes about 15 to 20 minutes, therefore, this part of the decay curve is lost. In an ion collector recently developed, the collection is obtained on the walls of a thin-wall Geiger counter and beta activity of the collections is studied. The counter has a glass wall of 15 mg per cm^2 thickness and the cathode is silvered on the glass wall. The counter wall is 8 cm long and 8 mm in diameter. The outer surface of the wall is coated with a thin layer of aquadag. The counter is placed in the wind tunnel or simply exposed in the open air with the collecting potential applied to the aquadag coating and a collection is obtained in the outer wall of the counter. The counting is started immediately after the collection is stopped. This ion collector has been successfully used in the laboratory. A number of collections have been studied during the past five months. The results are in general agreement with the previous results. This collecting and counting arrangement is simple and rugged as compared to proportional counter arrangement which requires a highly stabilised supply and a high gain linear amplifier. Owing to its simplicity, the ion collecting Geiger counter is easily adaptable to field investigations.

CONCLUSION

The technique of ion collection can be successfully used to estimate and analyse the decay products of radon and thoron in the air. Ion collection can give detailed information about the decay products which cannot be obtained by the methods of filtering or precipitation[3,9] recently used for natural radioactivity studies. Nevertheless, the filtering and precipitation techniques can be used to supplement the analysis. The "age" determinations in the present theory can be fairly satisfactory in the case of thoron contamination. In the case of radon the decay curves are not sensitive to the "age" of the air but the relative concentration of the decay products is "age" dependent. Therefore the theory is being further developed to give the activity ratios of radon and radon decay products. This ratio is sensitive to the "age" of the air. The radon can be freed from its daughters and measured independently by other methods.[10]

With the standardised apparatus the measurements could be carried out at fixed stations in a selected area, along with the relevant meteorological measurements. These measurements taken over a long period

of time will tell the general nature of radioactive minerals in the surrounding areas. New stations could then be established in the areas found suitable for detailed prospecting. Within a distance of a few hundred miles, the location of the mineral deposits could be predicted from the "age" determinations. The present experiments have established this possibility.

REFERENCES

1. Rutherford, E., *Radioactive Substances and their Radiation,* ch. 19, Cambridge University Press, Cambridge, Eng. (1913).
2. Aliverti, G., *Atmospheric Radioactivity,* N. Cimento 9: 313–327 (1932).
3. Kuper, J. B. H., Foster, E. H. and Bernstein, W., *Monitor for Radioactive Dust,* Nucleonics 6, No. 4, 44 (1950).
4. Chalmers, J. A., *Atmospheric Electricity,* ch. 3, Oxford University Press, London E.C. 4 (1948).
5. Schonland, B. F. J., *Atmospheric Electricity,* ch. 1, Methuen and Co. Ltd., London (1953).
6. Kendrew, W. G., *The Climates of the Continents,* ch. 19, Oxford University Press, London E.C. 4 (1953).
7. Hevesy and Paneth, *A Manual of Radioactivity,* II ed., p. 274, Oxford University Press, London (1938).
8. Tsivoglov, E. C. *et al., Occurrence of Nonequilibrium Atmospheric Mixtures of Radon and its Daughters,* Nucleonics 11, No. 9, p. 40 (1953).
9. Wilkening, M. H., *A Monitor for Natural Atmospheric Radioactivity,* Nucleonics 10, No. 6, p. 36 (1952).
10. Evans, R. D., *Apparatus for the Determination of Minute Quantities of Radium, Radon and Thoron in Solids, Liquids and Gases,* Rev. Sci. Inst., 6, p. 99 (1935).

Geophysical Exploration for Uranium on the Colorado Plateau

By R. A. Black,* USA

Uranium deposits are widely scattered over the Colorado Plateau region of Colorado, New Mexico, Arizona, and Utah. The major uranium-bearing formations are the Shinarump conglomerate and the Chinle formation of Late Triassic age, and the Entrada sandstone, the Todilto limestone, and the Morrison formation of Late Jurassic age. The deposits in the Shinarump and Morrison have been the chief target of the geophysical methods. The Morrison formation in western Colorado consists of the upper Brushy Basin and lower Salt Wash members. The Brushy Basin member consists of alternating layers of sandstone and shale, and the Salt Wash member consists of beds of sandstone separated by mudstone splits. The uranium deposits of the Morrison are commonly found in the sandstone strata of the Salt Wash member as thin, irregular, tabular layers ranging in width from a few feet to several hundred feet. Their lateral distribution is irregular, and they tend to occur as clusters. The ore-bearing sandstone is commonly lenticular, is interbedded with mudstone, and in many places contains mudstone splits. The most favorable geologic conditions for the occurrence of uranium deposits in the Salt Wash sandstone member are considered to be the thickening of the lenticular sandstone, pale-brown to light-brown color of the sandstone, and presence of altered gray-green mudstone underneath the Salt Wash member.[1] In the unfavorable areas the sandstone is thin, contains many mudstone splits, is red brown in color, and is underlain by red brown mudstone.

The Shinarump conglomerate varies in composition from a fine-grained sandstone to a coarse conglomerate, is usually crossbedded, contains local lenses of shale and mudstone and much silicified wood. The Shinarump conglomerate unconformably overlies the Moenkopi formation of Early and Middle(?) Triassic age. The Moenkopi is composed of thin, hard, red shales, red sandy mudstones and siltstones, and occasional layers of sandstone. The top of the Moenkopi formation is generally considered to be an erosion surface over which the conglomerates and sandstones of the Shinarump are spread. The Shinarump uranium deposits occur mainly in channel fillings in the Moenkopi formation, particularly where the channels contain carbonaceous matter and mudstone beds. The Shinarump conglomerate in turn is overlain by the Chinle formation which consists of a thick series of mudstones, sandstones, and conglomerates.

Since 1949 the applicability of many geophysical techniques to the search of this ore have been tested. These techniques include magnetic, electrical resistivity, natural potential, electric logging, seismic refraction and reflection, and surface-inhole electrical methods. The methods have been tested by making measurements over known Morrison and Shinarump ore deposits and over terrane known to be favorable for ore deposition, first in areas where the Salt Wash sandstone member and the Shinarump conglomerate were exposed at the surface, and then in areas where the Salt Wash and the Shinarump are overlain by rocks of different thicknesses and types. The various exploration methods were then used in areas which were geologically similar to those in which the particular method had been demonstrated to be successful.

SURFACE ELECTRICAL METHODS

Electrical-Resistivity Methods

Electrical-resistivity methods were among the first geophysical methods tested on the Colorado Plateau. Tests of the resistivity method were made over known ore bodies in the Salt Wash member during 1949–1950. During 1951–1952, several electrical-resistivity surveys were made to map favorable ground prior to drilling. In 1952 the electrical-resistivity method was successfully applied to the problem of locating buried Shinarump-filled channels.

Measurements were made with direct-current equipment and nonpolarizable electrodes; both the vertical and horizontal profiling techniques with the Lee partitioning configuration were used. In vertical profiling the electrode configuration is expanded outward from the station center, using increasing increments of electrode spacing. In horizontal profiling, several profiles are made with different electrode spacings, and when the optimum spacing is determined, this spacing is then used for the remainder of the profiles. The field procedures used on the Colorado Plateau are substantially the same as those in common use throughout

* US Geological Survey.

the arid sections of the world. One of the biggest problems is that of making satisfactory electrode contact with the earth. In many places on the Colorado Plateau the surface consists of thin, sandy alluvium overlying sandstones and shales which occasionally crop out at the surface. The potential electrodes are usually placed in shallow water-filled holes to establish a moist contact zone between the potential electrodes and the earth. In areas of exposed bedrock, small sections of copper screening covered with earth and saturated with water are used for potential electrodes. In areas of poor electrode contact it is necessary to balance the current electrode contact resistances to get reliable data.

The electrical-resistivity methods used on the Colorado Plateau have been primarily concerned with exploration for uranium deposits in the Morrison formation and in the Shinarump conglomerate. In areas where the deposits are in the Morrison formation, the resistivity depth profiling method proved capable of delineating the thick and thus more favorable parts of the ore-bearing Salt Wash member in areas where the member was not overlain by thick sections of the Brushy Basin member of the Morrison formation. The resistivity depth curves could be used to determine the relative thickness of the ore-bearing sandstone and the relative amounts of mudstone present in the sandstone. In general, the thicker, more favorable parts of the ore-bearing sandstone exhibited a higher resistivity than did the unfavorable sandstone. By making several vertical depth profiles on a grid pattern and evaluating each profile as favorable, semifavorable, or unfavorable on the basis of the indicated thickness of sandstone, amount of mudstone in the sandstone, and the resistivity of the sandstone, maps could be prepared showing the areas considered favorable, semifavorable, and unfavorable. Resistivity horizontal profiles were also made to detect the favorable spots to drill for uranium deposits. The thicker, more favorable parts of the ore-bearing sandstone could often be found as zones of anomalous high resistivity on the horizontal profiles.

Shinarump-filled channels are the principal target for resistivity surveys made to guide exploratory drilling for uranium deposits in the Shinarump. The Shinarump conglomerate in the Monument Valley area of southeastern Utah and northeastern Arizona forms two electrical layers in many places. The upper electrical layer, when present, is a thin layer in which the resistivity is high, ranging from 100,000 to 200,000 ohm-cm. In the thicker, main body of the Shinarump the resistivity is from 4000 to 12,000 ohm-cm. The high resistivity in the thin upper layer is probably due to the very dry well-cemented surface. The Shinarump is underlain by shales and siltstones of the Moenkopi in which the resistivity ranges from 30,000 to 90,000 ohm-cm. The resistivity of the Moenkopi is somewhat lower when it is exposed to surface weathering.

A combination of vertical and horizontal profiling techniques is usually used in surveys to locate the buried channels. The size of the channels may vary over a considerable range but an average channel is of the order of 100 to 200 feet wide with a depth of scour of 20 to 100 feet. In areas where there are no channels the Shinarump conglomerate is some 20 to 100 feet thick.

Figure 1 shows electrical resistivity depth curves and the resistivity horizontal profile over a Shina-

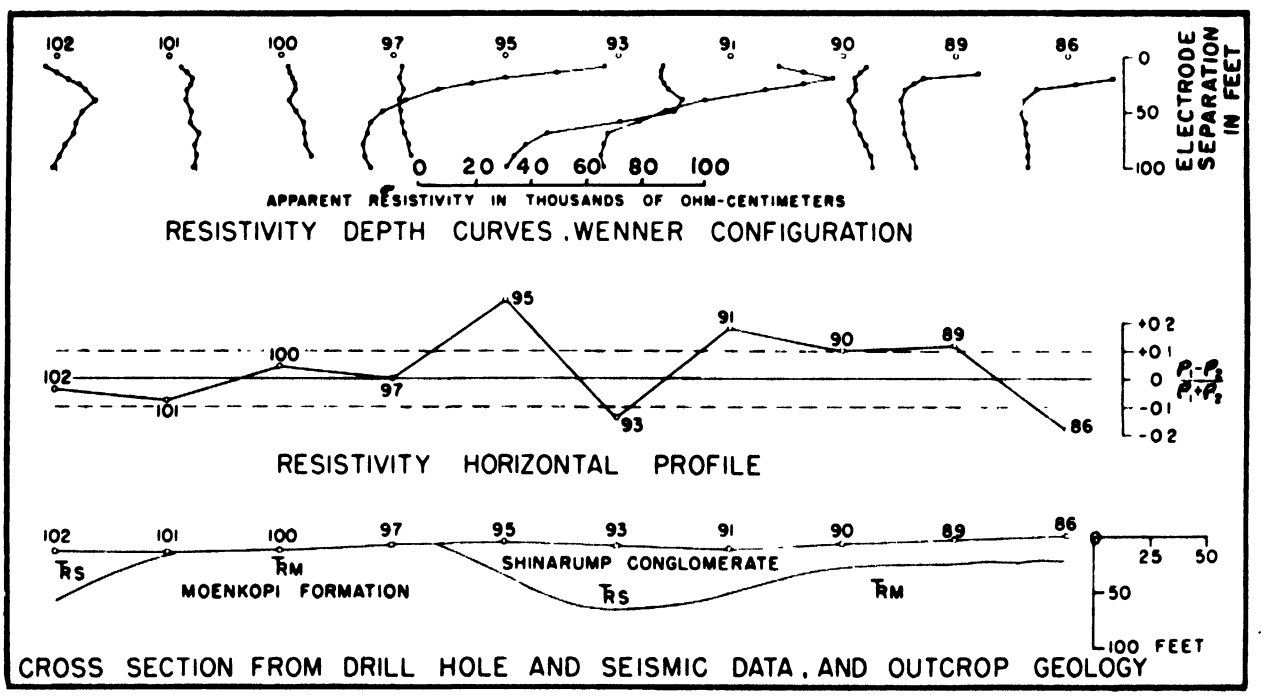


Figure 1. Resistivity depth curves and horizontal profile, and corresponding geologic cross section

rump channel. The depth curves and the horizontal profile show definite evidence of the buried channel. Methods used to interpret the depth curves range from matching the field curves to theoretical 2- and 3-layer curves, to simply correlating changes in curve character with known geology and extrapolating into unknown areas. The horizontal profiles are plotted as the ratio of the differences to the sum of the resistivities on either side of the Lee partitioning configuration. The area between the dashed lines represents "background noise" due to surface lateral variations and contact resistances. Figure 2 shows a number of resistivity horizontal profiles, made at an electrode separation of 60 feet, over known Shinarump channels and a profile over a non-channel area for comparison.

Natural Potential

The natural-potential method, where applicable, is undoubtedly one of the cheapest and most rapid methods of exploration for shallow ore deposits. Natural-potential methods have for this reason been extensively tested in various areas of the Colorado Plateau. Measurements have been made over uranium ore bodies buried at shallow depths and known to be undergoing active oxidation, but, in general, no significant natural-potential anomalies have been detected over these ore bodies.

SEISMIC METHODS

Seismic-Refraction Surveys

The seismic-refraction method was first used for mapping buried channels in exploration for uranium on the Colorado Plateau by Wantland and Casey of the US Bureau of Reclamation.[2] Additional field tests were made by the US Geological Survey in 1953. These tests showed that the seismic-refraction method could be used to locate buried Shinarump-filled channels where there was no Chinle overburden, and during 1953 and 1954 numerous seismic-refraction surveys were made in Monument Valley, Arizona, to outline major channel trends prior to exploration drilling.

The seismic-refraction measurements were made with standard portable seismograph equipment, installed in a four-wheel drive vehicle to permit more rapid coverage of rough areas.

The method of continuous profiling with reversed shots was used in making the seismic-refraction surveys. To map the average Shinarump channel, shot points were 500 feet apart and the geophones were spaced at 25- and 50-foot intervals. Air shooting was extensively used for the refraction seismic work. Single charges of 5 to 10 pounds of 60 percent seismic dynamite were fired from special shooting poles at heights of 3 to 5 feet above the ground. The records obtained from these air shots were comparable to those obtained from hole shots, and air shooting proved to be more economical because of its greater speed.

Inhole-velocity surveys were usually made to provide advance information on velocity characteristics of the formations to be investigated. These in-hole velocity measurements were made with inhole piezoelectric detectors and surface shots.

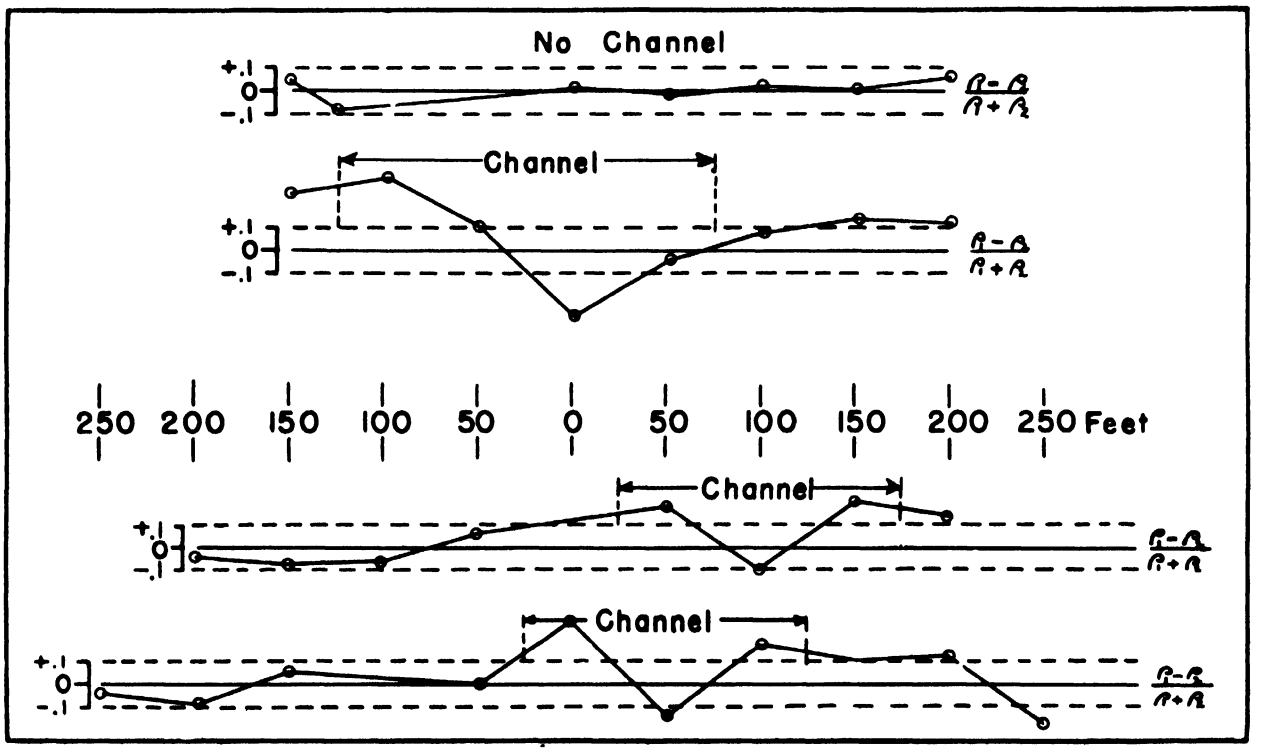


Figure 2. Electrical resistivity horizontal profiles over Shinarump conglomerate, Monument Valley, Arizona

To date, use of the seismic-refraction method on the Colorado Plateau has been restricted to the problem of locating buried Shinarump-filled channels. The velocity in the Shinarump conglomerate ranges from 3000 to 6000 fps, and in the underlying shale of the Moenkopi the velocity is 10,000 to 15,000 fps. Figure 3 shows a series of time-distance plots drawn from records obtained by continuous profiling and reverse shooting.

The method of interpreting the seismic data is a modification of a method suggested by Barthelmes[3] for calculating the depth to curved surfaces by the use of delay times. Depths to the Shinarump-Moenkopi contact at each shot were computed by conventional critical-distance or time-intercept methods. The dashed lines on the time-distance plots represent an average velocity in the Moenkopi in this area. Using this average velocity line and the apparent Moenkopi velocity line, delay times were plotted as shown. These delay times were migrated toward their respective shot points and then averaged. The adjusted delay time curves for the zones between the shot points were converted to differential depths, and using the shot point depth computations as control, the topography of the Shinarump-Moenkopi contact was determined. In this particular instance, a small channel was revealed that did not show from the computed shot-point depths alone.

Figure 4 is a subsurface-contour map of the Shinarump-Moenkopi contact in an area in Monument Valley, Arizona. A channel clearly indicated by the seismic data was verified by subsequent drilling in this area.

Shallow Seismic-Reflection Surveys

In the summer of 1954, experimental shallow-reflection measurements were made to determine if usable shallow reflections could be obtained under the stratigraphic conditions present on the Colorado Plateau. The equipment used to make these experimental measurements consisted of a 12-channel portable reflection seismograph with high frequency response, high paper speed, and variable presuppression control.[4] The equipment is a conventional reflection seismograph modified to permit the recording of higher frequencies, at shorter time intervals after the first energy arrivals.

Shallow-reflection tests were made in three areas representing geologic conditions typical of Morrison and Shinarump uranium deposits. Shallow reflections were recorded in all three test areas, although they were often discontinuous and showed erratic step-outs which made interpretation difficult. More work is planned, using pattern charges and multiple geophones, to improve the character of the reflections. If record quality can be improved, it is possible that the shallow reflection technique will prove a valuable aid to uranium exploration.

BOREHOLE GEOPHYSICAL METHODS

Electric Logging

Although surface electrical-resistivity methods have been successfully used in exploration for relatively shallow Morrison uranium deposits, such methods could not be used where the overburden is thicker than 800 feet.

Experimental electric-logging tests were made in

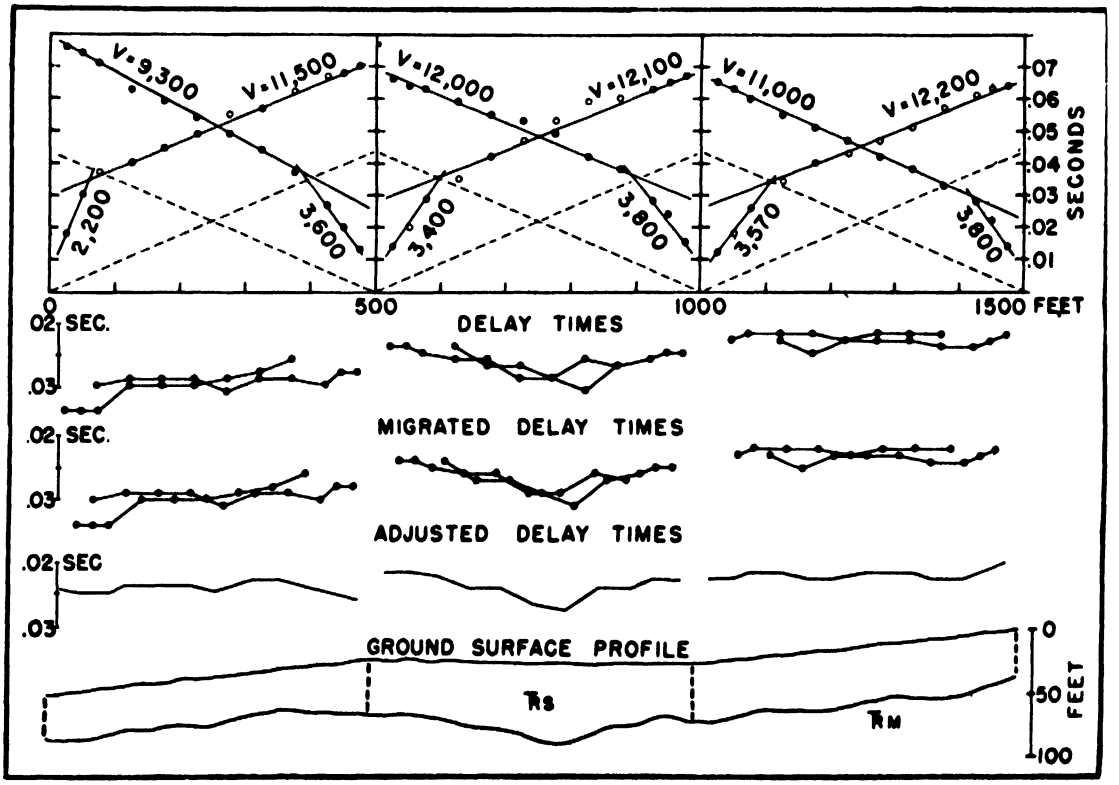


Figure 3. Time-travel plots, delay times, and corresponding geologic cross section

1953 by Keller[5] and 1954 by Miller using multiple electrode equipment, capable of recording self-potential logs, single-point resistance logs, 4-inch and 24-inch normal resistivity logs, and 18-inch lateral logs.

The electric logging tests suggested several possibilities that deserve further investigation. The single-point resistance log can furnish an accurate lithologic log, which can be used for stratigraphic correlation between drill holes from which there is poor or no core recovery. A combination of a single-point resistance log, a gamma-ray log, and wagon drilling would be a cheap, efficient exploration method. Electric logs, combined with inhole-velocity logs, provide an excellent means of evaluating the possibilities of surface geophysical work in any new areas in which the physical properties of the formations are unknown or in doubt. The discovery by Manger[6] of the possible association of changes of amount and salinity of pore water with uranium mineralization may mean that variations in pore-water saturations, and thus proximity to uranium ore deposits, can be mapped with electric logs.

Surface-Inhole Electrical Methods

Tests have also been made of combinations of surface and inhole electrical methods, in an attempt to extend the effective radius of drill holes by mapping directional resistivity trends from these drill holes. Variations in apparent resistivity were measured in a radial pattern around drill holes, employing both surface and inhole electrodes. A modified electric logging unit was used with surface electrode configurations to make the directional resistivity measurements. A number of different electrode configurations[7] were tested using a 16 cycles-per-second current and recording the potential readings continuously as the inhole electrode moved up the hole.

Lateral-resistivity changes can be mapped with this method, but great care must be taken to avoid false directional resistivity anomalies due to variable contact resistances between the surface electrodes and the earth. Surface-inhole electrical methods may prove to be of value by effectively increasing the area investigated by a drill hole from a matter of inches to as much as 200 feet.

OTHER GEOPHYSICAL METHODS

The electrical properties have been determined for several cores of the Morrison formation obtained by special drilling procedures to preserve the natural water content. These measurements indicate that significant differences exist between the dielectric constants of the mudstones and sandstones of the Morrison, when measured at low frequencies. The measurement of charge-discharge curves may be useful in tracing lithologic variations in the Salt Wash sandstone member of the Morrison formation.

The laboratory measurements on natural state Morrison cores also indicate that radio waves may be useful in investigating lithologic variations in the sandstones of the Morrison. The rate of attenuation of radio waves in mudstones of the Morrison is many times greater than in sandstones of the Morrison, and the sandstones may thus act as dielectric wave guides. It is possible that measurements of the rates of decay of radio waves initiated within the sandstone may permit mapping of lithologic variations within the sandstone.

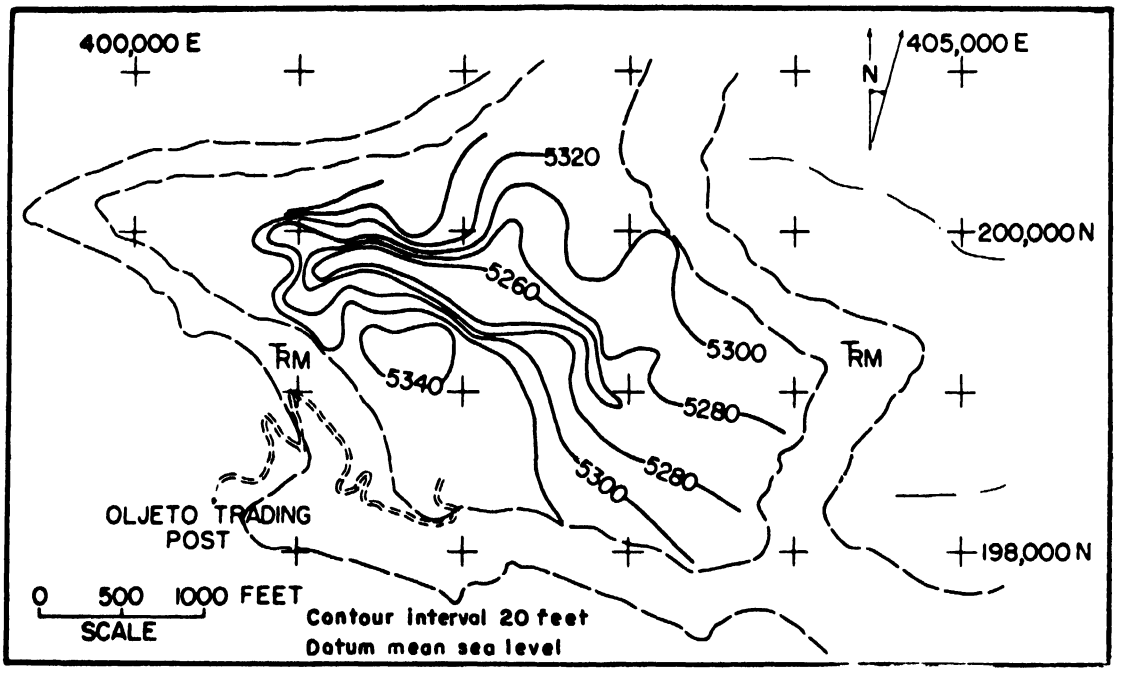


Figure 4. Subsurface countour map of top Moenkopi formation as determined from seismic data

The electromagnetic induction method may also prove applicable to prospecting for uranium deposits. Arid country, with its dry surface layer, is particularly favorable for the electromagnetic-induction method as a nonconducting surface layer permits greater depth penetration. Experimental surveys are to be made in the summer of 1955.

SUMMARY

The US Geological Survey has tested a wide variety of geophysical methods on the Colorado Plateau to determine which could be used to aid in exploration for uranium deposits. The seismic refraction and the electrical resistivity methods have proved particularly applicable to uranium exploration. Magnetic and natural potential methods have as yet proved to have no direct application to uranium exploration.

Shallow seismic reflection, electric logging, and surface-inhole electrical methods have been tested, but not enough information has been obtained to determine fully their application to uranium exploration. Induced polarization, radio frequency, and electromagnetic induction methods look promising and will be further developed in the near future.

REFERENCES

1. Weir, D. B., *Geologic Guides to Prospecting for Carnotite Deposits on the Colorado Plateau*, US Geological Survey Bulletin 988-B (1952).
2. Wantland, D. and Casey, R. D., *Field Tests for the United States Atomic Energy Commission on the Use of the Seismic Geophysical Method for Tracing "Buried Channels" in the Monument Valley Area, Arizona*, US Bureau of Reclamation Geology Report G-123 (1952).
3. Barthelmes, A. J., *Application of Continuous Profiling to Refraction Shooting*, Geophysics 11: 24-42 (1946).
4. Pakiser, L. C. *et al.*, *Mapping Shallow Horizons with Reflection Seismograph*, American Association Petroleum Geologists Bulletin 38: 2382-94 (1954).
5. Keller, G. V., *The Application of Electric Logging to a Mineral Exploration Program*, Geophysics 19: 631-632 (1954).
6. Manger, G. E., *Original State Core Studies, in Geologic Investigations of Radioactive Deposits, Semiannual Progress Report, June 1 to November 30, 1954*, US Atomic Energy Commission, TEIR-490, Technical Information Service, Oak Ridge, Tennessee, 92-94 (1954).
7. Black, R. A., *District Geophysical Studies, in Geologic Investigations of Radioactive Deposits, Semiannual Progress Report, June 1 to November 30, 1954*, US Atomic Energy Commission TEIR-490, Technical Information Service, Oak Ridge, Tennessee, 78-85 (1954).

Geophysical-Geochemical Prospecting for Uranium

By M. E. Denson, Jr.,* USA

Geophysical and geochemical exploration methods are based upon determination of variations in some physical or chemical property associated with a mineral deposit. The unique property of radioactive disintegration of thorium and uranium has aided immeasurably in surface prospecting for these metals. A thin (2 feet or less) rock cover absorbs such radiation and, when the deposit is buried, other geophysical and geochemical techniques must be applied.

Proven aids in the search for radioactive materials are: seismic reflection and refraction, continuous interval velocity logging, electromagnetic induction, electrical well logging, surface resistivity, surface radiometric, and geochemical determinations of trace elements and associated anions.

Decisions on the kind and sequence of geophysical and geochemical techniques which may be most suitable for a given area are based upon geological, geophysical, and geochemical reconnaissance. To this end and also for interpretational purposes, representative soil, water, or rock samples are analyzed for physical property variations and chemical content.

Inherent variations attributable to topographic, geographic, and climatic or atmospheric effects are considered. Their effects may be evaluated empirically or statistically by means of extensive laboratory and field data.

FIELD SURVEY DATA

Southern Black Hills, South Dakota

Surface resistivity studies carried out at various locations in the southern Black Hills (area 1, Fig. 4), were initiated to confirm an apparent relation between permeable fracture systems and mineralizations and to outline known ore bodies.

Data have been obtained using modified Gish-Rooney equipment designed for use with three current and three potential electrodes and having a variable power supply. One man can complete eight depth profiles per day with this equipment; three men, thirty or forty profiles. Depth profiling ("electrical drilling") was carried out using the four equidistant electrode Wenner arrangement and the five electrode Lee configuration.

Surface resistivity data obtained from the East Red Canyon area are shown in Fig. 1. These results, which show apparent resistivity to a depth of 70 feet, clearly indicate that in this case mineralization is associated with anomalous values of resistivity. Both the ore-bearing horizons and the over-lying sediments exhibit resistivity values abnormally high for such thicknesses of clays, mudstones, silts and sands. Theoretical calculations to determine true resistivity were not made in view of the great number of lateral and vertical changes in stratigraphy.

Electric logs (single electrode, resistance) from the drilled holes along profile AA' (Fig. 1), and surface resistivity and geochemical data along the same profile are shown in Fig. 2. Water leaches of the soil samples were analysed for content of Ca, Mg, Na, K, HCO_3, CO_3, Cl, pH, conductivity and total dissolved solids.

These results indicate that at this locality the Ca/Mg ratio appears to be a significant exploration parameter. Displacement of the anomalous values down slope along the topographic surface is evident. When used in conjunction with surface resistivity surveys, geochemical field determination is economic and simple. The in-hole electric logs demonstrate that the contrasting variations shown in the electrical data obtained from surface measurements are related primarily to variations in sedimentation. Fracture systems may be of significance since different results were obtained (Fig. 2) from depth profiles run over the same points but laid out in different directions. Electric logs from Holes 5 and 19 at the ends of the section show a similar type of sedimentary unit which is totally different from the mineralized units which lense in and out between Holes 5 and 19.

Physical property determinations and petrographic inspection of cores indicate that the major sand unit at Holes 5 and 19 contains minor amounts of silica cement (locally recrystallized) and abundant clay cementing material. Porosity of this main unit is about 28% and permeabilities range from 600 to 900 millidarcies. Preliminary analyses (insufficient in amount for generalization) suggests that the porosities of the sharply bounded sand units in the intervening holes will average 23% or less and will have permeabilities considerably higher than those of Holes 5 and 19. Since the beds lie above the water table and are not water-saturated, infiltration of water from the bore hole takes place during logging operations. This precludes quantitive comparison of the departure magnitudes of the electric logs; however, the lower resistance values of the sand units at Holes 28, 30, 31, 34, and 35 denote a high water inhibition and hence a high permeability.

* US Atomic Energy Commission.

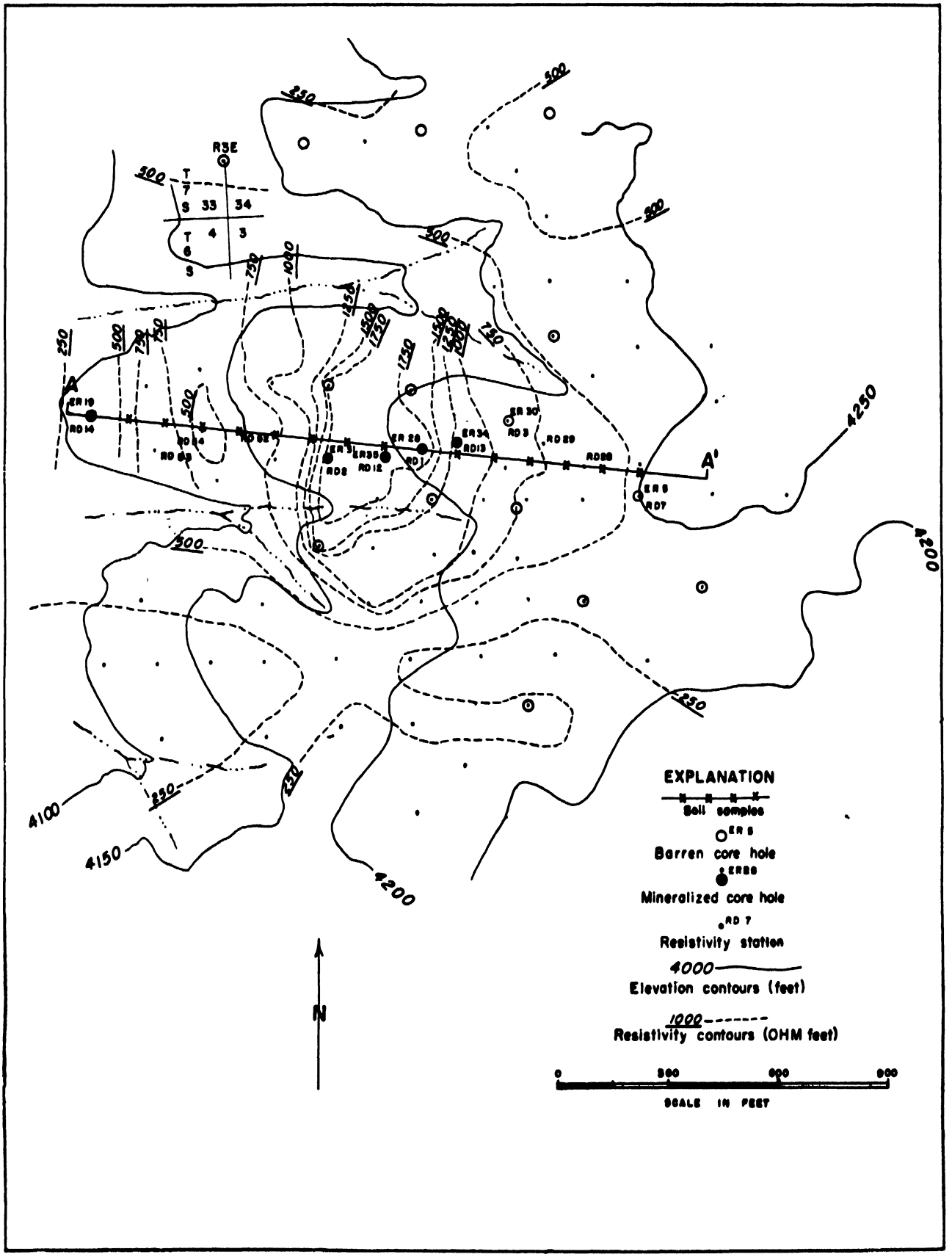


Figure 1. Surface resistivity data, East Red Canyon, Fall River County, South Dakota

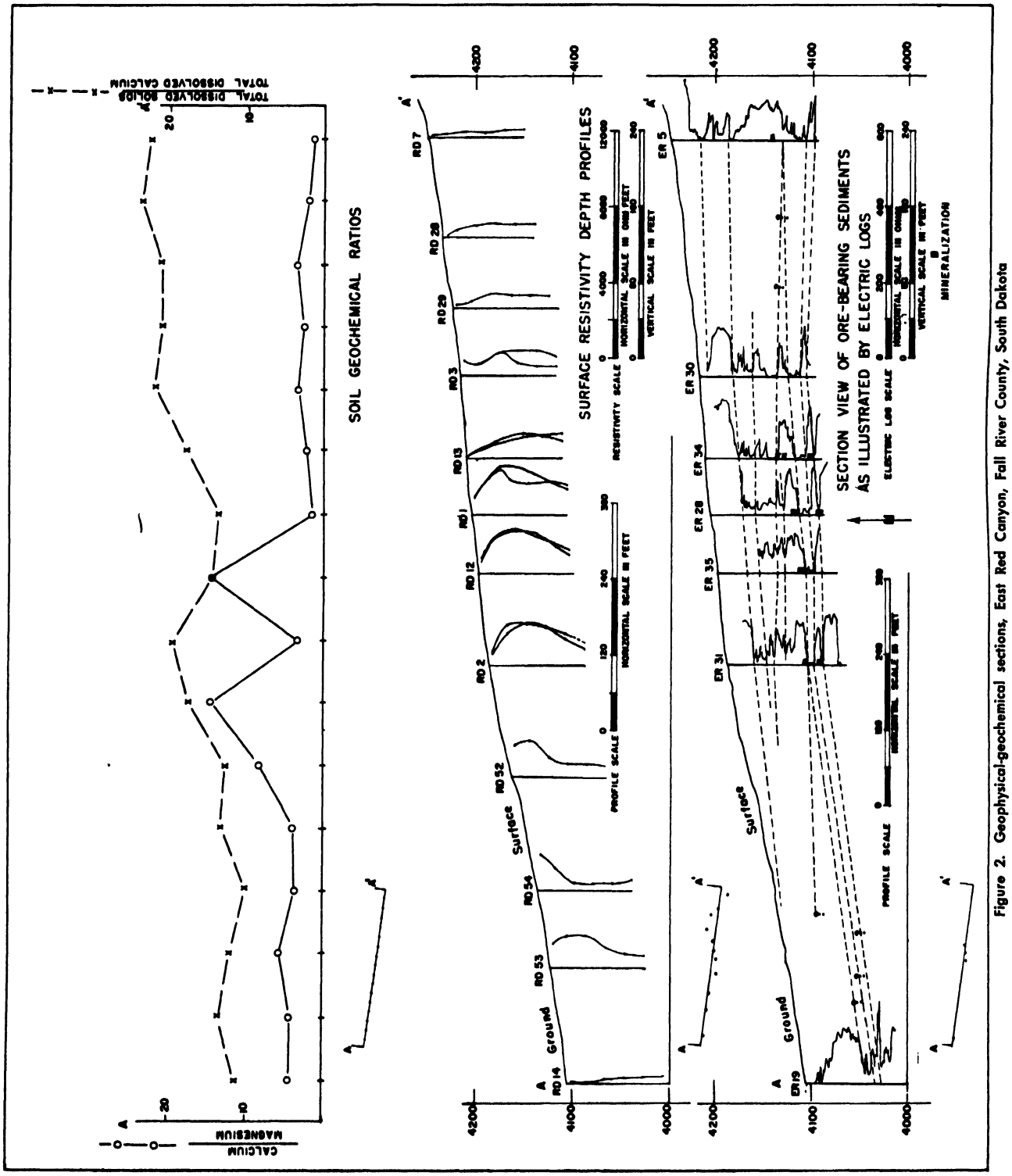


Figure 2. Geophysical-geochemical sections, East Red Canyon, Fall River County, South Dakota

Correlations extending in a north-south direction indicate a local sedimentary trend. This trend could be of a scour and fill deltaic depositional pattern or a change of facies as would occur along a terrestrial shore line. Data presented are believed to indicate a "channel-like" deposit having a hydrologic system different from the bounding strata. Measured electrical conductivities of water from wells in the southern Black Hills aquifers range from 1000 to 3150 microhms. Measurements on cores indicate that the formation waters of the East Red Canyon mineralized sediments contain very small amounts of dissolved solids and the formation resistivities range from 1400 to 10,000 ohm-cms. Mineralization in this area appears to be controlled both by structural and depositional factors.

Data from the Gould area, southern Black Hills, are shown in Fig. 3 and 4. Soil profiles (Fig. 3) were laid out in relation to resistivity patterns and sampled every 50 feet to determine possible useful relations between ore location, resistivity, and soil chemistry. Water leaches of the samples were analyzed for Ca, Mg, Na, K, HCO_3, CO_3, Cl, pH, conductivity, and total dissolved solids. No general relations can be stated but values shown on Fig. 3 indicate that variations in the ratio of HCO_3 to water conductivity are higher over non-ore bearing beds. Ca/Mg values vary in a manner consistent with variations at East Red Canyon although the values are more erratic, apparently because of topography. Correlation on the cross sectional fence diagram (Fig. 4) made from single electrode in-hole electric logs illustrate the complexity and variability of the stratigraphy in this area. Magnitudes of the electric log departures are not comparable since some holes would not hold water without continuous replenishment during logging operations. However, the types of departures at Holes 1, 7, and 9 illustrate scour and fill deposition where the high resistance sandstones (marked *A*) lie directly over impermeable mudstones of varying thickness. This type of departure contrasts sharply with the upward gradational transitions from mudstones to sandstones (marked *B*) on logs from Holes 11, 27*N*, and 135.

The linear patterns of the surface resistivity data (shown for a depth of 100 feet, Fig. 3) are interpreted as dominantly sand-filled scour channels braiding throughout the area. These high resistivity channel-like areas grade to low resistivity areas, as at 27*N*, 11, and 6 and at these locations the in-hole electric logs indicate transitional deposition. Limited analyses indicate that permeabilities in the channel-like units range from 2000 to 5500 millidarcies, while in the transitional units variation ranges from 30 to 2000 millidarcies. Decreases in permeability are caused by diminishing grain size and increased content of clay-sized cementing material.

The most abundant mineralization occurs at Holes 27*N*, 135, and 6 in or near surface resistivity transitional zones. The slight mineralization at Holes 1 and 9 at the base of the channel-like sand units may suggest that these permeable units have served as conduits for the mineralizing solutions. Variations in surface electrical data, interpreted to indicate changes in permeability between channel and transitional zone sediments are a useful exploration guide. Although no faulting is evident from the field data it is reasonable to assume that small scale faulting may have served as one of the controls on mineralization.

Wind River Basin, Wyoming

Results of in-hole electric logging studies and surface electrical surveys over the Bull Rush prospect, Gas Hills Area, of the Wind River Basin are shown on Fig. 5. Results from surface electrical depth profiles indicate the ore body there is centered in low resistivity sediments. The variations though clear, are of small magnitude, implying a high degree of water saturation. The concave-shaped low resistivity pattern on Fig. 5 (apparent depth 80 feet) which is bounded by higher resistivities suggests an overlapping transitional sedimentary sequence.

Correlations of the electric logs from open holes along the north-south profile (Fig. 5) illustrate the factors controlling the resistivity variations of the surface data. The logs indicate a slightly dipping, transitional sequence of sands and clays. The overlap or gradation of the predominant sands at Hole *A*-9 to predominant sandy clays or mudstones at Hole *A*-13 causes the change from higher to lower resistivity determined on the surface. The slight southern dip of the beds intersecting the topographic nose causes the anomalous pattern to be bow-shaped.

Whether the sediments close to Hole *A*-15 change in dip or in facies is not clear in view of lack of electric logs from the nearby holes, but a change in facies appears reasonable. A small flexure or fault, accompanied by dip changes near Hole *A*-15, would be consistent with data.

Electric logs from this area were obtained using a dry hole contact logging unit only recently developed. Axial length of the electrode contact (1 inch) is less than one quarter of the hole diameter which permits determination and comparison of the resistivities of beds whose thicknesses exceed about two feet. For such beds direct proportionality exists between true resistivity and measured resistance between 1 and 1000 ohms. This dry-hole tool has much advantage not only for indicating stratigraphic detail but also for quantitive interpretation of resistivity parameters. Magnitudes of the electrical departure on the logs are comparable. This dry hole unit has been run in holes which had been filled with fluid and logged with conventional single-point equipment. The dry hole logs are repeatable and compare closely with the wet hole logs except that more detail and definition is obtained with the dry hole unit.

DISCUSSION OF DATA

Surface and in-hole resistivity indicate that uranium mineralization is accompanied by variations in the sediments which are detectable by electrical

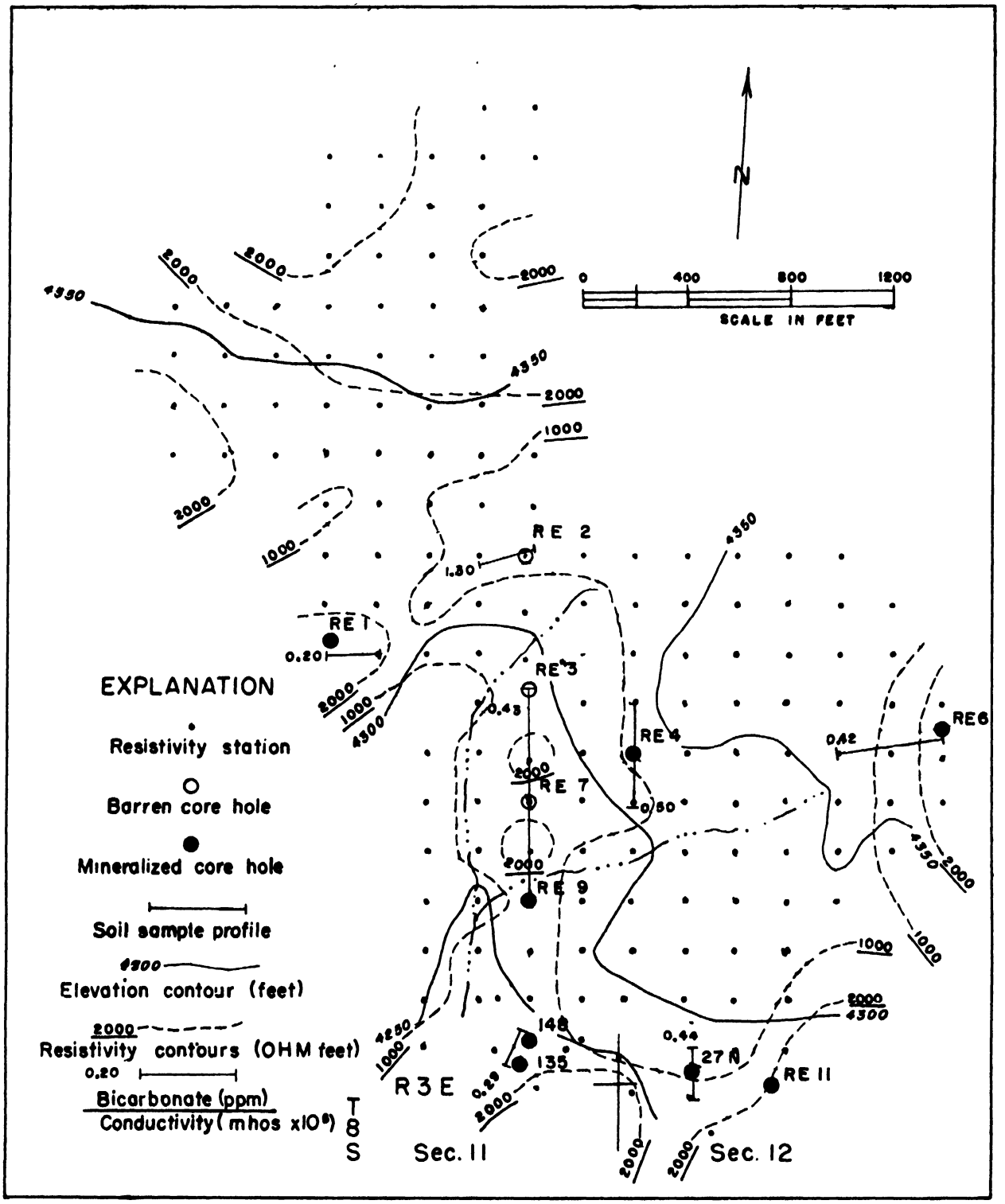


Figure 3. Surface resistivity data, Gould area, Fall River County, South Dakota

means. No significant variation in resistivity of a mineralized sand is known to be attributable to the uranium mineralization. However, it may be instructive to note that in the three sets of data shown, the first two (southern Black Hills) display predominantly high resistivity values; the mineralization is dominantly carnotite. At the Wind River Bull Rush prospect the resistivities are low and the chief minerals are the calcium-uranium-phosphate, autunite, and the uraniferous calcite, liebigite. It is interesting to speculate that the differences in the sediments as indicated by resistance measurements reflect a set of conditions which relates to the type of mineralization.

Geochemical analyses of soils over deposits 80

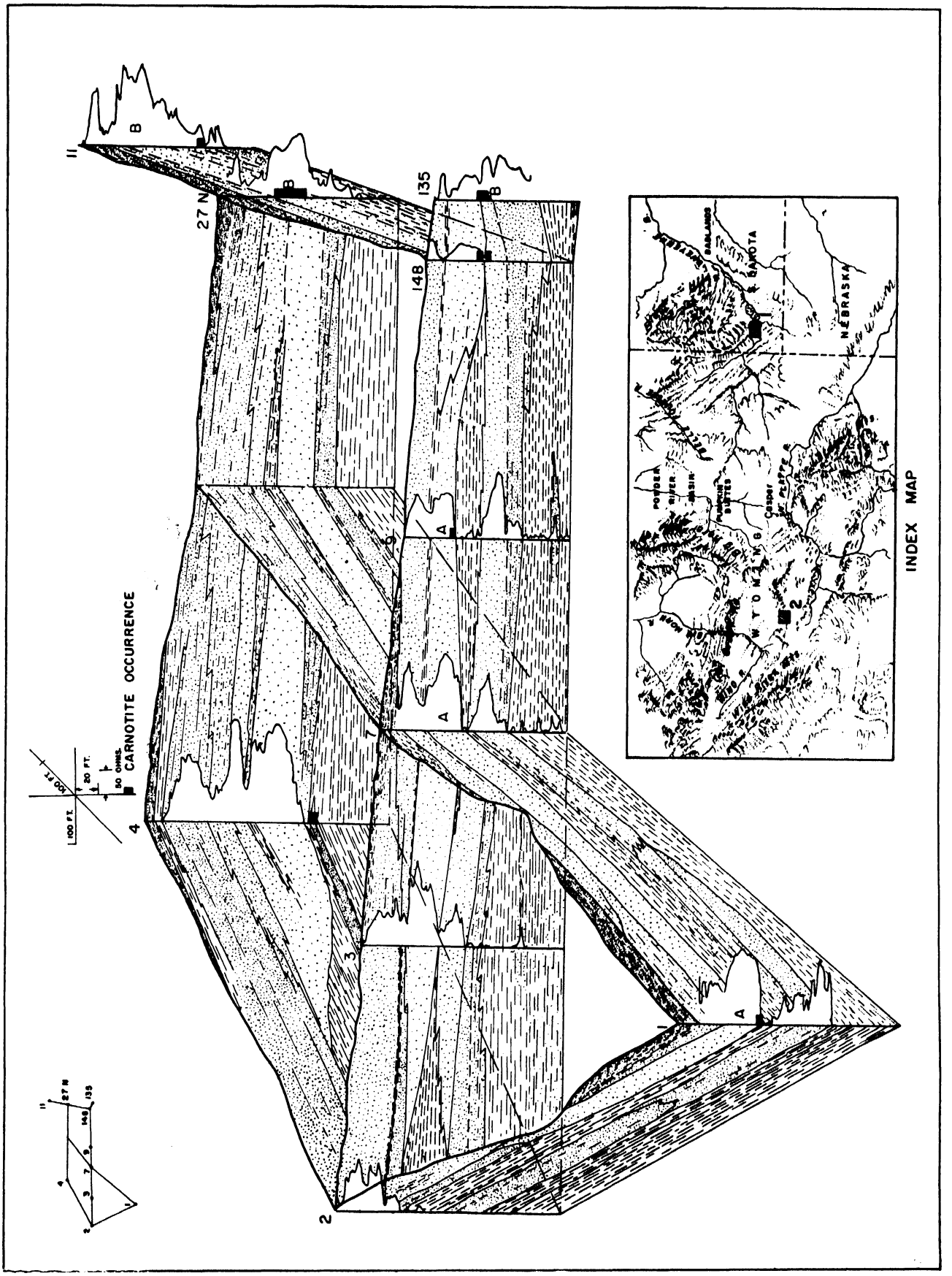


Figure 4. Stratigraphic relations of ore-bearing sediments as illustrated by electric logs, Gould area (1), Fall River County, South Dakota

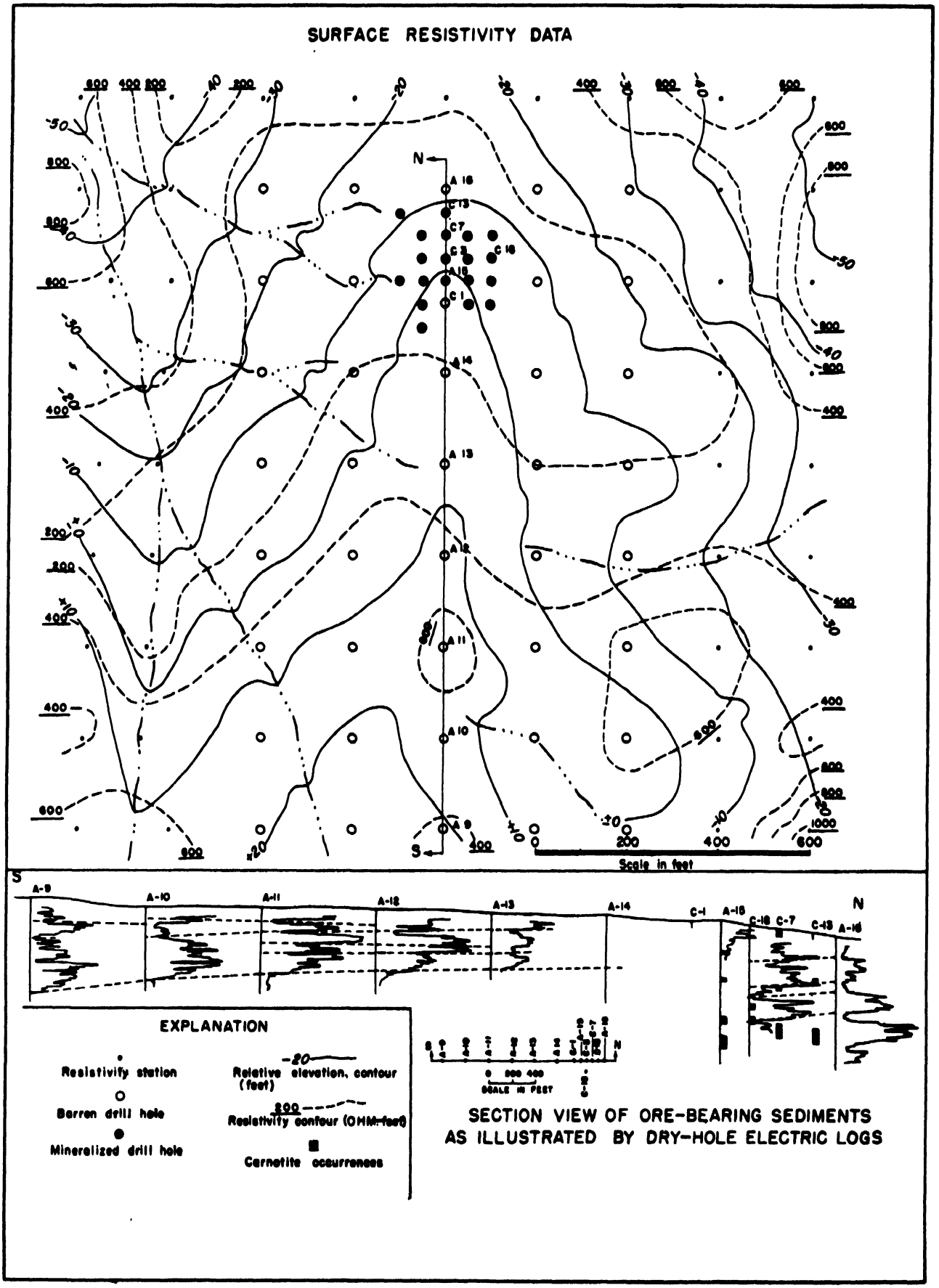


Figure 5. Bullrush prospect data, Wind River Basin, Fremont County, Wyoming

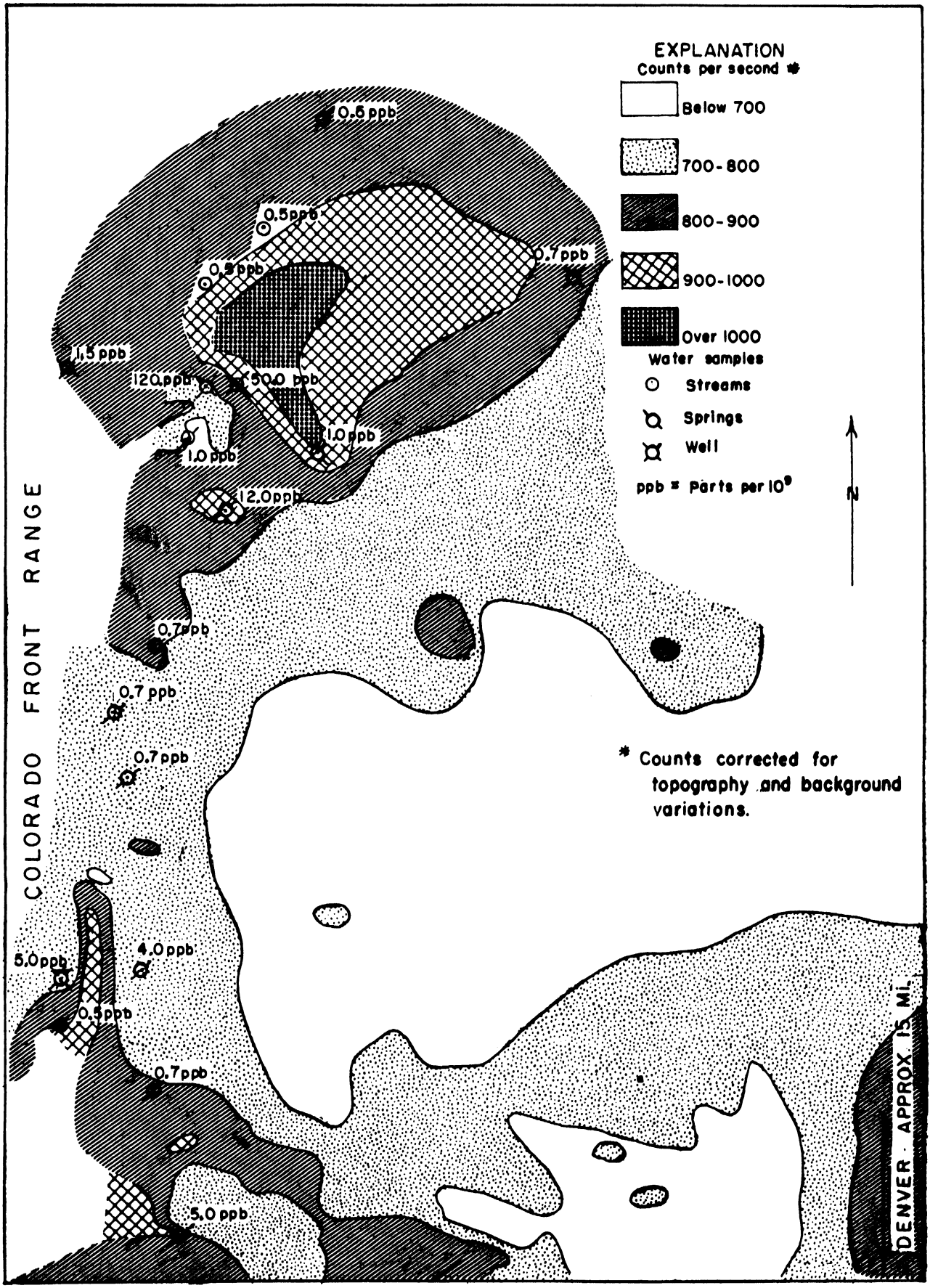


Figure 6. Radiometric-geochemical reconnaissance data, Colorado Front Range, Colorado

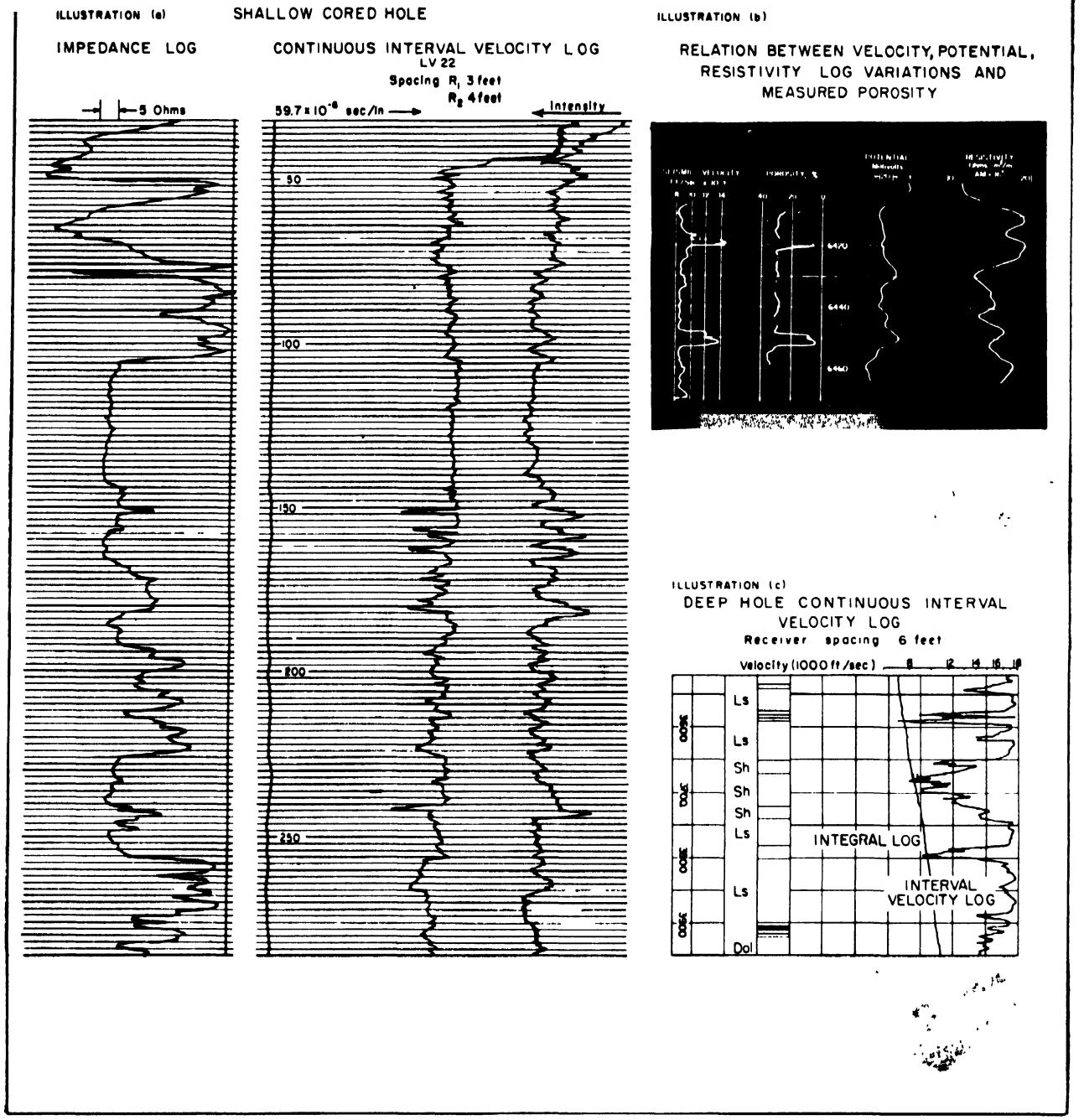


Figure 7. Continuous-interval-velocity-log data

feet or more below the surface may or may not show readily recognizable relation to the location of ore, depending upon the stratigraphy involved. However, these analyses do relate to the directly underlying sediment and under certain conditions afford very useful data. When used in conjunction with geophysical surveys, geochemistry becomes more practical and economic.

RECONNAISSANCE DATA

Colorado Front Range

Small magnitude anomalies of extended pattern are screened by carrying out geochemical analysis on soil, water, and rock samples, collected in relation to the anomalies.

Low level radiometric data are obtained by a high sensitivity detecting unit with a sensitivity of about 120 cps per mr per hour, mounted on a jeep station wagon. Data are recorded on a strip chart synchronized to run at three inches per mile. Traverses may be spaced from ½ to 1 mile apart.

Variations in the recorded values of counts per second are transferred from the strip chart to a base map and contoured. Corrections are applied for cosmic effect and typographic features. Cosmic variations are determined by re-traversing and by base

line measurements. Topographic corrections are applied empirically. Uniform radioactive content of the exposed surface area is assumed except where outcrops or measurments indicate otherwise. Surface geology exerts a marked influence particularly where carbonaceous shales crop out.

Recorded anomalies are checked by carrying out geochemical analyses for uranium, thorium, and potassium on specially picked samples. Scattered anomalies of small extent can usually be ascribed to alluvial variations, unless they maintain abnormal patterns of distribution. Drainage ways are most frequently characterized by an increase in count, which is not generally an effect of topography.

Figure 6 is an example of combined radiometric-geochemical reconnaissance data from an area where no previous exploration of this type has been carried out. Traverses were run arbitrarily about 1 mile apart over the greater part of the area. Anomalous areas were checked by running traverses at ¼ mile spacing and shorter where possible. The area to the north and east consists of flat-lying sediments partially covered by alluvial material of varying thicknesses.

Water samples were collected close to the three anomalous areas shown. Variation in uranium content of these waters range from 0.5 to 120 parts per billion (10^9). The correlation of high uranium content in waters and areas of slight increases in radioactivity is clear. Uranium contents of 120 to 50 parts per billion in formation waters are believed to indicate destruction of a uranium deposit.

EXPERIMENTAL DATA

In order to obtain adequate depth control for shallow resistivity and seismic data, evaluation of high resolution seismic reflection equipment is in process. Continuous velocity logging equipment was used in conjunction with the high resolution equipment to obtain detailed velocity-depth relations. This provides information on the thickness and acoustic impedance contrasts necessary to obtain high frequency (up to 500 cps) reflections as well as to determine possible correlations between resistivity and velocity. Further, the limitations to be expected using seismic refraction and reflection equipment can be determined. Results and correlations obtained using continuous interval velocity logging[1] are shown in Fig. 7. The shallow hole velocity log (Fig. 7*a*) shows the detail obtained with two receivers spaced 1 foot apart. Variations in interval velocity are here recorded as variations in travel time differences between the two receivers. The distance of the recording trace from the base line represents 59.7×10^{-6} sec. per inch. The right-hand trace is related to signal intensity. The single-point impedance log on the left permits comparison. Integral and interval velocities may be calculated from the time differentials shown. Data from such equipment make possible detailed comparisons between the resistance and velocity parameters.

Figure 7*b* shows an example of the degree and significance of correlations between velocity, resistivity, self-potential (as determined from in-hole logs) and porosity (as determined from core measurements). In the silica and carbonate-cemented sediments, increases in velocity relate to decreases in porosity. Determination of such relations in ore-bearing areas is of importance and interest in exploration.

Figure 7*c* (after Seismograph Service Corporation) shows an example of the velocity variations at greater depths as indicated by a single receiver unit. Correlations between velocity and lithology are evident.

REFERENCE

1. Vogel, C. B., *Seismic velocity logging methods,* Geophysics 27: 586–97 (1952).

The Use of Geochemical Techniques and Methods in Prospecting for Uranium

By T. S. Lovering, F. C. Canney, H. W. Lakin, and F. N. Ward,* USA

Geochemistry is a broad, borderland field of science concerned with the relative and absolute abundance of the elements in the earth and the laws covering their distribution, dispersion, and concentration. Most scientific prospecting, whether geological or geophysical, uses geochemical facts and laws to help interpret observations in an effort to hasten and cheapen the discovery of mineral deposits. By general consent, however, the term geochemical prospecting refers to the search for concealed mineral deposits through the detection and proper interpretation of the subtle, yet diagnostic, chemical patterns that may be present in naturally occurring materials in the vicinity of an ore body. The patterns most commonly sought are variations in the content of certain diagnostic minor elements in readily accessible material—variations in either the ore metals or in associated indicator elements. All good prospecting techniques fulfill three requirements: they must be adequate, relatively cheap, and rapid. Geochemical prospecting has been very successful in attaining these requirements.

Geochemical techniques were first used some 20 years ago by Scandinavian and Russian geologists to locate certain types of ore deposits, but it was not until after World War II that the use of geochemical prospecting became widespread. Geochemical techniques have had their greatest success in the search for deposits of copper, lead, and zinc, but many of the techniques and principles established are of value in the search for deposits of uranium and thorium.

A significant departure from the average abundance or background value of an element in materials where the distribution has not been disturbed by mineralization is called a geochemical anomaly, values less than background would be called a negative anomaly, whereas those above background constitute a positive anomaly or simply "an anomaly". Although background values can vary widely as a result of natural processes, in most barren materials the distribution of elements has a log normal distribution as recently suggested by Ahrens,[1] and there is a figure near which most of the values lie, with higher and lower figures in rapidly diminishing frequency on either side. The threshold of significance is commonly about twice the value of the peak for the background, and the importance of a geochemical anomaly is best brought out by using a geometric ratio for isograms; when representing geochemical results on a map the isograms would represent 2, 4, 8, 16, and 32 times the background value of an element, rather than 2, 3, 4, 5, and 6 times the background figure. Our present knowledge concerning the mechanisms by which anomalies form is so scanty that there is considerable risk in any attempt to correlate the contrast and size of an anomaly with the tenor of the underlying mineralized body. Nevertheless, an area surrounded by several such isograms would seem more worthy of immediate attention than an area with but one.

Geochemical anomalies are of two general types: primary anomalies are genetically related directly or indirectly to ore-depositing processes and may be regional or local in extent. Secondary anomalies are those formed at the surface of the earth by agents of weathering, erosion, surficial transportation, or biological activity. Evidence is accumulating that suggests certain broad regions having a very marked increase in the background value of an element may be considered geochemical or metallogenetic provinces. Intrusive rocks in some uranium-rich regions show a much higher background of uranium than do similar rocks in regions lacking uranium deposits. Similar relations hold for several other elements such as cobalt, nickel, tin, thorium, niobium, chromium, and some other elements. High cobalt content is characteristic of the country rock of the Blackbird district in Idaho, miles away from the known cobalt deposits, and high antimony content is characteristic of rocks some distance from ore in the antimony districts of Alaska. In establishing a regional anomaly, it is necessary to compare the metal content within specific rock types, as there may be a far greater variation between different rock types within a metallogenetic province than between the metal content of a specific rock type within and outside of the province.

Metallogenetic provinces usually have a background several times that of the average for a given rock type, and within the province there may be local concentrations that are still broader than an individual ore deposit—district anomalies—which may run several times the background of the metallogenetic province. Many uraninite-bearing veins have

* US Geological Survey.

been found in the early Tertiary mineral belt of the Colorado Front Range, and both Precambrian and Tertiary intrusive rocks have a much higher uranium content than the average of their types. In addition, there are regional variations within a given variety of igneous rocks that show the uranium content is severalfold greater in districts containing uraninite veins than elsewhere.

The background that is characteristic of different rocks, such as granite in contrast to gabbro, may vary severalfold, or even by an order of magnitude. The anomalies that reflect this kind of variation in the original composition of the rock yield primary anomalies of little value in the search for individual ore deposits and must be distinguished from other anomalies caused by the impregnation of rocks by ore-bearing fluids. These other primary anomalies may be more limited in extent but are of the utmost importance and include chiefly wall-rock and leakage halos. Wall-rock halos probably form during the emplacement of the ore by the impregnation of a sheath of the surrounding wall rock with those associated elements that are relatively mobile. Leakage halos are similar in nature but follow the channelways along which the ore-forming fluids moved.

Each area studied is unique and requires its own adaptation of geochemical techniques, but certain principles can be used in deciding on the combination of methods most suitable. The study of primary anomalies must be based on a knowledge of the geology and mineralogy of the mineral deposits. It is also important to realize that a primary leakage halo may be either on the outlet side of a blind ore body or on the inlet side of an eroded ore body and, furthermore, that an anomaly at the surface may not be vertically over the ore. Leakage of solutions that moved upward at an angle would result in an anomaly that was offset from a vertical position over the blind ore body sought—a "displaced anomaly." Pyritic halos that are so commonly associated with uranium ore deposits, whether of the sandstone type or of the cross-cutting vein variety, may be regarded as the outer ring of a target area; the problem of the prospector is to find the "bull's eye" which may be at the side, the center, or in between. Similar dispersion of niobium around some thorium deposits has been observed, and it is known that minor amounts of vanadium, copper, lead, zinc and other metals are locally associated with certain uranium deposits. Some sandstone-type uranium deposits have only a small primary anomaly of uranium itself but may be prospected geochemically by a search for the more extensive primary anomalies of these associated metals.

Anomalies of surficial origin—secondary anomalies—result from the weathering of rocks and ores, from biogeochemical processes, and from dispersion of ore minerals and metals through transportation by glacial ice, by slide and creep of colluvium, and by moving ground water and surface water. The shape and size of the secondary anomaly depends on the climate and topography, and on the mobility of the various elements present under the conditions of weathering that obtain where the deposits crop out or underly the soil. Mobility, as the term is generally used, is a measure of the tendency of an element to dissolve in the zone of weathering and to migrate from the original deposit. The dispersion pattern reflects the chemical equilibria characteristic of the local environment, the abundance of the element in the disintegrating rock, and the movement of earth material from one environment to another. Dispersion patterns that are mapped at the surface are usually regarded as 2-dimensional features, but the fact that dispersion has 3-dimensional geometry is important when interpreting secondary anomalies and is vital to success when considering primary anomalies.

Dispersion patterns are commonly classified as halos, fans, and trains, depending upon the characteristic shape of the pattern and its relation to the locus of primary concentration. A halo encloses the source of the material; a fan is a pattern spreading outward in a fan-shaped mass from a source at the apex of the fan; a train is a linear dispersion pattern commonly trending downgrade away from the deposit in secondary anomalies and downgrade toward the deposit in a primary anomaly.

In areas where pyritic halos have weathered to form limonite, the edge of the limonitic area will commonly be enriched in manganese and zinc and the weathered pyritic area will commonly be impoverished in these metals. This distribution gives rise to a negative anomaly in the weathered pyritic area and to an encircling positive anomaly where the metals have been concentrated by precipitation from supergene solutions. These anomalies obviously do not reflect the presence of an ore deposit but only decreased acidity in the surface solutions and surrounding rocks lacking high sulfur, and illustrate the necessity of proper geochemical interpretation of anomalies and the importance of distinguishing between anomalies related to ore-forming processes and those that are not.

In many areas, the analysis of soils for uranium or other ore metal gives a fairly reliable and consistent indication of ore that is concealed beneath. Biogeochemical processes tend to concentrate certain elements at the surface even though the source of the element may be at a depth of many meters. The accumulation of zinc, uranium, vanadium, selenium, sulfur, and other elements in plant tissues has long been known, and convincing evidence has been found that these elements tend to enrich the surface layers as the organic material in which they were concentrated is decomposed through biogeochemical agencies at the surface. In areas where there is an appreciable zone of plant litter, samples of the underlying soil must be studied with the possibility in mind that the minor-element content has been pumped to the surface through the root systems of plants. It is quite possible, however, to establish target areas on the

basis of geochemical anomalies produced in this way. In semiarid regions where little or no plant debris accumulates, analysis of the vegetation itself for uranium or other ore metal may provide the information necessary to disclose the presence of a hidden ore body tapped by the root systems of the plants.

Under favorable conditions metals in small amounts are also introduced into transported soil which covers a truncated ore deposit. Unlike the anomalies caused by concentration in decaying vegetation these superimposed halos show a concentration gradient increasing downward and probably reflect diffusion or capillary movement in moist regolith overlying an oxidizing ore body. Such anomalies may be the geochemical analogue of geophysical self-potential anomalies related to decomposing sulfide ores. The more mobile elements, such as sulfur, zinc, cobalt, uranium, and—under alkaline conditions —molybdenum, are the elements most likely to be found in superimposed or diffusion halos. These are also the metals most likely to be leached from the residual soil or gossan over an ore body. The metals sought in residual material over an ore body would be those of low mobility, such as thorium, lead, copper, vanadium, niobium, selenium, and arsenic, although there is usually a perceptible rise in the concentration of the more mobile elements associated with the ore in the general vicinity of the ore deposits as contrasted with the barren rocks surrounding it.

The search for geochemical anomalies in transported material is most commonly directed toward finding a dispersion train or fan that may lead the prospector back to the bedrock source of detrital ore minerals. Such a search is merely a modern extension of the age-old techniques of searching out lodes by panning gravels for gold or other heavy minerals and of following the increasing concentration of the detrital minerals upstream to their source.

In using geochemical methods to search for uranium, both the direct search where uranium itself is sought, and the indirect method where primary or secondary haloes of associated elements are the targets have considerable promise. Although geochemical methods have not been widely used to detect uranium because of the ease with which radiometric anomalies can be found by airborne, truck-borne and hand-carried instruments, the importance of a radiometric high must always be ascertained by chemical analysis. In areas subject to radioactive fallout from atomic fission devices, contamination may make radiometric techniques nearly useless without constant chemical check. A simple, sensitive, and inexpensive field method of analysis for uranium (reported later in this paper) allows quick evaluation of such anomalies and makes it possible to discriminate between anomalies caused by uranium in contrast to those related to thorium, or to daughter products. This chemical method is also of value in testing nonradioactive materials for recently deposited uranium or in areas where there is a substantial cover over uranium bodies and, as a consequence, the radioactivity of the ore bodies is not appreciable at the surface. In the surface soil horizons of such localities a very slight concentration that diminishes downward may be highly significant and suggests the probability of biogeochemical concentration from depth.

It is always desirable to make preliminary orientation surveys in geochemical investigations so that the geochemical problems can be evaluated before embarking on a full-scale program. The use of geochemical techniques is especially advantageous when searching for ore bodies that have primary or secondary halos much larger than the ore deposits themselves; the size of such halos can be determined by studies near known ore deposits. Geochemical surveys may fail needlessly even when the analytical work is satisfactory, if the type of anomaly sought does not exist or if the samples were taken in the wrong places, in the wrong materials, or with the wrong spacing. Preliminary work should establish the proper procedure to be followed.

For successful geochemical work there are five problems that must be considered: (1) the element to be sought and the establishment of valid background values; (2) the material best suited for sampling; (3) the geometric pattern for sampling best suited to the geology; (4) the maximum permissible spacing of the samples necessary to reveal anomalies; and (5) the most effective analytical procedure. The answers to these problems depend on the kind, size, contrast, and homogeneity of the anomaly, and on the chemical facilities available. Since most geochemical anomalies result from movement of solutions, soil, or rock, it is apparent that the climate, the topography, and the size and shape of the source of the material are the most important factors determining the geometry of a sample pattern. After some information has been obtained from preliminary orientation studies about the expected general size and shape of the dispersion pattern sought, the geometry and spacing of the samples are chosen so as to assure that at least two, and preferably more, samples will fall within the zone of an anomaly. Where the size and shape of the mineral deposit are unknown, it is common practice to run traverses parallel and at right angles to topographic features, such as ridge crests and valleys. Anomalies developed by diffusion into barren material above ore are usually of small extent and may require sample spacing of 3 to 20 meters. In glacial till, a spacing of 100 to as much as 500 meters may be effective in locating ore-bearing detritus in dispersion trains or fans.

Ore deposits of uranium and of thorium make up a very small fraction of the earth, and one of the principal objectives of the prospector is to pick up the most favorable area for intensive study as quickly and cheaply as possible. To explore a new region the geologist must use rapid reconnaissance methods so far as is feasible, striving to eliminate the least favorable areas quickly so that an increasingly intensive study of the favorable zones may be made in a pro-

gressive effort to reduce the size of the target that must ultimately be proved by physical investigation. It is hardly necessary to call attention to the importance of geological and geophysical methods for this work; it is perhaps worth emphasizing the fact that geochemical methods provide an additional technique that may be of great value in supplementing the geological and geophysical guides to ore.

ANALYTICAL METHODS FOR GEOCHEMICAL EXPLORATION

The analytical methods used should be simple, rapid, inexpensive, and adequate. Low-cost personnel should be able to operate them with little training. A fair degree of precision—reproducibility of results—rather than a highly quantitative accuracy is the end sought in applied geochemical prospecting. The accuracy need only be adequate to distinguish between areas appreciably above or below background.

Colorimetric and spectrographic methods of chemical analysis that find wide use in geochemical prospecting must meet several exacting requirements, which range from those directly related to the methods themselves such as simplicity, brevity, and accuracy, to those unrelated but important factors of cost and ease of application to large numbers of samples. These requirements will be discussed separately for convenience.

When two or more types of analytical methods possessing the desired sensitivity and precision are available, the type selected for a given geochemical prospecting program is related in part to the size of the program. The number of samples processed may be a few hundred performed by an individual prospector on a small program or several hundred thousand for a large-scale exploration program. The initial cost of a truck-mounted spectrographic laboratory, which would provide one type of useful analytical method for certain elements, would be prohibitive in a small program but economically feasible and desirable in a large-scale program.

A productive analytical method in geochemical prospecting must be simple enough to be performed by technicians in lieu of professional personnel. The term "simplicity" connotes in colorimetric analytical methods few chemicals and a minimum of apparatus so that the methods become essentially "test tube" methods, and in spectrographic methods it means short procedures and quick comparisons made on sturdily assembled equipment.

Useful chemical procedures in geochemical prospecting should be moderately accurate, but what constitutes sufficient accuracy for one element may be very different for another element. The desired accuracy will often be determined by the type of matrial sampled, as well as by the significant variation in concentration of the element in the material. For example, biogeochemical prospecting by determining small amounts of molybdenum in plant materials requires that the useful method be sufficiently accurate to detect differences in the molybdenum content of plants growing in soils containing relatively large amounts of molybdenum and in plants growing in soils relatively free of molybdenum, but the useful method need not detect small variations caused by factors such as the health of the plant, differences in soil moisture, and other unrelated ecological components.[2]

The analytical methods used in geochemical prospecting are methods of trace analysis. Trace analysis is the process of determining exceedingly small amounts of the desired constituent in the presence of large amounts of other elements, many of which may interfere seriously in the reactions involved. Consequently, the simple methods involved in determining a very small amount of the desired element in the pure state are not adequate. However, if such a method exists, the problem of determining the desired element in various natural materials such as soil, rock, water, or vegetation, may be relatively simple or complex, depending on the nature of the reaction used in the method and the ease with which interferences may be overcome. When a method of trace analysis applicable to these materials is available, the development of a suitable field method becomes one of engineering and adaptation namely, volumes and weights are decreased, apparatus and operations are modified. Separations are held to a minimum by the use of complexing agents and changes in valence, but unavoidable separations are made by using immiscible solvents, usually with a relatively small volume, to concentrate the element being measured. For example, the molybdenum method described later is an adaptation of a method that originally required a high-temperature furnace, platinumware, large separatory funnels, and a spectrophotometer.

Similarly, spectrographic methods and equipment that find use in geochemical prospecting are engineered and adapted to use under field conditions. In contrast to the usual techniques of quantitative spectrography, which involve measurements of intensity ratios of line pairs on a photographic plate or film, semiquantitative methods are used, and the concentration of an element is determined by visually comparing the blackness of a line of an element with the blackness of the same line emitted from standards having known amounts of that element. Standard and unknown samples should be as nearly alike as possible in chemical composition and physical characteristics and must be treated alike in the procedure used to produce the spectra. It is expected that spectrographic methods will find their maximum usefulness in large-scale programs where each sample must be analyzed for several elements in an early survey to help select the most diagnostic group of elements.

Although the preceding discussion is limited to colorimetric and spectrographic analytical methods, the US Geological Survey is at present investigating the applicability of techniques involving X-ray fluorimetry, polarography, and paper chromatography including paper electrophoresis.

Specific applications of paper chromatography and colorimetry to methods useful in prospecting for uranium and for possible associated elements are made below. Each method is fast, simple, and moderately accurate, and each is designed to give positive tests for background material in large areas of the United States and to give results within 30 to 50 per cent of the correct value for materials containing anomalous amounts of a given element.

Many comparisons of the results obtained by these methods with those obtained by recognized procedures show that they have adequate accuracy for use in geochemical prospecting for uranium and associated elements.

Some of the elements most commonly associated with uranium deposits in the United States include vanadium, molybdenum, selenium, niobium, copper, and cobalt; the methods used to determine uranium and these indicator elements by the US Geological Survey are outlined in the following pages. With no exception all the methods described below have been used to delineate areas of mineralization in various parts of the United States; with the exception of selenium all the methods have been used by technicians in the field and in the analytical laboratory to analyze anywhere from 30 to 80 samples in an 8-hour day.

DETERMINATION OF ELEMENTS

Uranium

This method permits the determination of 4 to 400 ppm of uranium in a soil or sedimentary rock without modification. It is unsatisfactory for the determination of uranium occurring as a constituent of a refractory mineral. The method described below is a modification of a paper chromatographic procedure for use in geochemical prospecting described by Hunt *et al.*[3] A 1-gram sample is digested for 1 hour in a boiling water bath with 2 ml of 1+3 nitric acid saturated with aluminum nitrate. A 0.01-ml aliquot of the supernatant solution is placed on a Whatman CRL/1 filter paper and dried in a desiccator over calcium chloride for 8 minutes at ambient temperatures of 60° to 90°F and for 5 minutes when temperatures exceed 90°F. The lower end of the dry paper is immersed in a developing solution (30 ml ethyl acetate, 3.5 ml concentrated nitric acid, and 10 ml of water contained in a 600-ml beaker) until the solution has risen about 8 cm in the paper. Then the paper is removed from the developing solution, dried, sprayed with a 5-per cent aqueous solution of potassium ferrocyanide, and the resulting stain of the brown-colored uranium complex is compared with standards similarly prepared.

This procedure differs from that of Hunt *et al.* by the addition of a relatively large amount of aluminum nitrate to the sample solution to facilitate the determination of uranium in phosphatic materials. In addition, the residual salts on the filter paper after evaporation are essentially constant, and differences resulting from varying solubility of the sample are nullified.

Vanadium

Without any modification the vanadium method given here[4] is useful on soils or rocks containing from 0.03 to 2.0 per cent vanadium. It is particularly applicable to oxidized materials and suffers from no interferences except that of niobium.

This wet chemical method for determining small amounts of vanadium in soils or rocks is based on a hitherto unused reaction of vanadium(III) with thiocyanate in acid medium. A 0.1-gram sample is heated with 1 ml of 9 molar sulfuric acid, and after cooling, is treated successively with 4 ml of 10 per cent aqueous sodium citrate, 2 ml of 2 per cent disodium ethylenediamine-tetraacetic acid, 3 ml of 15 per cent stannous chloride in concentrated hydrochloric acid, and 2 ml of 20 per cent aqueous potassium thiocyanate. The yellow-colored complex is extracted into 1 ml of ethyl ether, and the intensity is compared with that obtained from standard solutions to determine the vanadium content.

Molybdenum

The field method for molybdenum can be applied to soils and rocks containing from about 1 to 32 ppm of molybdenum, and in this concentration range the precision of repeat determination is within a few parts per million.

This method for determining traces of molybdenum in soils and rocks[5] is based on the reaction of molybdenum(V) with thiocyanate in dilute hydrochloric acid and subsequent extraction of the complex into isopropyl ether.

A 0.1-gram sample is fused with 0.5 gram of a 1+1 mixture of sodium carbonate and potassium nitrate, in a borosilicate glass test tube, and the fused mass is extracted with 4 ml of hot water. A 1-ml filtered aliquot of the aqueous extract is neutralized with molar hydrochloric acid and treated with 0.5 ml of 10 per cent aqueous potassium nitrate and 0.2 gram solid sodium tartrate. The volume is adjusted to 5 ml with water and treated successively with 0.5 ml concentrated hydrochloric acid, 0.3 ml of 5 per cent aqueous potassium thiocyanate, and 0.5 ml of 10 per cent stannous chloride in 2 molar hydrochloric acid. The amber-colored molybdenum complex is extracted into 0.3 ml of isopropyl ether to concentrate the colored complex and increase the overall sensitivity of the method. The colored ether layer obtained from a sample is compared with that obtained from standard solutions to determine the molybdenum content of the samp'e.

Selenium

This method is useful for the semiquantitative determination of selenium in soils, rocks, and vegetation containing from 2 to 100 ppm of selenium. It is not suitable for field use. The method is a microchemical adaptation of the well-known distillation procedure of Hillebrand *et al.*,[6] combined with Franke's confined spot method of estimation.[7] A 1.0-gram sample of the soil, rock, or vegetation is evaporated slowly with 10 ml of nitric acid containing

10 mg each of mercuric oxide and ammonium metavanadate, until 2 ml remains. The mixture is fumed with 10 ml of concentrated sulfuric acid and then centrifuged at 1500 rpm for 10 minutes, after which the supernatant liquid is decanted into a 125-ml distillation flask. Ten milliliters of concentrated hydrobromic acid and a few drops of bromine are added, and 8 to 10 ml is distilled into a beaker containing 2 ml of water and a few drops of bromine. The distillate is reduced with sulfur dioxide and 1 ml of a saturated aqueous hydroxylamine hydrochloride solution, digested on a steam bath for 20 minutes, and set aside for 12 hours. The precipitated selenium is collected on a paper disc covered with a barium sulfate mat by filtering the distillate through the disc fixed between two sections of glass pipe held firmly together with a suitable coupling. The pink selenium spot is compared with standard spots prepared similarly.

Copper

The colorimetric method described here is designed for the estimation of copper in soils and rocks containing 20 to 4000 ppm.[8] The method is based on the reaction of copper in an acidic solution with diphenylthiocarbazone (dithizone) to form a pink copper dithizonate soluble in carbon tetrachloride. A 0.1-gram sample of soil or rock is digested for 1 hour on a boiling water bath with 3 ml of 1+3 nitric acid and then diluted to 10 ml with metal-free water. A suitable aliquot is transferred to a test tube containing 1 ml of 10 per cent sodium citrate solution and 2 drops of thymol blue solution. The pH is adjusted to 2.5 with 1*N* hydrochloride acid. To this solution 2.5 ml of 0.001 per cent dithizone solution in carbon tetrachloride is added, the mixture is shaken vigorously for 2 minutes, and the resulting color of the organic phase is compared with that of standards similarly prepared.

Cobalt

The cobalt method[9] is applicable to soils and rocks containing from 10 to 500 ppm cobalt. It is based on the reaction of cobalt with 2-nitroso-1-naphthol to form a pink-colored complex soluble in carbon tetrachloride. A 0.1-gram sample is fused with 0.5 gram of potassium pyrosulfate, and the cool melt is extracted with 10 ml 0.5 molar hydrochloric acid. A 2-ml aliquot is treated with 1 ml of 10 per cent sodium citrate and 4 ml of 2 per cent aqueous disodium hydrogen phosphate dodecahydrate. The pH is adjusted to 6.5; 3 ml of 0.01 per cent aqueous 2-nitroso-1-naphthol and 1 ml of carbon tetrachloride are added. The pink-colored cobalt complex is extracted into the organic layer, which is separated and shaken with 10 ml of 0.05 per cent aqueous potassium cyanide to decompose the Ni and Cu complexes.

The intensity or shade of pink is a measure of the cobalt present, and the comparison of the color produced by a sample with that produced by a cobalt standard provides a means of measuring the cobalt content of the sample.

Niobium

The method given below can be applied to materials containing from 20 to 2000 ppm of niobium. It is based on the reaction of niobium(V) with thiocyanate in hydrochloric acid and subsequent extraction of the niobium complex into ether.[4] A 0.2-gram sample is fused with 4 grams of potassium pyrosulfate and extracted with 10 ml of 1 molar aqueous tartaric acid. A 1-ml filtered aliquot is treated with 5 ml of 9 molar hydrochloric acid, which is also 1 molar in tartaric acid. To the cool solution (20° to 25°C) 5 ml of 20 per cent ammonium thiocyanate and 5 ml of ethyl ether are added. After shaking, the ether phase is separated and treated successively with small portions of 10 per cent stannous chloride in 2 molar hydrochloric acid to remove iron, titanium, and other reducible metals whose lower valences are insoluble in ether. The yellow-colored ether phase is diluted with an equal volume of acetone to stabilize the solution and inhibit side reactions. Niobium is determined by comparing the intensity of the yellow color of the ether solution obtained from a sample with that obtained from a standard. The niobium can also be determined by measuring the absorbance of the yellow-colored ether solution at 385 millimicrons and referring to a previously established standard curve.

REFERENCES

1. Ahrens, L. H., *The Lognormal Distribution of the Elements,* Geochimica et Cosmochimica Acta 5: 49–73 (1954).
2. Reichen, L. E. and Ward, F. N., *Field Method for the Determination of Molybdenum in Plants,* US Geological Survey Circular 124 (1951).
3. Hunt, E. C., North, A. A. and Wells, R. A., *The Application of Paper Chromatographic Methods of Analysis to Geochemical Prospecting,* The Analyst 80: 172–194 (1955).
4. Ward, F. N. and Marranzino, A. P., private communication.
5. Ward, F. N., *Determination of Molybdenum in Soils and Rocks,* Analytical Chemistry 23: 788–791 (1951).
6. Hillebrand, W. F., Lundell, G. E. F., Bright, M. S. and Hoffman, J. I., *Applied Inorganic Analysis,* 2d Edition, John Wiley and Sons, Inc., New York, 330 (1953).
7. Franke, K. W., Burris, R. and Hutton, R. S., *A New Colorimetric Procedure Adapted to Selenium Determination,* Industrial and Engineering Chemistry, Analytical Edition 8: 435 (1936).
8. Bloom, H. and Crowe, H. E., private communication.
9. Almond, H., *Determination of Traces of Cobalt in Soils,* Analytical Chemistry 25: 166–167 (1953).

Geochemical Prospecting for Uranium by Sampling Ground and Surface Waters

By P. F. Fix,* USA

Hydrogeochemical methods[1] of finding and estimating the economic possibilities of uranium deposits, based upon differences in the uranium content of natural waters,[2] were developed and tested under known conditions in uranium-mining areas in 1952 after earlier work had shown promise. These methods are now sensitive and accurate, as the result of continuing refinement of field and laboratory techniques and standardization for different types of environment in which uranium may occur. Their validity has been proved by data from more than 700 water samples from uraniferous localities in the United States. Results agree closely with those of radiometric and geologic methods, but hydrogeochemical methods, because of the deep penetration by water underground far below the instrumental zone, also can be used in some places where other methods fail.

Comparative studies were made with both borosilicate glass and polyethylene bottles (in various sizes), with and without stabilization by hydrochloric or nitric acid. Hydrochloric acid is used in the standard procedure adopted. The few samples that contained sediment were decanted into clean bottles after standing for a short time. Filtering was avoided. Uranium is determined fluorimetrically in laboratories of the US Geological Survey,[3] and as yet there is no field method for the determination of the small amounts of uranium present in most samples.

This paper summarizes some of the results of more than 700 uranium determinations, 170 semiquantitative spectrographic analyses in which 60 elements were sought, and 230 chemical analyses for major and some minor elements in water samples representing most of the western United States and southeastern states. In addition to these data, 2400 uranium determinations were made on water samples collected by other members of the US Geological Survey.

FACTORS AFFECTING HYDROGEOCHEMICAL EXPLORATION

Uranium deposits seldom occur under simple geochemical conditions, hence a hydrogeochemical search for them involves appraisal of the net relative effect of such complex variables as the mineralogy of the deposit; the oxidation of associated sulfide minerals; the geology of the area; the pH, chemical composition, oxidation-reduction potential, temperature, and content of colloids, clays, and organic matter of the waters; the season; the climate; the relationship between stream underflow and surface flow; and the circulation pattern of the ground water. With due regard for these variables, the uranium content of the water serves as a rough index of the uranium concentration in the geologic materials hydrologically tributary to the sample site.

Hydrogeochemical methods of finding and appraising uranium deposits are based upon the fact that weathering and erosion produce a secondary dispersion aura of uranium dissolved in ground and surface waters. The aura ordinarily resembles the deposit in ground plan, although it is much more extensive, except in the direction of the hydraulic downgradient where it is sharply asymmetric owing to the ease with which most waters can dissolve and carry uranium.

Most of the uranium is carried away in ground water and appears ultimately at the land surface in streams. Ordinarily, little is carried away directly in surface water, but the amount may be large where easily soluble uranium minerals in dry-season efflorescences or uraniferous dusts from mining operations or haulage are swept away by storm waters.

The effect upon the uranium content of ground waters by snow melt or storm waters ordinarily is one of proportional dilution, but where ground water at low stage is reduced to virtual stagnancy by a dry season or draught, the sudden influx from the surface above may steepen the hydraulic gradient and flush the ground water from crevices where it has been enriched by long soaking contact with uranium minerals. The sudden addition of such water to other ground water that has been circulating may result in a large increase in the net uranium content of the whole immediate body of ground water, until dilution by the surface water can take effect

Ground water enters streams as underflow and hillside springs. Thus, streams are used to detect uranium deposits by hydrogeochemical methods because of the great distances at which dispersion auras can be detected in streams. The sampling pattern resembles that of gold panning. Water samples are collected from streams above their confluences, as well as at any intermediate points that may be promising geologically. Samples are taken far enough

* US Geological Survey.

above confluences to be certain that the sample site is not affected by underflow from the other fork of the stream. Samples are never taken immediately below confluences, as the chemical blending of two streams requires distances ranging from several hundred meters in small streams to several kilometers or more in rivers.

A single aura, even from a small deposit, ordinarily is easily detected and evaluated downgradient at distances of hundreds of meters in ground water, and at least 20 kilometers in streams. The auras of closely spaced deposits blend into a single composite aura. The greater the number of deposits per unit area and the greater the solubility of the uranium minerals, the shorter is the distance at which an individual aura can be distinguished from its neighbors.

Under favorable conditions, the dense aura of a large uranium deposit, or a major composite aura, is easily detectable quantitatively downgradient as far away as several kilometers in ground water, and probably at least a hundred kilometers in streams. Work in progress on the Dolores River in the semiarid Colorado Plateau suggests that the effect of a major aura may decrease only 50 per cent in a distance of about 80 kilometers downstream, where dilution by large tributaries is a minor factor.

A typical example, taken from the Boulder batholith in Montana, includes detection of an individual aura and tracing its effect through a neighboring composite aura from a uranium mine and several prospects. The climate in the region is semiarid, and the samples were taken after a dry summer when both surface and ground-water inflow to the streams were at a minimum. Mine water from a sulfide base-metal vein with some radioactive black mineral contains 11 ppb (parts per billion) uranium at the portal. Uranium in this mine was discovered by the writer with the following suite of samples, after an earlier sample at the 3-kilometer point had disclosed the presence of uranium in the drainage basin. Table I shows the effect downstream from the mine.

Influx of ground water in the first 9 kilometers is very small, and probably none contains more than 2.7 ppb U. The changes in uranium content of water in the 18 kilometers are in almost exact proportion to the volume and uranium content of incoming streams and well-controlled estimates of ground water influx. The effect of the first aura downstream decreases about 50 per cent in the first 6 kilometers, when the additive effect of the second small tributary is considered. The following effects are shown successively: the additive effect of the tributary from the first unit of the composite aura, the effect of the creek upon the uranium content of the master creek, and the net effect of all at the lower end of the composite aura. At that point, the effect of the first aura can still be detected when relative volume of water is considered. Its effect has been detected several kilometers farther downstream.

Standardization of appraisal techniques for the many types of environments requires detailed geochemical information from as many diverse types of uraniferous waters as possible. The great diversity in the large number of samples examined is shown by the following index of selected major items.

Table I. Source of Water Sample

Distance (km)	*U* (ppb)*	*Source of water sample*
0	11.	Mine water at portal
0	0.9	Creek above mine portal
1	4.3	Creek after blending with mine water
1.5	0.8	Small tributary
2.3	2.7	Small tributary
3	4.3	Creek after blending with tributaries
4.7	1.0	Large tributary
6	2.3	Creek after blending with large tributary
9	5.9	Small tributary at edge of composite aura
9.5	3.2	Creek above confluence with master creek
—	1.3	Master creek 0.3 km above confluence
10	1.7	Master creek after blending with creek
18	3.0	Master creek at lower end of composite aura, after influx of ground water and large tributaries ranging from 4.1 to 7.9 ppb U

* ppb denotes parts per 1,000,000,000.

Constituent	*Maximum*	*Minimum*
U (ppb)	5300	$< 0.02 \pm$
Fe (total) (ppm)	2310	< 0.1
Ca (ppm)	1190	0.6
Mg (ppm)	1520	0.1
Na (ppm)	13,400	0.3
K (ppm)	1100	0.1
HCO_3 (ppm)	2630	0
SO_4 (ppm)	8820	0.7
Cl (ppm)	25,000	< 0.1
Total dissolved solids	42,200	23.
Total carbonate hardness	7250	2.0
pH	9.3	2.5

Thermal springs are lower in uranium content than are cold waters under equivalent conditions. This is probably due to the increased chemical reactivity of hot waters and the removal of uranium minerals early in the life of the springs. The highest uranium content found to date is 7.0 ppb in the Alhambra hot spring, in Montana. Cold water in a uranium prospect only a few hundred meters distant on the same mineralized structure contains 140 ppb U.

BACKGROUND CONCENTRATION OF URANIUM IN WATER

The background concentration of uranium in natural waters, expressed in parts per billion (ppb), is roughly analogous to the background intensity of radioactvity, expressed in milliroentgens per hour (mrh); but, as one measures uranium directly and the other does not, they are not to be equated. The standards of reference are entirely different.

For clarity two types of hydrogeochemical background are distinguished in appraising uranium deposits. The regional background is the average uranium content of waters in a given region that are not

appreciably affected by dispersion auras. The areal background is the average for waters in a given area, ordinarily much smaller than a region, that are materially affected by dispersion auras, yet are not actually in or immediately adjacent to economic or near-economic deposits.

Regional background (Table II) is represented by 108 of some 700 water samples from 11 states and Alaska. The average of all 108 is 0.10 ppb, and this is thought to be reasonably representative of background for the United States and Alaska. The observed maximum is 0.5 ppb, and the minimum is 0.02 ppb U.

Table II. Regional Background

State	No. of samples	Uranium content (ppb)		
		Average	Maximum	Minimum
Colorado	33	0.19	0.5	< 0.1
Montana	22	0.16	0.3	0.1
Georgia	14	< 0.1	0.2	< 0.1
Washington	9	0.07	0.1	< 0.02
South Carolina	7	0.1	0.2	< 0.1
Utah	7	0.10	0.2	< 0.1
Wyoming	6	0.22	0.4	< 0.1
Florida	5	< 0.1	0.1	< 0.1
Idaho	3	0.22	0.3	< 0.1
North Carolina	2	0.1	0.1	0.1

Areal background (Table III) is represented by 195 water samples from 9 states and 8 from Alaska. The average of the 195 samples is 0.80 ppb U, and this is thought to be reasonably representative for the uraniferous areas of the United States, although in the Colorado Plateau it may be considerably more. The observed maximum for all 203 samples is 2.5 ppb, and the minimum is 0.2 ppb U.

Table III. Areal Background

State	No. of samples	Uranium content (ppb)		
		Average	Maximum	Minimum
Montana	91	0.69	1.7	0.3
Colorado	52	0.62	1.8	0.3
Texas	32	1.47	2.5	< 0.5
Utah	9	1.13	2.0	0.4
South Carolina	3	0.2	0.2	0.2
Florida	2	0.2	0.2	0.2
New Mexico	2	0.55	0.6	0.5
Wyoming	2	0.65	0.8	0.5
Idaho	2	0.65	0.8	0.5
Alaska	8	0.45	0.5	0.4

ANOMALY

The threshold of anomaly (a rough guide to waters requiring further investigation) is about 1.0 ppb U, or 10 times the regional background in the western United States generally. In the tuffaceous rocks of the Great Plains it is about 2 ppb in surface waters and 5 ppb in ground waters. In the Colorado Plateau, it is about 4 ppb in surface waters and at least 5 ppb in ground waters.

The threshold for uraniferous phosphate deposits is about 0.3 ppb U. This is not to be equated with the threshold level in other terranes, because it actually refers to phosphate deposits rather than uranium *per se*, which at best can be mined only as a by-product.

The upper limits of anomaly differ greatly between ground and surface waters, and also within each type with differences in geochemical conditions. The following data concerning the range found in the two types refer only to true natural values unbeneficiated by evaporation or recent mining operations, the effects of which are discussed later.

Surface waters in most uraniferous areas ordinarily contain from 1 to 10 ppb U. The greatest content found to date in small streams is 32 ppb in Bishop Creek in southwestern Montana, 2 kilometers below drainage from a uraniferous base-metal mine. In rivers, the greatest content found is 4 ppb in the Sevier River below the Marysvale uranium-mining district in Utah. The chief controls in surface waters seem to be the extent of dilution by low-uranium waters from barren areas, and the pH. The pH in most surface waters sampled ranges from 5.5 to 7.5; a high uranium content does not occur in this pH range. The more acid the waters, other things being equal, the greater the uranium content.

Ground waters in most uraniferous areas ordinarily contain from 1 to about 120 ppb U. Those within the pH range of 5.5 to 7.5 contain moderate amounts, but strongly acid waters may contain very large amounts of uranium if they have access to sufficient uranium mineralization.

The greatest uranium content found to date is 5300 ppb in water with a pH of 2.5 in a large uraniferous base-metal mine in Arizona.

The uranium content of any water must be appraised in terms of the net effect of the conditions controlling that particular water, including the degree of access it has had to uranium. Unevaluated data where uranium contents alone are quoted have little significance. For example, waters that contain as little as 4.8 ppb uranium are known from mines that have actually produced uranium, whereas waters from mines that have produced no uranium ore are known to contain more than 100 ppb U, and one very acid water in a mine that to date has produced no uranium contains the maximum found—5300 ppb U.

The observed range in uranium content of waters in mines that have produced at least some uranium ore is from 4.8 ppb at the Free Enterprise uranium mine in the Boulder batholith area of Montana, to as much as 535 ppb in some uranium mines of the Colorado Plateau where the waters have been beneficiated to some extent by recent mining operations and excessive evaporation caused by arid climate. The low content in the Free Enterprise mine water is the result of rapid circulation of a large volume of ground water that allows the unit volume of water minimum time to dissolve uranium.

The true natural uranium content of water in uranium mines under ordinary conditions is thought

to range from about 15 to 400 ppb, but when pH is lower than about 4.0, the content may be much larger.

Uranium deposits differ in the amounts of major and particularly in the minor elements they contain. These differences inevitably modify the chemical nature of waters passing through them. Hence the location, size, and possibilities of deposits are appraised by the peculiarities of chemical makeup disclosed by analysis of the waters. This consists of semiquantitative spectrographic analysis for 60 elements, chemical anlyses for major and some minor elements, and fluorimetric analysis for uranium. These data are interpreted after taking into account the geologic controls such as faults, concealed bedrock groundwater dams, and permeability of formations.

SEASONAL FLUCTUATIONS IN URANIUM CONTENT

The uranium content of waters fluctuates seasonally because of dilution by snow-melt and storm waters low in uranium. Ordinarily the content is inversely proportional to the abundance of surface water, but it may be somewhat proportional if the surface water has taken up an abundance of uranium from dry-season efflorescences or dust. The fluctuation in ground water ordinarily is much less than in streams.

A typical example of fluctuations in smaller streams draining uraniferous areas is Prickly Pear Creek, Montana, at the mouth of its canyon. The uranium content at seasonal peak discharge in June 1954 was 1.5 ppb, but at low stage in September 1953 it was 4.2 ppb. A typical creek in the uranium-mining area of the Front Range near Denver, Colorado, contained 4.2 ppb late in November 1954 when drought had reduced the water supply materially, but the content was 1.5 ppb U in March 1955 as the result of dilution of ground-water increment by snow-melt water.

Seasonal fluctuations in the uranium content in shallow ground waters resemble those in surface waters, but in deep ground waters the fluctuations are less. Water from the Argo Tunnel that drains the uraniferous Central City mining district near Denver, Colorado, contained 76 ppb U in May 1954 when snow-melt water descending through old workings was diluting the ground water, 89 ppb in September 1954 when the ground-water level was low, and 81 ppb in April 1955 when dilution by surface water was unusually low because of drought.

EFFECT OF EVAPORATION AND MINING OPERATIONS

The uranium content of water may be increased greatly by excessive evaporation, recent drilling or blasting, or disturbance of ground as in placer mining. The increase may be as much as several hundred times the true natural value. Evaporation effect ordinarily is negligible, but an arid climate, power ventilation in mines, or evaporation-basin conditions may have great effect.

Recent drilling or blasting may increase the uranium content as the result of comminution or fine grinding of uranium mineral to allow water to attack more surface area per unit volume per unit time. The increase is thought to range from about 25 to 250 times the true natural value, depending on the uranium content of the ground. The increase is about 25 times true natural value in one uraniferous Montana base-metal mine where conditions are closely controlled. In a uranium mine with rich ore near Denver, Colorado, the increase caused by drill water seeping through normally dry workings is about 250 times. The effect decreases more rapidly where drainage is good but is thought to require about a year to be eliminated under ordinary conditions in mine workings. In drill holes the effect may last longer. The effect has been encountered in samples from deposits affected by placer mining in Idaho and Alaska, but its extent and duration are not yet known.

The effects of evaporation by mine ventilation and of drilling and blasting are commonly found together, as in the Sligo adit, which is in Chattanooga black shale in central Tennessee. A stagnant pool near the face, 150 feet from the portal, contained 690 ppb U when sampled, but after the pool was drained and samples were obtained from seepage in the walls, the uranium content was about 1 ppb. The joint effect of evaporation and mining was to increase the uranium content about 500 or 600 times the true natural value.

CONCLUSION

The large number of analyses now available establishes hydrogeochemical exploration for uranium as a valid means of appraising the uranium possibilities of regional and local areas. The many factors that must be taken into consideration can be evaluated as suggested in the foregoing text. It is very apparent that the uranium content of a water by itself means little without geologic background and a satisfactory sample pattern in which to place the figure. Given the required information, however, the uranium content of natural waters, both surface and underground, should reveal the presence of much uranium ore at present undiscovered.

REFERENCES

1. Ostle, D., *Geochemical Prospecting for Uranium*, Mining Magazine 91: no. 4, 201–208 (1954).
2. Judson, S. and Osmond, J. K., *Radioactivity in Ground and Surface Water*, American Journal of Science 253: 104–116 (1955).
3. Grimaldi, F. S., May, I. and Fletcher, M. H., *US Geological Survey Fluorimetric Methods of Uranium Analysis*, US Geological Survey Circular 199 (1952).

Measurements on Natural Water Sources as an Aid in Prospecting for Underground Deposits of Uranium

By Saadia Amiel and Lester Winsberg,* Israel

In prospecting for underground deposits of uranium considerable help may be derived from a detailed examination of radioactive materials brought up by water or gases. Further aid may also be obtained from the study of the isotopic composition of non-radioactive elements.

Among the radioactive elements which are of importance in this connection are (1) uranium, (2) radium, (3) radon, (4) krypton-85, (5) xenon-133, and (6) tritium. The first three are, of course, members of the uranium family. Krypton-85 and xenon-133 are produced by fission (both spontaneous and neutron induced) of uranium, and tritium originates primarily with meteoric water. Among the properties of non-radioactive elements, of special significance are changes in the isotopic abundance of deuterium, oxygen, nitrogen, helium and argon. This paper is devoted mainly to work involving the radioactive elements and helium. Work involving the stable isotopes, other than helium, will only be mentioned in passing.

DECAY PRODUCTS OF URANIUM

Water sources may be classified according to the content of radium and radon[1] as follows:

1. Radium present (> 5 $\mu\mu$curies/liter) and high radon content ($> 10^3$ $\mu\mu$curies/ liter).
2. Little or no radium present ($<$ $\mu\mu$curies/liter) but radon present ($> 10^3$ $\mu\mu$curies/liter).
3. Little or no radium (< 5 $\mu\mu$curies/liter) or radon ($< 10^2$ $\mu\mu$curies/liter) present.

These results depend not only on the size and nature of the deposits but also on the nature of any intervening structures, the motion of the underground water, and the chemical and nuclear properties of the two indicators. In order for radium to be present, the water must have passed through the deposit (Type I). This need not be the case for radon since it is a chemically inert gas and can, therefore, be transported by other gases or move by means of its own diffusion.

Because the half-life of radon is short relative to most geological processes, water of Type II probably passes close to a deposit. On the other hand, lack of radon does not necessarily mean the absence of a deposit in the vicinity since the intervening structures may not be sufficiently permeable to permit the passage of radon in a time of the order of its half-life. Thus Type III may either conform to this situation or be due to an absence of an appreciable deposit.

A value for the minimum size of a deposit associated with a well being pumped continuously or with a flowing spring can be calculated from the radon content and the rate of flow. We can take as a typical example a spring containing 10^4 $\mu\mu$c Rn/ liter with a flow of 100 liters per second, i.e., having an output of one μc Rn/sec. This corresponds to 1.3 tons of uranium under equilibrium conditions.

The actual size of the deposit is certain to be much greater than this figure. It would, therefore, be useful to have other evidence to bear on this point. Among the various decay products of uranium, the rare gases are most useful for this purpose. These are helium and radon from alpha decay and krypton-85 and xenon-133 from spontaneous fission of uranium-238 and from neutron induced fission of uranium-235. Because of the difficulty of decontaminating from radon, the content of xenon-133 is not being measured in this laboratory.

Let us again consider a spring flowing at the rate of 100 liters per second but containing 0.01 cm helium per liter, i.e., having an output of 1 cm^3 per second. To produce this quantity of helium under equilibrium conditions, the deposit must contain 2.5×10^8 tons of uranium. The extreme magnitude of this figure suggests that most of the helium content of such a spring originates from a trapped helium source.

In principle the krypton-85 content provides a better indication to the size of the deposit than radon because of its relatively long half-life and its smaller atomic weight. We have so far achieved a sensitivity of 0.1 disintegration per minute per liter of gas, or per 50 liters of water at ordinary temperatures, since the dissolved gas is primarily air or nitrogen. For a flow of 100 liters per second, this corresponds to the order of 10^6 tons of uranium. For a smaller water flow the minimum size of deposit which can be detected is proportionately smaller.

Other information may throw light on the nature and location of the deposits. The alpha particles from the decay of uranium can react with the constituents

* Israel Atomic Energy Commission and Weizmann Institute of Science, Rehovoth, Israel.

of the deposit forming neutrons. Reactions induced by neutrons and alpha particles can cause changes in the isotopic ratios of the rare gases. For example, very low values of the He^3/He^4 ratio have been found in rich uranium ores.[2,3] Changes in the abundances of the argon isotopes by way of secondary reactions depend on the presence of chlorine[4,5]. Low values for the N^{14}/N^{15} ratio have been found in gases occluded in uranium and thorium minerals.[6] This field of investigation is just developing and it is, therefore, not yet possible to evaluate the usefulness of this type of measurement.

Besides all the preceding information the following additional data can be brought to bear on the location of the deposit: the salt content; temperature; seasonal variation of flow; the presence or absence of dissolved oxygen; tritium content; and the isotopic abundance of deuterium and oxygen. These are clues as to whether the water is of recent meteoric origin, whether the water originates from a great depth, or whether mixing has occurred.

Together with knowledge of the geology of the region, the information gained from a detailed investigation of natural water sources should prove helpful in planning a drilling program.

REFERENCES

1. Amiel, S., Dostrovsky, L., Winsberg, L., *Bull. Res. Council Israel, 4,* 94 (1954).
2. Aldrich, L. T. and Nier, A. O., *Phys. Rev., 74,* 1225, 1950 (1948).
3. Coon, J. H., *Phys. Rev., 75,* 1355 (1949).
4. Fleming, W. H. and Thode, H. G., *Phys. Rev. 90,* 857 (1953).
5. Wetherill, G. W., *Phys. Rev., 96,* 679 (1954).
6. Yagoda, H. and White, W. C., *Phys. Rev., 78,* 330 (1950).

Water Sampling as a Guide in the Search for Uranium Deposits and its Use in Evaluating Widespread Volcanic Units as Potential Source Beds for Uranium

By N. M. Denson, H. D. Zeller, and J. G. Stephens,* USA

As part of the investigations of uranium occurrences in carbonaceous rocks and sandstones the writers and associates collected a large number of water samples for analyses of their uranium and other trace-metal content in several areas in the Great Plains and in Tertiary basins of the Rocky Mountain region. The samples were obtained during the period 1950 to 1954 to accumulate data on the uranium content of water in different rock types and stratigraphic units and to evaluate water sampling as a technique in search for uranium deposits. The waters sampled were collected mostly from seeps, springs, and wells and are mostly derived from underground sources. A smaller number of surface-water samples collected from streams, lakes, and reservoirs were difficult to evaluate. Attention was directed mainly toward terraines underlain by tuffaceous sedimentary rock equivalents of acid volcanic rocks, fluviatile arkosic sandstone and shale, and areas containing known secondary occurrences.

The writers are indebted to many of their colleagues who collected and supplied data on a number of water samples. The analyses were made by personnel of the US Geological Survey.

Pint samples of ground water were collected in polyethylene bottles, and acidity of the water was determined in the laboratory with a pH meter, with a glass electrode. The uranium content was determined by ethyl acetate extraction method as follows: an acidified aliquot of the sample, usually 100 to 500 ml, was evaporated nearly to dryness and then diluted with distilled water acidified with nitric acid. An aliquot of this solution was salted with recrystallized aluminum nitrate, and the uranium was extracted with ethyl acetate. The extract was then burned off in a platinum dish, and the residue was fused with a sodium fluoride carbonate flux. A sensitive fluorimeter was used to compare the fluorescence of the unknown with standards treated in a similar manner, and the uranium content was calculated in parts per billion. The probable limits of accuracy of this method range from about 1 ppb (parts per 1,000,000,000) for samples containing 10 ppb, to about 10 ppb for samples containing 100 ppb uranium. A small number of large bulk samples of water were collected for determining other trace elements.

URANIUM IN GROUND WATER

Results of systematic sampling in four areas in South Dakota and Wyoming showing the average uranium content of ground water in the different geologic environments in each area are summarized in Table 1. The variation in uranium content of water is shown on the generalized geologic maps (Figs. 1–4).

At Slim Buttes in southwestern Harding County, South Dakota (Fig. 1) some lignites of Paleocene age contain small amounts of uranium. Uranophane and autunite locally impregnate carbonaceous sandstones in rocks of the same age. Both the uranium-bearing lignite and sandstone closely underlie tuffaceous rocks of Oligocene and Miocene age. Carnotite occurs locally in tuffaceous sandstone and claystone of the Oligocene rocks.

In the Powder River Basin in eastern Wyoming (Fig. 2) carnotite and uranophane occur in fluviatile sandstones of Eocene age. Erosional remnants of Oligocene and Miocene tuffaceous sediments in the basin indicate that most of the basin was once covered by these sediments. In the Gas Hills area, Wyoming (Fig. 3), uranium deposits occur in the Wind River formation of Eocene age, with the exception of two minor occurrences in subjacent Mesozoic rocks. Meta-autunite and an unnamed yellow uranium phosphate are the most common ore minerals and generally occur as interstitial fillings in coarse-grained, arkosic sandstone of fluviatile origin. Meta-zeunerite, uraninite, and other uranium minerals also are found in the area. In the Crooks Gap area, Fremont County, Wyoming (Fig. 4), uranium minerals, principally uranophane and minor amounts of autunite impregnate arkosic sandstone of the Wasatch formation of Eocene age.

OTHER TRACE ELEMENTS

Trace elements other than uranium were determined by chemical and spectrographic analyses of residues obtained by evaporation of large water samples from ground water in late Tertiary tuffaceous units from localities in Kansas, Montana, South Dakota, and Wyoming. A comparison of the

* US Geological Survey.

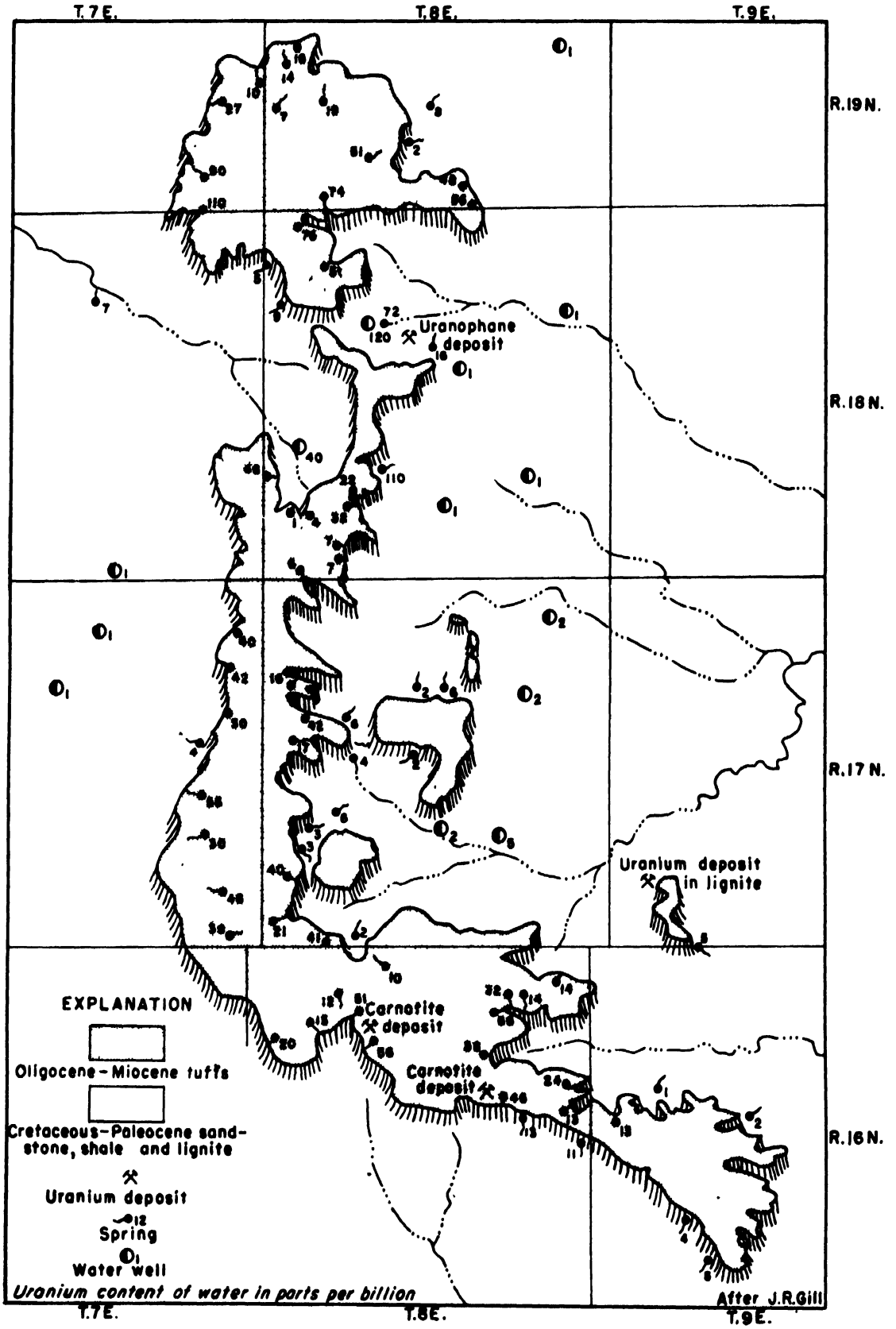


Figure 1. Map showing distribution of uranium in water from Slim Buttes, and vicinity, Harding County, South Dakota

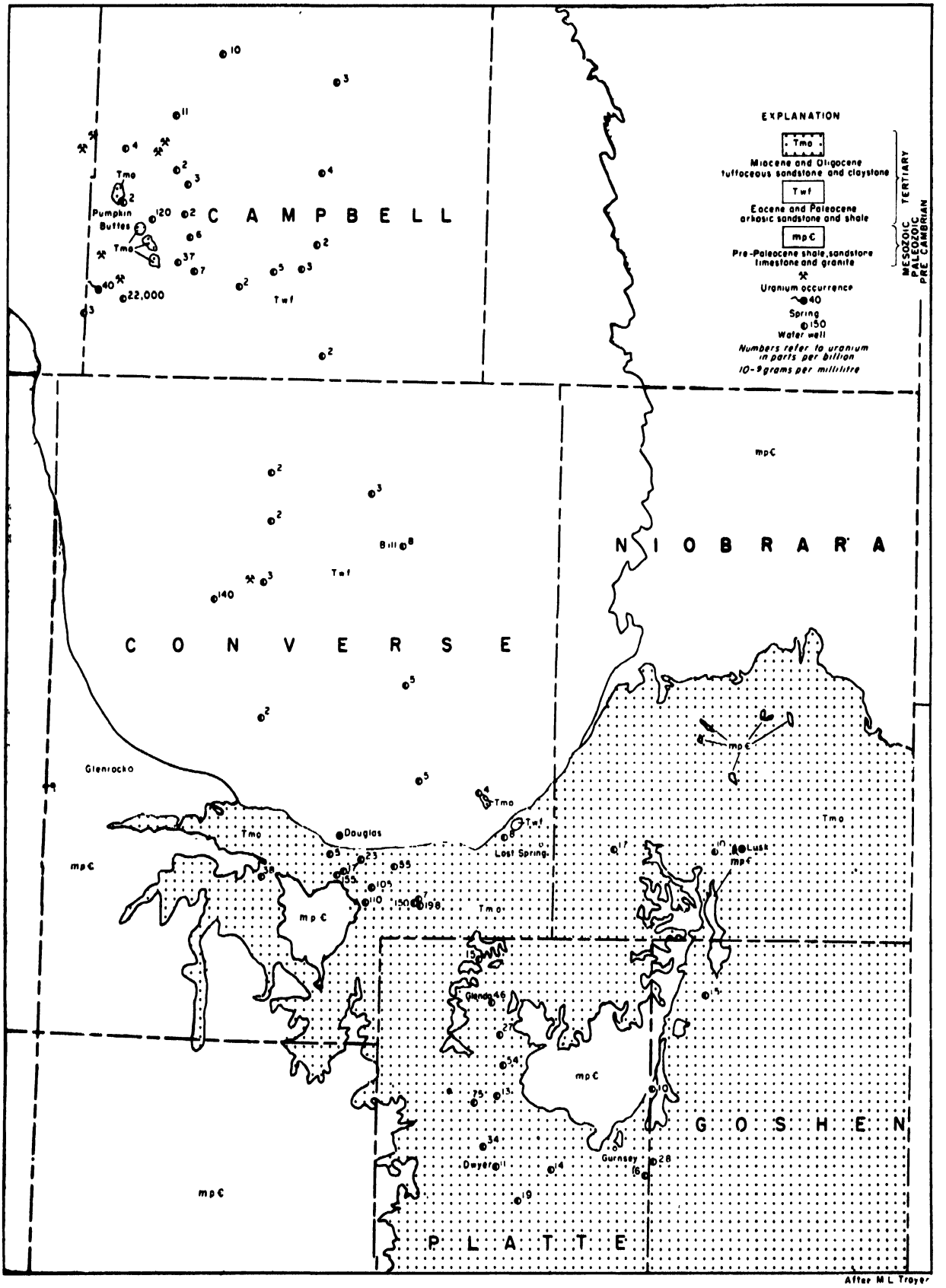
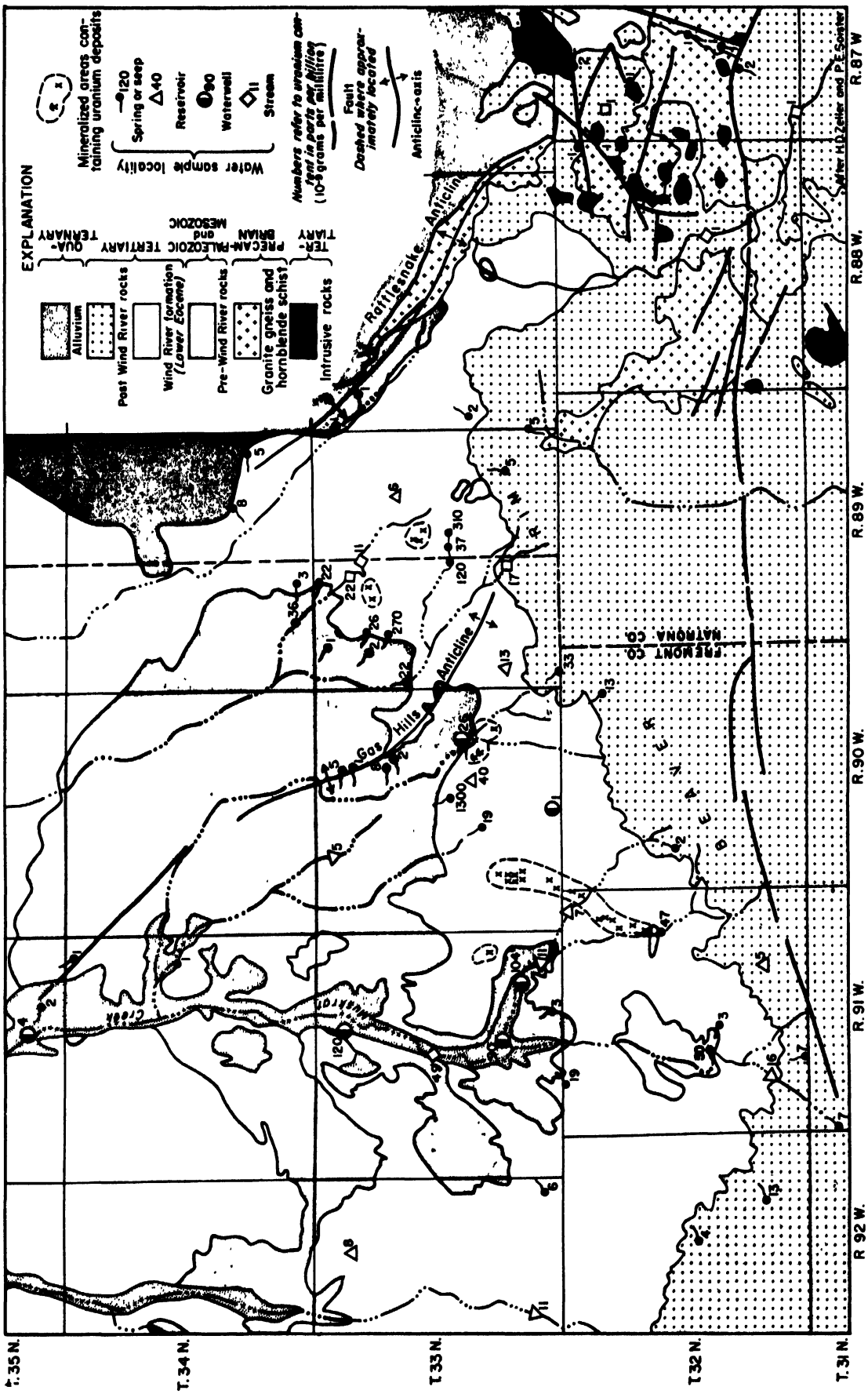


Figure 2. Map showing variation in uranium content of ground water in the southern part of the Powder River Basin, Wyoming


EXPLANATION
QUA-TERNARY
TERTIARY
MESOZOIC
PRECAM-BRIAN
TER-TIARY
Alluvium
Post Wind River rocks
Wind River formation (Lower Eocene)
Pre-Wind River rocks
Granite gneiss and hornblende schist
Intrusive rocks
Water sample locality
Spring or seep
Reservoir
Waterwell
Stream
Mineralized areas containing uranium deposits
Numbers refer to uranium content in parts per billion (10⁻⁹ grams per milliliter)
Fault
Dashed where approximately located
Anticline—axis
Rattlesnake Anticline
Gas Hills
Gas Hills Anticline
Beaver Rim
Sand Draw
Crooks Gap
Sweetwater Co
Fremont Co
Natrona Co
Sweetwater R.
Wind R.
Sinks Canyon
Sweetwater Canyon
Sweetwater Gap
Sweetwater Lake
Sweetwater Peak
Sweetwater Station
Sweetwater Station
Sweetwater Station

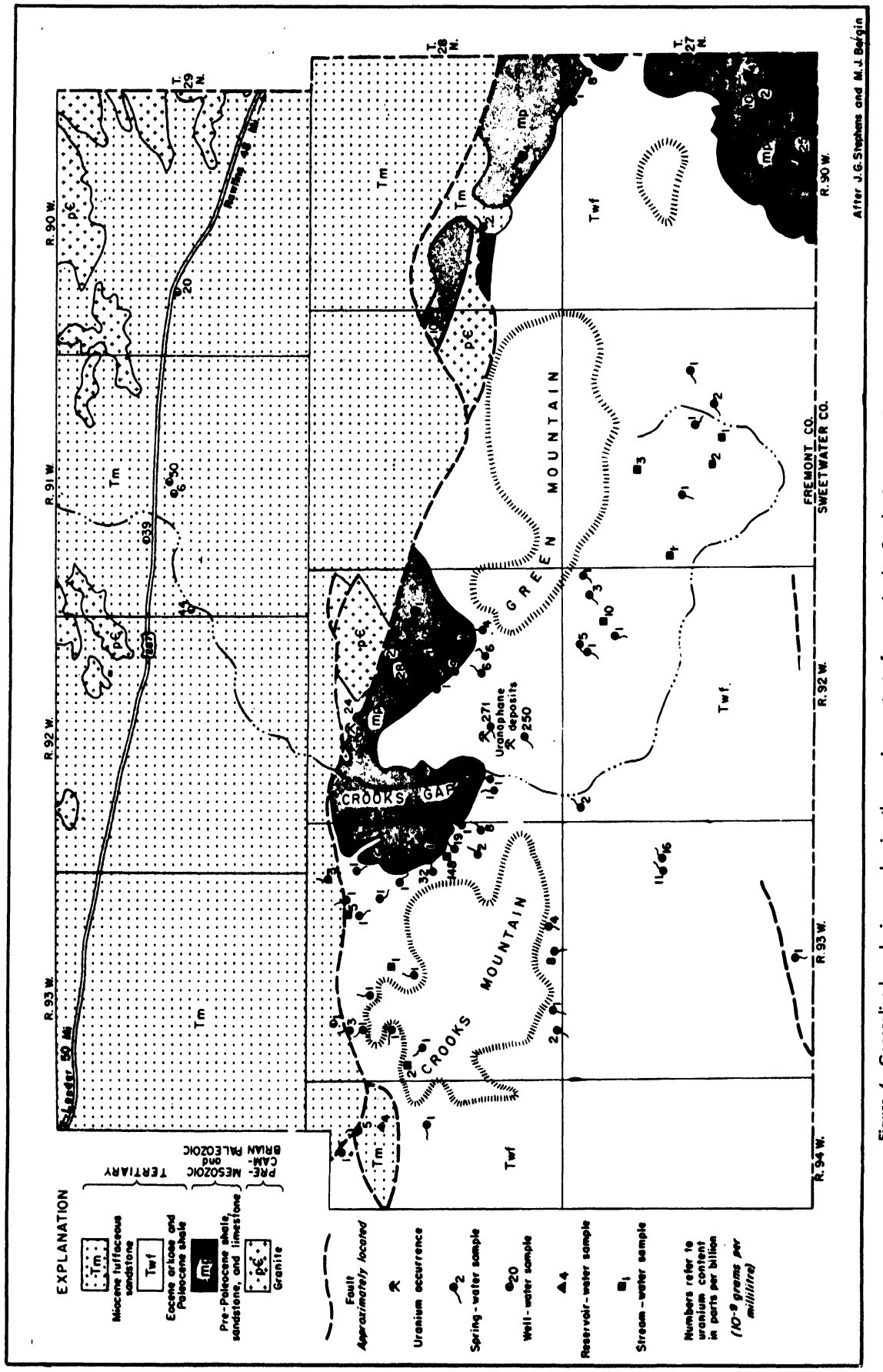


Figure 4. Generalized geologic map showing the uranium content of water in the Crooks Gap area, Fremont County, Wyoming

Table I. Summary of Uranium Content of 277 Water Samples from Areas Described in this Report

Units from which water was sampled	*Springs and wells sampled*	*Average uranium content of water (ppb)*	*Average pH*
Slim Buttes, South Dakota			
Oligocene and miocene	49	34	8.9
Cretaceous and Paleocene	34	4	8.9
Mineralized areas	5	72	8.6
Total samples	88		
Powder River Basin, Wyoming			
Oligoecne and Miocene	28	46	8.1
Eocene and Paleocene	25	4	—
Mineralized areas	4	84	—
Total samples	57		
Gas Hills, Wyoming			
Oligocene and Miocene	6	12	7.92
Eocene and older	37	6	7.86
Precambrian and Tertiary intrusives	3	1	7.43
Mineralized areas	16	98	6.81
Total Samples	62		
Crooks Gap, Wyoming			
Miocene	9	19	—
Eocene and older	55	4	7.5
Mineralized areas	6	124	7.5
Total samples	70		

trace elements present in these residues with those elements present in the uranium minerals found in the region shows that most of the elements in uranium minerals are also present in the water residues. For example, the important secondary minerals common to a number of the deposits in the areas considered in this report are carnotite $K_2(UO_2)_2(VO_4)_2 \cdot 1\text{–}3H_2O$, autunite $Ca(UO_2)_2(PO_4)_2 \cdot 10\text{–}12H_2O$, and meta-zeunerite $Cu(UO_2)_2(AsO_4)8H_2O$. In addition to uranium, ore samples contain varying amounts of vanadium, phosphorus, arsenic, and copper. Analyses of the water residues from the tuffaceous units shown in Table 2 indicate the presence of more than normal amounts of these elements.

SUMMARY OF RESULTS

The uranium contents of ground water of the different sedimentary terranes in the areas studied show marked variations. The highest concentrations of uranium in ground water are generally found in areas near known uranium deposits; greater than normal concentrations of uranium in ground water are found in acid tuffs and tuffaceous sedimentary rocks of Oligocene and Miocene age; and ground water from arkosic and other sedimentary terranes that are not near uranium deposits generally contain only a few parts per billion of uranium. The most highly mineralized water in tuffaceous terranes has an alkaline pH range of 7.5 to 9.5. In general the

Table II. Quantitative Analyses of Selected Trace Elements in Water

Rock unit and age	*Area*	*As*	*Se*	*P*	*Cu*	*V*	*Mo*	*Zn*	*U*	*Na*	*Ca*	*pH*
		(ppb)								(ppm)		
Late Tertiary tuffaceous rocks												
Ogallala fm. Pliocene	Smoky Hill, Kans.	28	14	<42	10	10	477	70	49		230	7.8
North Park fm. Pliocene(?)	Miller Hill, Wyo.	2	<1	732	3	17	10	37	14			
Browns Park and	Long Pine Hills, Mont.	16	32	38	4	85	2	11	10	86		8.8
Arikaree fms.	Sweetwater Arch, Wyo.	6	1	26	9	42	4	66	50		29	7.6
Miocene	Saratoga Basin, Wyo.	<7	2	71	5	11	24	43	16			7.4
	Poison Basin, Wyo.	60	7	82	9	5	0	32	11		368	7.5
	Washakie Basin, Colo.	19	<4	96	13	6	0	2882	8			7.7
White River fm.	White River Badlands, S. Dak.	20	4	15	8	17	170	25	13	125		8.5
Oligocene	Southern Black Hills, S. Dak.	19	5	22	3	15	15	27	8	132		8.2
	Powder River Basin, Wyo.	18	11	44	14	139	30	71	150	255		8.6
	Beaver Divide, Wyo.	11	1	19	3	13	1	<7	13	71		7.4
Early Tertiary arkosic rocks in mineralized areas												
Wind River and	Gas Hills No. 1, Wyo.	<11	<1	?	18	3	3	233	270			3.9
Wasatch fms.	Gas Hills No. 2, Wyo.	<25	10	<125	113	8	85	50	310		503	7.7
Eocene	Crooks Gap, Wyo.	< 3	1	14	9	2	0	19	271	30	53	8.3

more alkaline waters from these rocks carry the most uranium in association with proportionately larger amounts of sodium and calcium, the Oligocene being more sodic and the Miocene more calcic. The relationship of other trace elements to the uranium content of these waters has not been determined, but laboratory data show that they also contain greater than normal amounts of molybdenum, vanadium, copper, phosphorous, zinc, and arsenic.

The relatively high uranium concentrations in the water from the Oligocene and Miocene units probably is due to the uranium content of its tuffaceous constituents. These rocks are mostly water-laid and contain large quantities of airborne volcanic sediments. Owing to their high porosity and permeability water is permitted relatively easy circulation. Although the uranium content of these rocks varies markedly from place to place as well as within short distances along the same stratigraphic horizon, chemical analyses show a maximum uranium content of 0.0030 per cent and an average of about 0.0015 per cent. Uranium disseminated in these rocks may have been an important primary source of uranium later concentrated in the secondary deposits in the underlying sedimentary rocks through ground-water circulation.

Botanical Methods of Prospecting for Uranium

Prepared by H. L. Cannon, and F. J. Kleinhampl,* USA

Prospecting for mineral deposits at depth by observing unusual growth characteristics or distribution patterns in surface vegetation has been used through the ages in the search for many metals. Botanical methods of prospecting are dependent upon the absorption and accumulation of metals and associated elements by plants growing over metalliferous deposits.

Two methods of botanical or biogeochemical prospecting have been developed and used by the US Geological Survey to locate uranium deposits on the Colorado Plateau which includes parts of Colorado, New Mexico, Utah, and Arizona. The deposits are chiefly the carnotite type and occur as irregular tabular masses in rocks of Triassic and Jurassic age. The ore commonly contains about 2 per cent V_2O_5 and 0.25 per cent U_3O_8 with minor amounts of selenium, sulfur, arsenic, cobalt, copper, and traces of other metals. One method of botanical prospecting currently used is based upon the uranium content of plants; another is based upon the distribution of indicator plants—those that are dependent either directly or indirectly upon the presence of abnormal amounts of uranium and associated elements. Basic studies in the development of the methods have been described in previous papers.[1,2] Subsequent laboratory and experimental plot studies have supplemented field observations.

During the past five years, nearly 10,000 samples have been analyzed for uranium, and distribution studies of indicator plants have been made along 80 kilometers of outcrop. A positive correlation has been shown between botanically favorable ground and major ore deposits, and preliminary results indicate that ore may be found at depths to 25 meters by botanical methods of prospecting.

PROSPECTING BY TREE ANALYSIS

Prospecting by tree analysis is based on the uranium content of trees growing in the area to be prospected. Uranium occurs in all plants in small but measurable amounts. Plant ash normally contains 0.2 to 1.0 parts per million uranium. The uranium content of plants rooted in ore, however, may range from 1 to 100 ppm uranium. Therefore the uranium content of plants rooted in ore or within the chemical halo of the ore body may be used as an indication of mineralized ground.

The uranium content of vegetation varies for many reasons, which should be understood and evaluated before a project of plant analysis is undertaken. The uranium content of trees and herbaceous plants varies slightly with the seasons and the amount of rainfall, but in an area being prospected by day-to-day sampling, this small variation can be discounted. A large part of the uranium absorbed by the plant root is precipitated within the root cells. A lesser amount is transported to the leaves and branches and is in direct proportion to the total uranium absorbed by the roots, so that the presence or absence of mineralized ground may be inferred from leaf or twig analyses. Of importance in prospecting is the variation in uranium content from one side of the tree to another. As the roots of one side of the tree are directly connected to a particular set of branches, the uranium content of the branches may vary depending upon the position of the mineralized ground. It is important, then, to sample a tree on all sides to obtain a representative sample.

Some plant species absorb much more uranium than others. The mechanism by which plants absorb uranium is not a matter of ion transport in a water solution but of ion exchange. Plant families differ in regard to the amounts of the various ions absorbed because they have different and characteristic buffer systems and resulting variations in cell sap pH. Plot studies indicate that those plants that readily absorb large amounts of sodium, sulfur, selenium, and calcium but small amounts of potassium will also absorb uranium readily. These plants generally have a cell sap pH of less than 5.2. For this reason, conifers and desert shrubs of the rose family that have these characteristics and are common in uranium districts of the Colorado Plateau can be used successfully in sampling programs.

The amount of uranium absorbed by plants is dependent also upon the percentage of water-soluble uranium in the vicinity of the plant roots. The amount of water-soluble uranium present is due in part to the interaction of uranium with other ions present in unusual amounts and does not necessarily reflect the total amount of uranium present. For instance, the percentage of water-soluble uranium in the soil is increased when gypsum, selenium, or lime is added. The addition of carnotite increases the solubility of sulfur and selenium. The latter relationship is important in the localization of sulfur- and selenium-bearing indicator plants. The described

* Including work by H. L. Cannon, H. F. Froelich, F. S. Kleinhampl and P. F. Narten, US Geological Survey.

changes in solubility of uranium take place under oxidizing conditions, and important differences in the relative absorption of uranium by deep-rooted trees and shrubs have been noted only in areas of oxidizing ore.

The depth to which ore can be detected by plant analysis depends upon the root habits of the species sampled and upon the availability of water. In semi-arid country, shrubs and trees commonly have root systems 15 to 25 meters in length. In many uranium districts of the Colorado Plateau, the ore-bearing rock is an aquifer. The roots of junipers, pinyons, and desert shrubs penetrate long distances through cracks and crevices connecting with the water-bearing zone, and act as phreatophytes or ground-water plants. Mineralized areas of a coal bed on LaVentana Mesa, New Mexico, were outlined effectively by analysis of pinyon and juniper whose roots penetrated a 25-meter sandstone capping the mesa. It is probable, however, that plant analysis is not generally effective in prospecting at depths of more than 20 meters.

In prospecting by the plant-analysis method, a preliminary study must first be made of the geologic relations. This should include observations on the extent, depth, and inclination of the ore-bearing strata, the size and habits of the ore bodies, the probable grade of the ore, the presence or absence of a chemical halo in the surrounding barren rock, and the relation of the ore-bearing bed to the water table and the plant roots. Botanical studies should be made of the growth habits of species available for sampling. Preliminary samples should be collected on both mineralized and barren ground and then analyzed to determine the amount of uranium absorbed by trees in the area under study. Finally, from this geological and botanical information, the sampling medium, the sampling pattern, and sampling interval may be determined.

Several coniferous species have a wide range on the Colorado Plateau, have deep roots, and absorb about the same amounts of uranium. These species, listed in Table I, have been used as the sampling medium on several projects.

Table I. Trees Used in Sampling on the Colorado Plateau

	Altitude (feet)
Pinus ponderosa Doug. (Ponderosa Pine) *Pseudotsuga taxifolia Britt* (Douglas fir) *Abies concolor Lindl.* (White fir)	7000 to 9000
Pinus edulis Engelm. (Pinyon) *Juniperus scopulorum Sarg.* (Rocky Mt. juniper)	6000 to 7000
Juniperus utahesis Sarg. (Utah juniper) *Juniperus monosperma Engelm.* (oneseed juniper)	4000 to 6000

Samples of the last year's growth of needles or branch tips collected from the entire periphery of the tree have given the most consistent results.

In areas where the ore-bearing bed occurs in a broad flat bench with a uniform vegetative cover, systematic tree sampling on a grid pattern may be used. Favorable areas may be found by drawing isograms on the uranium values. In areas where the ore-bearing bed crops out in sharp cliffs, line traverses with particular emphasis on close-spaced samples collected on talus-covered areas may prove to be the best sample pattern.

The distance between sampled trees depends in part upon the objective of the project. For rapid reconnaissance, an initial spacing of 75 meters is usually adequate, and in anomalous areas later fill-in samples with 15-meter spacing may be desirable. A shorter interval of 5 to 10 meters is useful for sampling across talus-covered rim or cliff outcrops.

ANALYTICAL METHODS

A fluorimetric method of analysis is used by the Geological Survey for the determination of uranium in plant ash; the method has been described by Grimaldi and others.[3,4] A portable fluorimeter, powered by batteries, has been designed for field use, and a chromatographic field test for uranium in soils and in plant ash has also been used in Survey laboratories. A method of analyzing the radioactivity of plant ash by alpha count has been developed at the University of Arizona and has been described in a recent paper by Anderson and Kurtz.[5]

A pint container of fresh plant material is collected for fluorimetric analysis under present laboratory procedure. The precision to be expected from the method is 0.5 ppm uranium in the range from 0.3 to 5.0 ppm uranium. The chromatographic method requires much less sample, but is not as accurate in the low ranges as the fluorimetric method.

INTERPRETATION OF RESULTS

Although the amount of uranium absorbed by plants rooted in ore varies slightly with the type of ore and the species of plant sampled, contents above 1 ppm uranium in the ash are considered to indicate favorable and possibly mineralized ground in many areas sampled on the Colorado Plateau. This figure was arrived at empirically from early plant analysis studies and from a statistical analysis of 2000 tree samples. Trees rooted in barren ground were found to average 0.3 ppm uranium in the ash; trees rooted in mineralized ground averaged 1.5 ppm uranium.

Statistical study verifies the conclusions of other workers that a sampling program should be restricted to one kind of tree. However, when it is necessary to use more than one species of tree. special factors relating the different species to one another could be employed. These factors would be obtained by relating the statistical measures of the assay data of each population to the other populations used. The results thus obtained would define more exactly anomalously high values and

Figure 1. *Astragalus pattersoni*, Patterson's Loco, a selenium-indicator plant useful in prospecting for uranium ore

make the results obtained from the different species comparable.

PROSPECTING BY INDICATOR PLANTS

A plant may be used as an indicator plant in prospecting for metalliferous deposits if its distribution is affected by the availability of chemical constituents present in the ore. The plants used in prospecting for a particular type of deposit may not all be controlled by the same factor. They are usually common rather than unusual plants. Indicator plants for uraniferous sandstone deposits are controlled not only by the presence of unusual amounts of selenium and sulfur but by an increased availability of these elements in water-soluble form and by the increased availability of the major plant nutrients, calcium and phosphorus. Selenium and sulfur were found by plot experiments to be more readily absorbed by plants in the presence of carnotite, and uranium to be more readily absorbed in the presence of selenium and sulfur. The availability of calcium and phosphorus was also increased in the plots to which carnotite has been added. In addition, each indicator plant, depending upon the specific metabolic processes inherent in the species, reacted differently to the excess materials available for absorption. These experiments explain many irregularities in plant distribution noted in the field.

A correlation between the distribution of selenium-indicator plants and carnotite deposits of the Morrison formation was first noted by Beath in 1943, in conjunction with toxicity studies of range land.[6] The US Geological Survey has since established the use of selenium-indicator plants in prospecting for uranium. In general the plants are perennials with long tap roots; roots of *Astragalus* have been traced to a depth of more than 10 meters in mine workings. Under favorable conditions the use of *Astragalus* has led to the discovery of ore bodies 25 meters below the surface. *Astragalus* (Fig. 1) and other seleniferous genera have distinct distribution patterns depending upon the amount of selenium in the ore and the amount required by the plant. Preliminary studies are mandatory in advance of prospecting in each new area to determine the species best correlated in distribution with mineralized ground.

Astragalus pattersoni, A. Gray, belonging to the vetch group is the most useful indicator plant on the Colorado Plateau (Fig. 1). The plant requires large amounts of selenium and commonly absorbs several thousand ppm selenium from uranium ores. Plot experiments suggest that the presence of carnotite increases the absorption of selenium by this plant many times.

The following species of *Astragalus* are also useful in some areas of the Plateau: *Astragalus preussi* A. Gray, *Astragalus thompsonae* S. Wats, *Astragalus confertiflorus* A. Gray, *Astragalus bisulcatus (Hook)* A. Gray, *Astragalus lonchocarpus Torr*, and *Astragalus dodgeanus* M. E. Jones.

Other selenium-indicator genera that require only small amounts of selenium may act as indicators of uranium ore containing less than 2 ppm selenium. These include: *Aster venustus*, M. E. Jones (woody aster), *Grindelia* spp. (Gumweed), *Oryzopsis hymenoides*, (R. and S.) Rick (Indian ricegrass), and *Stanleya* spp. (Prince's Plume).

Many uranium ores contain sulfides that commonly form gypsum upon weathering. Sulfur- and calcium-absorbing ephemeral plants occur where this gypsum moves upwards into surface soil within reach of shallow plant roots. Sulfur- and calcium-absorbing ephemerals include: *Allium* spp. (wild onion), *Calachortus* spp. (Sego lily), *Zigadenus* spp. (Camas lily), *Sisymbrium* spp. (tumble mustard), *Lepidium* spp. (pepperweed), *Eriogonium inflatum*, Torr. (desert trumpet), *Cryptantha* spp. (cryptanth), *Oenothera caespitosa*, Nutt. (Tufted evening primrose), *Oenothera albicaulis*, Pursh. (white-stemmed evening primrose), *Stipa comata*, *Trin.* and *Rupr.* (needle-and-thread), *Elymus salina*, Jones (Salina wild rye), *Aplopappus armeriodes*, A. Gray (goldenweed), *Senecio longilobus*, Benth (threadleaf groundsel), and *Mentzelia multiflora*, Nutt. A. Gray (desert blazingstar).

It should be emphasized that the plants used as indicators in prospecting may be common roadside weeds in other areas of the country. The chemical elements that control their distribution around metalliferous deposits, particularly selenium and sulfur, are present in all rocks but their concentration varies greatly in different stratigraphic units. The plants may be useful prospecting tools where the difference in chemical composition between barren parts of the ore-bearing bed and the ore itself is enough to affect the flora.

The effectiveness of indicator plants as a guide to uranium deposits depends largely on the depth to mineralized ground and the availability of selenium and sulfur to the plant roots. In turn, species of indicator plants vary in their root habits and in their capacity to absorb selenate and sulfate ions. Much depends on whether the elements in question are

present only at ground-water level or have migrated to the soil surface along fractures or through permeable beds.

The distribution of indicator plants can be plotted directly on maps or photos as a result of field observation without the necessity of collection or analysis. Indicator-plant prospecting is rapid and inexpensive and therefore is preferred over prospecting by plant analysis if conditions permit.

Preliminary studies are necessary in each area to be prospected to determine what plants in this particular area correlate most closely with the extent of the mineralized ground. An initial mapping of several dozen plants may eventually resolve itself into a final mapping of 2 or 3 species which may be plotted by symbol on maps or on air photos. From a study of the resulting plant maps, favorable areas may be delineated for detailed geologic evaluation and possibly for exploration.

For the most effective use of plant distribution maps, a careful study should also be made of the sedimentary features, direction of ground-water movement, joint fracture patterns, folding, and other topographic and geologic features. Many drill holes have been inauspiciously placed in a futile attempt to test plant information without due regard to the probable origin and migration of water-soluble ions.

RESULTS OF BOTANICAL PROSPECTING ON THE COLORADO PLATEAU

Botanical prospecting studies have been made in advance of exploration in five districts of the Colorado Plateau. Of these only one area has subsequently been completely explored by diamond drilling. Preliminary drilling programs have been started in two other districts. Results indicate that prospecting by indicator plants is advantageous in areas of the Plateau where uranium ores average about 0.01 per cent selenium and are at an average depth of not more than 15 meters beneath the ground surface. Prospecting by tree analysis is advantageous in areas where the tree cover is continuous and the ores are not more than 25 meters in depth. It is also important that the ore-bearing formation be an aquifer.

Prospecting by indicator plants has been tested in the Yellow Cat area, Grand County, Utah, where plants were mapped over an area of 10 square kilometers and nearly 2000 holes were subsequently drilled. The ore in this area occurs in the Salt Wash sandstone member of the Morrison formation and contains vanadium, uranium, selenium, and sulfur. The distribution patterns of nine species of plants were originally mapped on a scale of 1:6000. Final maps were compiled on the distribution of four species.

An analysis has been made of the relation of plant distribution patterns to results of the first 1000 holes drilled in the area. Holes ranged in depth from 3 to 85 meters. A total of 26 holes were in ore in the first 1000 holes drilled, and all 26 penetrated ore at a relatively shallow depth. Twenty-one of the holes containing ore were in areas of indicator plants. Five ore bodies out of a total of 10 were found entirely on plant data. Indicator plants were found to reflect mineralized ground to an average depth of 22 meters but proved to be a more dependable ore guide when ore is at depths of less than 15 meters. Ten per cent of the barren holes, 50 per cent of the mineralized holes, and 80 per cent of the ore holes were drilled in areas of indicator plants.

A comparison of the effectiveness of indicator species in the area showed that the selenium-indicators *Astragalus pattersoni* and *A. preussi* are the most reliable indicators of mineralized ground and that the sulfur plants *Allium acuminatum* and *Eriogonium inflatum* may act as competent indicators where the ore lies at depths of no more than 10 meters.

Several ore bodies have also been found in the Grants district, New Mexico, as a result of indicator-plant prospecting. A project of prospecting by plant analysis was conducted during 1952–54 on the ore-bearing Jurassic Todilto limestone. Results of the program show that botanically defined anomalies delimit areas that are favorable for the discovery of uranium deposits, and preliminary drilling information indicates that botanical anomalies correlate with mineralized ground. On Elk Ridge, Utah, botanical sampling programs have defined areas where physical exploration for uranium may be warranted, as a study of the outcrop near botanically defined anomalies shows a positive correlation with geologically favorable criteria such as secondary copper and iron staining, carbonaceous trash, pyrite, and channel fillings.

SUMMARY

Two methods of botanical prospecting have been used in prospecting for uranium on the Colorado Plateau; first by analyzing for uranium content the foliage of trees collected on a grid or linear pattern; second by mapping the distribution of indicator plants.

The tree analysis method is dependent on the absorption of anomalous amounts of uranium by trees rooted in ore. In general trees rooted in barren ground average less than 0.5 ppm uranium but trees rooted in ore average 1.5 ppm or more. The uranium content of a plant varies with the organ of the plant sampled, the season, the amount of rainfall, the species, and the form in which the uranium occurs in the soil. The solubility of uranium has been shown experimentally to increase in the presence of selenium, sulfur, and calcium. The depth to which ore can be detected depends on the root habits of the plant and on conditions of ground water. Plants have been used effectively in outlining mineralized ground at depths of 25 meters.

Samples of plant ash may be analyzed by fluorimetric, radiometric, or chromatographic methods.

At the present time fluorimetric analysis is the most satisfactory method for uranium detection in low ranges. The results may be plotted on maps of the area with suitable isograms showing areas of anomalously high uranium content.

The indicator plant method is dependent on changes in the distribution pattern of particular species in the vicinity of ore deposits. The factors controlling indicator plants for uranium deposits are the presence of anomalous amounts of available selenium, sulfur, calcium, and phosphorus in the surface soil. The most effective indicator plants on the Colorado Plateau—species of *Astragalus*—are able to concentrate large quantities of selenium from the ore deposits. Plants of the lily, mustard, and buckwheat family, indicative of gypsum, are also locally useful. Areas favorable for geologic investigation can be delineated from maps of indicator plants in areas where the deposits are shallow and the geologic setting is thoroughly understood.

Results of botanical prospecting on the Colorado Plateau suggest that prospecting by indicator plants is advantageous where the uranium content is 0.01 per cent or more and the selenium content is also at least 0.01 per cent, if the ore bodies are at an average depth of not more than 12 meters beneath the ground surface. Prospecting by tree analysis is advantageous in areas of continuous vegetative cover where the ore-bearing stratum averages no more than about 20 meters in depth. Physical exploration of several areas prospected by botanical methods has shown a positive correlation between botanically defined favorable areas and mineralized ground and suggests that this technique has much promise as a method of finding worthwhile target areas in the United States and elsewhere.

REFERENCES

1. Cannon, H. L., *The Effect of Uranium-Vanadium Deposits on the Vegetation of the Colorado Plateau,* American Journal of Science 250: 735–770 (1952).
2. Cannon, H. L., *Geobotanical Reconnaissance near Grants, New Mexico,* US Geological Survey Circular 264 (1953).
3. Grimaldi, F. S., May, I. and Fletcher, M. H., *US Geological Survey Fluorimetric Methods of Uranium Analysis,* US Geological Survey Circular 199 (1952).
4. Grimaldi, F. S., May, I., Fletcher, M. H. and Titcomb, Jane, *Collected Papers on Methods of Analysis for Uranium and Thorium,* US Geological Survey Bulletin 1006 (1954).
5. Anderson, R. Y. and Kurtz, E. B., Jr., *Biogeochemical Reconnaissance of the Annie Laurie Uranium Prospect, Santa Cruz County, Arizona,* Economic Geology 50: 227–232 (1955).
6. Beath, O. A., *Toxic Vegetation Growing on the Salt Wash Sandstone Member of the Morrison Formation,* Journal of Botany 30: 698–707 (1943).

Record of Proceedings of Session 7B

THURSDAY MORNING, 11 AUGUST 1955

Chairman: **Mr. D. N. Wadia (India)**
Vice-Chairman: **Mr. R. Niini (Finland)**
Scientific Secretaries: **Messrs. D. J. Dewar and R. Hara**

PROGRAMME

P/764 Methods of prospecting for uranium and thorium.....C. F. Davidson and S. H. U. Bowie

P/1 Uranium prospecting in Canada—ground and aerial surveys .....A. H. Lang

DISCUSSION

P/763 Instrumental developments in the prospecting, mining and chemical processing of nuclear materials.....H. Bisby *et al.*

P/994 Radiation detectors with halogen counters for use in prospecting .....A. Milojevic *et al.*

DISCUSSION

P/132 Air survey applied to the search for radioactive minerals in Brazil .....D. A. MacFadyen and S. V. Guedes

P/625 Aeroradiometric prospecting for uranium and thorium deposits and the interpretation of gamma anomalies.....V. I. Baranov

DISCUSSION

P/503 Techniques for prospecting for uranium and thorium.....US AEC and Geological Survey

P/626 Radiohydrogeological method in prospecting for uranium deposits .....A. A. Saukoff

P/869 Remote location of uranium and thorium deposits.....K. G. Vohra

DISCUSSION

The CHAIRMAN: The mounting importance of uranium and thorium in the coming 50 years, the period envisaged in the Conference's programme, is realised on all hands. It is challenged only by such minerals as water, iron and petroleum. A great duty devolves on geologists and prospectors for finding new adequate natural sources of these metals and developing and mining them efficiently. For, in the ultimate analysis, the planning and development of nuclear energy for world use will depend upon the quantity of suitable raw mineral substances procurable for the purpose from the earth.

While there may not be much doubt that the earth's crust carries in the accessible depth enough reserves of uranium and thorium to cope with the energy needs of the world, finding and extracting the required amounts that will go on steadily mounting each year will tax more and more the resources of science and technology. The demand will fall heavily particularly on the geologists and prospectors. With the speed at which thousands of new prospects are discovered and exploited annually at present, exhaustion of surface and immediately sub-surface deposits, at any rate of the moderate grade workable ores, is not many years remote. Depth probing by improved geophysical means, to an extent not envisaged today, and ability to process leaner and leaner ores carrying only values in hundredths of a per cent of the fuel metal will have to be resorted to.

This Session has received a number of papers presented to this Conference. Many of them contain valuable expositions of the present-day techniques employed for discovering geologically masked deposits of uranium and thorium ore bodies. All these papers will eventually be published and therefore will be availbale to everyone. For our present purpose we have to consider and discuss nine papers which are going to be presented now. Many of the techniques that are being discussed today will doubtless continue to be used in the future in an extended and improved form.

Our immediate business at this Session is the consideration of nine papers which are under discussion this morning before us. These papers give a cross-

section review of the methods of uranium prospection that have proved successful in producing thousands of tons of uranium in the last 10 years. Recent developments in radio-hydrogeological methods and in techniques in aeroradiometric prospecting for uranium are discussed in several of these papers. We, however, notice in these papers that opinion regarding the practical utility of air-borne radiometric instruments is sharply divided. While the results of such surveys in Brazil have proved highly productive and this method is viewed very optimistically for the future, expert opinion in other regions regarding the use of aeroradiometric surveys is rather sceptical and regard such surveys as of problematical use. In a number of experimental flights the ability of air-borne scintillometers in obtaining radiometric anomalies of direct use or value is not clearly established and the nature of the various interferences is yet in question.

Mr. S. H. U. Bowie (UK) summarized paper P/764 as follows: The main thesis of this paper is that successful prospecting for uranium and thorium is nearly always based upon the application of geological knowledge and on the adequate training of prospectors in making the best use of the numerous ancillary aids now at their disposal.

The first step towards making a systematic exploration for radioactive mineralisation in any region is to make a detailed study of all available geological information on the area in question. From this preliminary research it may in many instances be possible to postulate what are the most favourable localities in which to commence field operations. All areas in which there is evidence of acid igneous activity, for example, deserve attention, and all known occurrences of mineralisation, particularly sulphide mineralisation, should be systematically listed; for more uranium ore has been found in old prospects and in working or derelict mines than anywhere else. Particular attention should also be given to formations which bear a petrological similarity to known uranium provinces.

At the same time as the geological investigations are proceeding the prospectors to be engaged in the field operations should be trained in the recognition of common radioactive minerals—not only of the fine specimens found in museums, but more particularly of the paint-like traces of secondary uranium minerals and of the iron-rich gossans without visible uranium which so often are all that is seen at the surface. The type of training given must differ greatly according to the terrain to be explored, that appropriate to the glaciated lands of Canada, for example, being different to that necessary for successful work in the heavily weathered and soil-masked rocks of Central Africa. In this preliminary phase the prospector should also be instructed in the use and maintenance of the instrumental aids with which he may be supplied so that the most suitable prospecting techniques are employed.

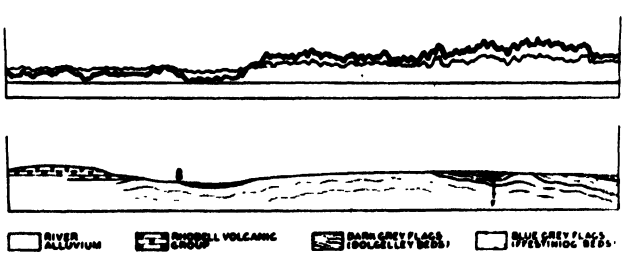
In circumstances where geological information is so inadequate that no guiding rules for exploration can be laid down, it is probably wiser not to undertake a specific search for uranium and thorium ores at all but instead to initiate a programme of geological reconnaissance mapping, coupled with a general prospecting campaign for economic minerals of any kind. Workable sources of radioactive minerals are of quite rare occurrence, and in completely unknown territory there is more hope of finding uranium as a by-product of a search for copper, cobalt, silver and other metals than in explorations directed solely towards uranium ores. Similarly the discovery of workable thorium ore could well result from a search directed more to the alluvial tinstone, columbite and ilmenite that it so often accompanies.

In all radioactivity explorations the principal tool of the prospector is a field ratemeter—either a Geiger-Müller counter or a scintillometer. Both of these instruments measure gamma radiation from near-surface occurrences of radioactive elements, but the scintillation counter has the advantage that whereas it has a similar efficiency to cosmic rays as a Geiger-Müller counter it is many times more sensitive to terrestrial gamma radiation. This means that the ability of a scintillometer to detect an anomaly near normal background level is greater than that of a Geiger-Müller counter.

In Slide 1, the thin line is the Geiger-Müller trace, the thick line is the scintillation counter trace over the same traverse. This is over normal rocks with very low radioactivity. This shows quite clearly that whereas the scintillation counter gives a lower count here over an alluvium, it gives a higher count over rock which has a slightly higher gamma radiation.

In prospecting, the choice of instrument depends largely on the degree of reproducibility sought in the proposed investigation. For routine prospecting, where no compensation is made for terrain factors such as local topography, absorption by soil cover, or disequilibrium due to weathering, a high statistical accuracy in the measurement of the count-rate is quite unnecessary. For example, a good prospecting instrument may have a count-rate as low as one or two counts per second over flat-lying, bedrock with a grade equivalent to 0.001% U_3O_8.

Slide 2 shows a typical scintillation counter used for prospecting. For more detailed studies, such as contouring the distribution of radioactivity at an anomaly, a ratemeter should have a count-rate of at least five pulses a second over similar bedrock. With instruments of this sensitivity the meter in-



Slide 1. Surface radioactivity profile and generalized geological section. Traverse north of Dolgelley, Merionethshire

tegration time can be adjusted so that the reproducibility of readings taken at selected stations are within ± 10%. However, to maintain a standard deviation of 10% in surveys made at a walking pace of three miles per hour, the background count of the instrument must be increased considerably. To measure the average radioactivity over traverse intervals of 10 feet the pulse rate would have to be about 40 counts per second, with a meter integration time of 2.5 seconds. It is not practicable for field geologists or prospectors to carry Geiger-Müller instruments containing single or multiple tubes with a large enough cathode area to give this response; but the required count rate can be achieved using a scintillometer with a thallium-activated sodium iodide crystal about a cubic inch in volume.

Unfortunately the operating voltage of present-day scintillometers is about four times that of halogen-quenched Geiger-Müller tubes, and from the aspect of the prospector the increase in battery weight necessary to maintain the high-tension supply to the photomultiplier tube largely offsets the advantages gained by the scintillometer's higher sensitivity. Within a short time, however, it is expected that small but thoroughly reliable scintillometers operating from ordinary torch cells through junction transistors should meet all the requirements of prospecting programmes, but reliable field assays will continue to be made on instruments fitted with a beta-sensitive Geiger-Müller tube and annular sample holder.

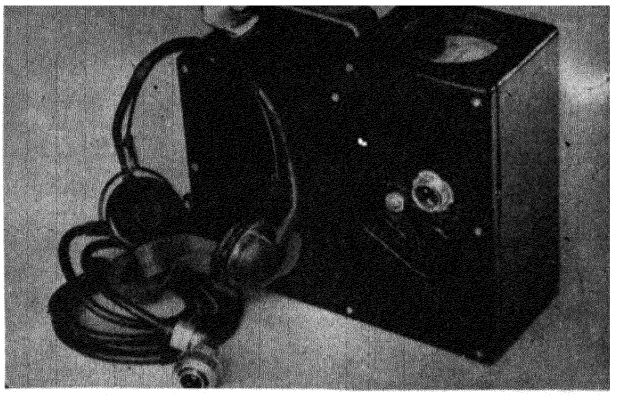
Slide 3 shows a more comprehensive Geiger-Müller counter with a beta probe attachment and annular assay container for doing assays in the field. The reliability of assays carried out in the field by this method is, we have found, very good indeed.

Coming now to car-mounted instruments, in countries where there is a good network of roads or dirt tracks, particularly where, as in Africa, these roads are not paved with introduced road metal, much useful prospecting can be carried out by the use of a sensitive radiation detector mounted in the prospector's vehicle.

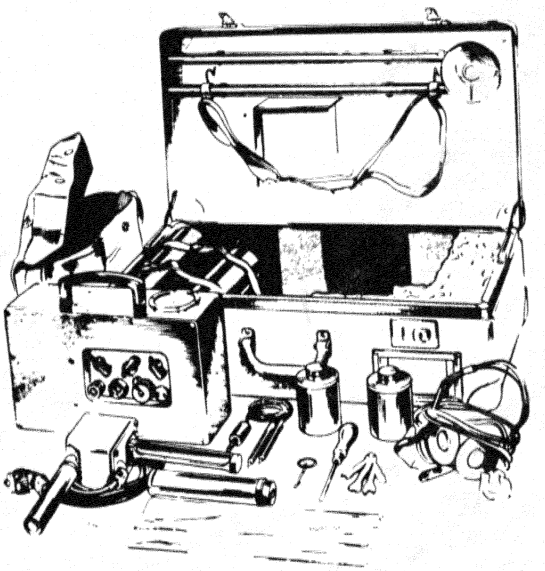
Slide 4 shows a typical set up. All the apparatus is installed in a standard Land-Rover vehicle with four-wheel drive, which can go almost anywhere.

A much wider radius is usually covered when the detector is mounted near the roof of the vehicle than is covered while prospecting on foot. For example, the effective area of coverage is about 10 feet if the ratemeter is carried at a height of 18 inches (½ a metre) above the ground whereas at 5½ feet (1.7 metres) the coverage is extended to about 50 feet.

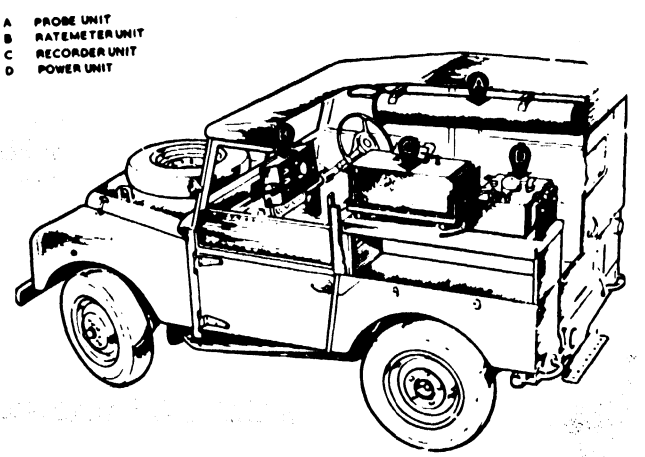
Surveying with car-borne equipment can be carried out conveniently at speeds of up to 30 miles per hour; and to obtain an accuracy of 10% over 50-foot traverses at this speed, the count-rate must be about 85 pulses per second over bedrock with a grade equivalent to 0.001% U_3O_8. This sensitivity



Slide 2



Slide 3



Slide 4. Typical installation of equipment in a land-rover

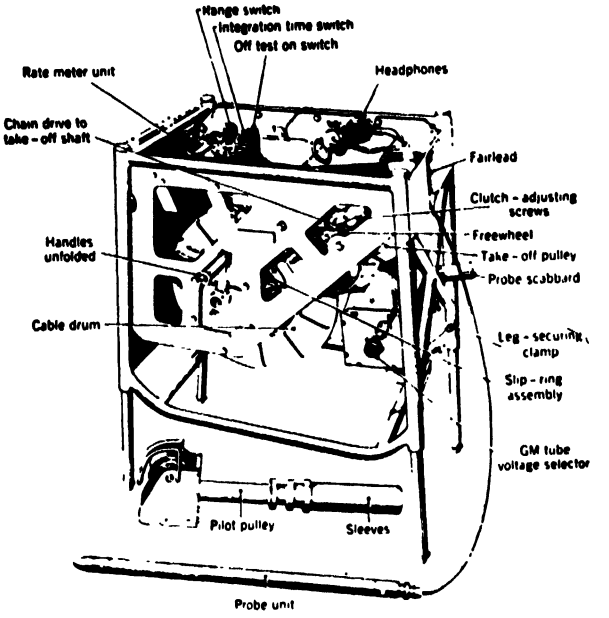
can be achieved either with Geiger-Müller or scintillometer units. To obtain the maximum signal from roadside rocks and minimum interference from cosmic rays the Geiger-Müller tubes should be arranged in a close-packed bundle with their long axes parallel to the path of the vehicle; and in the scintillometer equipment it is advantageous to use two crystals, one on either side of the vehicle.

Coming now to air-borne counters, the use of sensitive scintillometers in aircraft has in recent years been widely advocated as a rapid means of prospecting for radioactive minerals, but it is the opinion of the authors that although much money has been spent on this technique the results have been far from encouraging. Probably the main reason for the lack of success in most aerial exploration programmes is that they were carried out as wildcat enterprises, without any pre-conceived geological basis for the operations.

Aerial surveys should be flown at a very low altitude, certainly under 200 to 300 feet and if possible under 100 feet, before there is a reasonable chance of a virgin ore-body being discovered. This low flying must of necessity be undertaken by small slow aircraft, and simultaneous operation of a magnetometer is therefore precluded. For complete coverage at these altitudes strip flying along lanes not more than 400 feet (120 metres) wide is necessary, and the cost of an aerial operation of this kind is almost as high as that of a fair geological reconnaissance during which minerals other than radioactive ores may well be found.

Although the odds are high against success when using aerial radioactivity surveys in the primary or reconnaissance phase of exploration, the technique is valuable in secondary prospecting as a method of checking quickly whether or not abnormal radioactivity is present in some stratigraphical or structural environment which from experience elsewhere the geologist considers to be favourable to mineralisation. Where, for example, some stratigraphical horizon is known to be mineralised at one locality, and where geological maps or aerial photographs showing the disposition of the strata are available, check tests on the radioactivity can rapidly be made from the air at all other supposedly favourable exposures. Successful use of the scintillometer in this way has been made in the uranium fields of the Colorado Plateau in the USA and Blind River in Canada. Other comparable studies are to be found in the aerial radiometric mapping of deposits of phosphorite and of monazite-bearing beach sands. In work of this kind it seems probable that the helicopter will soon replace slow-flying aircraft.

Coming now to bore-hole counters the choice between scintillometer and Geiger-Müller counters will again have to be made for any bore-hole programme which follows on a surface discovery. Cosmic rays are unimportant in gamma-ray logging work, and for this reason one of the main advantages of the scintillometer is lost, but because of the higher specific activity of the scintillation phosphor compared with a Geiger-Müller tube, scintillometers are capable of recording much narrower and weaker zones of radioactivity than Geiger-Müller units. For this same reason the logging speed of the scintillometer, for the same statistical accuracy, can be much faster. Scintillometers are therefore particularly useful for logging feebly radioactive marker horizons for oil and coal, but the size of currently available photomultiplier tubes of high gain precludes the use of scintillometer probes in holes of less than 2 in. (5 cm) diameter—that is in most holes drilled in the search for uranium ore. Geiger-Müller probes, on the other hand, can be used for both AX (1⅞ in.) and EX (1½ in.) holes, and can also be made slim enough to be inserted within diamond drill rods and enable the hole to be logged without removing rods.



Slide 5

Slide 5 shows a versatile and compact bore-hole logging equipment which is transportable and can be used for all kinds of gamma-logging work.

Coming to other aids in prospecting, in addition to the electronic aids to prospecting which have been mentioned, the prospector should be conversant with geochemical techniques. These are considered to be particularly important when analytical examination can at the same time be made for other metals as in the recently developed method utilising paper chromatography. Chemico-botanical studies are also important but seem likely to be useful only in the exploration for extensions of known ore-bodies in sub-desert regions where there is a thick overburden and plants are deep-rooted. No direct ecological aids to uranium prospecting are known, but geobotanical studies can be of indirect assistance: in Colorado, for example, bushes of Astragulus are dwarfed where rooted in soils rich in the selenium that commonly accompanies the uranium ores; and in the Congo-Rhodesian Copperbelt certain plants which are commonly found in soils overlying copper-cobalt ores

direct attention to mineralisation in which uranium may be present.

Standard geophysical methods of exploration are as yet little developed in aiding the search for uranium, but there seems no doubt that as the near-surface deposits become exhausted deep geophysical methods of prospecting will have to be resorted to.

In conclusion I should like to mention that an interesting method of testing for the presence of uranium in large working mines is to examine the grille protecting the rotating blades of any upcast ventilation system. Both mineral dust and the daughter products of radon collect on the grille of fans drawing air from underground workings containing exposed uranium ore.

Mr. A. H. LANG (Canada) presented paper P/1.

DISCUSSION OF P/764 AND P/1

Mr. V. V. SHTCHERBINA (USSR): The paper by Mr. Davidson and Mr. Bowie described in detail various geochemical methods of prospecting for uranium deposits.

Nevertheless, the following two questions arise:

1. What is there to account for the paradoxical fact that uranium deposits are often associated with rocks which are not highly uraniferous, and are often not associated with rocks which have a high uranium content?

2. Is it possible to distinguish with sufficient certainty between anomalies and halos caused by the presence of uranium deposits, and false deposits caused by a local concentration of radioactive elements occurring in rocks, under the influence of secondary processes?

Geochemical methods of prospecting for deposits of useful minerals are widely employed in the Soviet Union, the vast areas of which call for the utilization of prospecting techniques that are more advanced and speedier than conventional geological methods. Owing to the fact that very large areas of the USSR are masked by a thick soil cover, deep geochemical prospecting methods have to be employed.

In prospecting by geochemical methods it is necessary to study the existing minerals and the relative proportions of the rock components and so investigate the possibility of those chemical reactions in which uranium compounds are able to participate and which may cause their concentration or dispersion. The following, for example, are uranium concentrators in friable surface formations: certain organic compounds, especially in conjunction with phosphates, sometimes manganiferous oxides of iron, and, on the surface, siliceous or calcareous crusts, also vanadates and molybdates in conditions of alkaline weathering.

The success of future prospecting depends to a considerable extent on a correct choice of geochemical methods.

Mr. BOWIE (UK): I am afraid I did not quite understand the first question but perhaps we might discuss this later. As regards the second question, false deposits can only be recognized by experience —in other words, geological knowledge is the only method we have of dealing with them.

With regard to your comments on geochemical prospecting, I agree entirely that in certain countries—and I imagine this applies to the Soviet Union —geochemical techniques would be very valuable indeed. In the case of some of the British colonies, geochemical prospecting, particularly in river basins, has been very useful.

The CHAIRMAN: The next question is from Mr. H. Rahman (Pakistan): "What factors, apart from experience, distinguish a skilled prospector?"

Mr. LANG (Canada): So far as prospecting in Canada is concerned, the main distinguishing features are a sound working knowledge of geology, mineralogy, and the elementary principles of judging the value of a mineral discovery. It is not necessary for a competent prospector to know these subjects to the degree that they are known by professional geologists or mining engineers, but it is necessary to have a sound working knowledge of them. In the first place, unless the prospector is working under supervision he must select the area for his general operations, and he must do that by reading published geological maps and reports or by studying air photographs, which are available in libraries in Canada. After he has selected his area, he needs to know enough geology to select favourable rock sites and structures to concentrate the work of the day. He needs knowledge of the fundamentals of judging the value of an occurrence, because small mineral occurrences which do not even rank as prospects can sometimes be found hourly, and it is not practicable to have mining engineers or geologists to confirm all such occurrences; it would require an army of professional men to do so. The prospector, therefore, must be able to make the preliminary choice himself. For that reason he needs to know something of the size of a deposit which might have economic possibilities and to know something about taking preliminary samples.

These matters cannot be learnt by experience alone, but only by a combination of experience and training. We supply that training by various organisations holding evening classes in the winter, which are a form of adult education.

Mr. M. N. ALTHAUSEN (USSR): We have listened with great interest to the paper by Mr. Davidson and Mr. Bowie, and also to that by Mr. Lang. With reference to these papers, I should like to draw your attention to a few geological signs of sedimentary uranium deposits which are of significance to the prospector and are being used in the Soviet Union in the selection of areas for exploration. These signs may very likely facilitate prospecting in other countries also, and I therefore beg leave to describe them briefly.

Age signs: while uranium deposits are encountered in the sediments of almost all geological systems, they are, nevertheless, found to be preferentially asssociated with rocks of a definite age. Four periods

are particularly prominent: the Cambro-Ordovician, the Permian, the Jurassic and the Paleocene.

An important fact is that deposits of the minerals that accompany uranium, and in the first place phosphorites and caustobiolites, are also mainly associated with the sediments of these systems. This convinces us that our classification of uranium epochs is correct.

Palaeogeographical signs: an analysis of the data on the distribution of uranium deposits within the limits of sedimentation of a specific age indicates that higher concentrations of uranium in marine sediments are, regardless of the composition and particle size of the detrital material, localized in limited facial zones developing parallel to the shore line, more frequently at 5 to 10 kilometers and up to 40–50 kilometers from it.

A particularly characteristic feature of deposits associated with continental sediments is their concurrence with the marginal areas of coalfields—areas often lacking in commercial quantities of energy-yielding coals—and with the sediments of swampy river beds and deltas.

Geochemical signs: all uranium-bearing rocks are significantly enriched with either phosphorus or organic matter or both. This is not a coincidence, as in many cases it is precisely in the calcium phosphate and organic matter that much of the uranium occurring in a given sedimentary rock is concentrated.

A characteristic sign is the association of the mineralization with areas of transition from oxidizing to reducing conditions, and vice versa, which is readily determined during field work by a shift from reddish-brown to greenish-grey rock tints.

Among the elements which accompany uranium the following must also be mentioned: vanadium, molybdenum, barium, strontium, also (less frequently) lead, zinc, copper, chromium, scandium, rare earths and zirconium. The geochemical associations noted can be utilized by geologists as one of their guides in prospecting.

In planning explorations for sedimentary deposits of uranium we endeavor to select areas and parts of the sections of sedimentary deposits in which all three of the indications referred to—the age, the palaeogeographical and the geochemical signs—occur in combination. This has led to the discovery of new ore beds in certain areas.

Our Chairman has already emphasized today that we geologists will have to continue intensive exploration for uranium and will therefore have to evolve and perfect prospecting criteria. It was to this important scientific field that I wished to draw attention.

Mr. A. P. VINOGRADOV (USSR): I should like to say a few words about the biogeochemical method of prospecting which is widely employed in my country, especially in prospecting for uranium. The possibility of utilizing the soil-flora (biogeochemical) method in prospecting and geological exploration for uranium has been demonstrated.

For this purpose soil and flora profiles of deposits were usually prepared, cutting across the lie of the known ore beds. After samples had been removed and analyzed for uranium, the gradient of the uranium concentration in the soils and plants could be plotted and its direction determined. The geochemical background for uranium is a soil uranium content of less than $1 \times 10^{-4}\%$.

In the enriched specimens of soils overlying ore beds the uranium content averages $5 \times 10^{-4}\%$, and in plants upwards of $1 \times 10^{-4}\%$.

To test its effectiveness, the soil-flora method was compared with the radiation method. For this purpose soil data and radiation logs were taken over the same profile. A comparison of the results showed that they fully coincided.

The soil-flora method (or the biogeochemical method, as we call it) was used in preliminary explorations for uranium.

The presence of high concentrations of this element in soils and plants was determined in areas situated above zones of fracture. The uranium concentration in these areas was comparable with the uranium content in the soils above ore beds, affording some indication of the possibility of a uranium mineral occurrence.

The method was also used for preliminary explorations in soils which had formed on lake sediments, where a uranium content of from 5.0×10^{-3} to $1.0 \times 10^{-2}\%$ was not infrequently found. This method has advantages in wooded territory.

Mr. H. BISBY (UK) presented paper P/763.

Mr. M. PETROVIC (Yugoslavia) presented paper P/994.

DISCUSSION OF P/763 AND P/994

The CHAIRMAN: The last two papers are under discussion. There is a question by Mr. E. Zimmer of Italy: What measures can be taken in borehole logging when the temperature is high owing to local sources of heat—water sources or to large thermal gradients? Would either of the authors of the last two papers like to reply to this question?

Mr. BISBY (UK): I would like to say very frankly that this particular problem has not had a great deal of work done upon it in the Atomic Energy Authority.

The CHAIRMAN: Has Mr. Petrovic anything to contribute on this?

Mr. PETROVIC: No.

Mr. S. V. GUEDES (Brazil) presented paper P/132 as follows: The establishment of uranium and thorium reserves has been a primary concern in Brazil during the past three years. An increasingly active program of exploration has not only kept the atomic raw materials picture in proper focus, but has demonstrated the probability that Brazil will become a supplier, as well as a user, of radioactive minerals for power production.

Air survey, as used in the title to this paper, in fact implies the full integration of air photography; photogrammetry, photo-interpretive, field and laboratory geology; radiometry, aeromagnetics; and the whole range of operations which are a part of minerals exploration. This presentation, however, emphasises the aspects of such integrated operations which are most characteristic of the search for uranium and thorium in Brazil, and most important to it.

The inventory concept implies a systematic determination of the quantity and quality of material on hand, kept up-to-date, as a basis for the planning and control of consumption and replacement. This paper deals with a radioactive minerals inventory in action, explaining how its basic stages are being carried out.

The primary facility used was a continuously recording scintillation counter of advanced type construction, electronically coupled with positioning cameras and radioaltimeter, viewing the terrain below under a 45-degree cone, and producing a continuous measurement in "profile" form, which is later plotted and contoured in map form as "isorads," in any arbitrary units chosen.

Brazil is a country characterized by deep weathering of surface rocks. This creates problems for the geologist, but becomes an important factor in the search for radioactive anomalous areas.

From practical experience, it has been learned that conducted under proper conditions of weather, with adequate equipments and procedures, airborne radiation detection is superior to ground radiometry, as a means of *locating* significant sources of gamma radiation. The cumulative form of radiation measurement, possible with a moving instrument observing a large surface, results in the ability to detect very low intensity emanations even at some distance.

In Slide 6 (Fig. 1 of P/132) is depicted an actual comparison of air-borne and ground scintillometric profiles, with an indication of relief and surface features. It will be seen that the ratio of anomalous signal to background in the case of the air-borne survey, is four to five times that of the ground survey.

The processes of integration which results in higher detectability from the air, place a limitation on discrimination of sources of emanation, making it essential to go on the ground before commencing preliminary sampling and drilling.

Helicopter flying is an effective compromise between the advantages of "aerial" detection and discrimination-proximity.

The weathering of rock and subsequent leaching tend to disseminate radioactive materials over areas much larger than the occurrences themselves, resulting in the detectability of the source of the radiation from several kilometers away.

In view of the facts stated in this paper, it can be assumed that systematic reconnaissance, properly planned and conducted at 4 to 5 km spacing, will detect a high percentage of important radiation zones.

Slide 7 (Fig. 2 of P/132) shows clearly the paramount importance of weather in radiation detection, depicting a given track flown under different conditions of humidity.

In Slide 8 (Fig. 3 of P/132) we demonstrate the effect of flying height on radiation detection over an anomaly.

Under the great majority of conditions, relief (proximity) effects can be kept under control by exacting flight demands and the use of a proper aircraft. Residual effects can be corrected through use of specially obtained calibration data.

In the preliminary radioactive investigation of alkaline rocks, the air-borne magnotometer has proved of great value in locating the intrusive bodies, assuring the examination of the whole geological unit under consideration.

Air photographs, essential for flight planning and navigation, when interpreted by competent geologists and integrated with aero-magnetics and ground work, are invaluable in establishing structural ambient and continuity of formations.

In a tentative effort to systematize the operations comprising an inventory plan, we have grouped them in an orderly fashion in five main phases.

Slide 9 (Table I of P/132) shows these phases and, for each one, the air and ground operations involved. From the broad coverage of the entire country at the widest spacing compatible with the geological conditions anticipated, the phases narrow down to a proving survey, comprising mostly ground operations.

In the execution of any project, these inventory phases are not necessarily successive, and the classification of exploration projects into phases is not intended to create technical restrictions, but to act as an essentially coordinating facility.

In carrying out the inventory, flying heights of the order of 100 to 150 meters above terrain have been adhered to, at a flight line spacing from 125 to 500 meters, using a PBY-Canso amphibian airplane. Whenever possible, the flight directions are at right angles to the dominant geological features.

To evaluate the methods utilized, we will quickly review some survey results.

Slide 10 (Fig. 5 of P/132) is the radiometric mapping of a well-known monazite-bearing coastal strip. A scintillation survey at 500 meter spacing, conducted at right angles to deposit trends, located and outlined all known occurrences, registered intensities in surprisingly accurate proportion to the known quantities of monazite lying about one meter below surface, and effected a complete new discovery. The survey is perhaps unique in having precisely indicated the presence of some bags of concentrate in a field storehouse.

Slide 11 (Fig. 6 of P/132) is the radiometric mapping of an occurrence of uraniferous zirconium and a nearby thorium/rare-earth deposit in an alkaline province. An interesting contrast of radiation intensity is shown, the alluvial zirconium/uranium producing relatively weak, scattered anomalies, while the thorium/rare-earth, under the same instrumental settings, was recorded "off scale." This investigation

was followed by a regional magnetic/radiation survey, aimed at correlation of the numerous anomalies encountered.

Slide 12 (Fig. 7 of P/132) is the radiometric mapping of a highly concentrated occurrence of columbium-pyrochlore. Radiation detection flights have outlined in considerable detail the surface exposure of the pyrochlore. Geologically, this is a very interesting occurrence, demonstrating the close association of alkaline instrusives with apatite, pyrochlore, magnetite, uranium, thorium and rare-earth minerals.

The noteworthy association of magnetics and radiometry is demonstrated in Slide 13 (Fig. 11 of P/132) an association which has proven common to several other similar occurrences and aided not only in their discovery but in structural determinations of great value in later operations. The limit of significant radiation is shown by the heavy broken line. The pattern of magnetite concentration in the instrusive and its later proven association with pyrochlore was determined from second derivative mapping of the total field magnetic measurements illustrated.

Slide 14 (Fig. 8 of P/132) is the radiometric mapping of half of a large anomaly caused by multiple veins of thorium/rare-earth-bearing minerals in a gneissic rock. This anomaly is continuous over 240 km².

Radiometric maps of the type shown are the principal product of their respective airborne surveys. Whether they are rough indications such as a Fig. 6 investigation, or detailed and precise, as in Fig. 7 project, these maps, and the topographic and geological data with which they are closely integrated, are highly significant steps in the sequence of location, identification and evaluation.

When it is realized that the discoveries of radioactive minerals discussed in this paper represent less than one-half of the successful search carried out by a single geophysical flying unit, operating intermittently during an eighteen-month period, the significance of air survey to the "atomic" future of Brazil may be assessed. Not only is this country most generously provided with major radioactive mineral occurrences, but air methods appear to be most effective in locating them.

In many instances, the mining and extraction of atomic minerals may not be economic for themselves alone, but quite feasible as a by-product or in conjunction with other minerals.

The current market value of the already proven reserves of an associated mineral discovered by one of the surveys demonstrated here, amounts to five thousand times the whole cost of all operations, air and ground, of the surveying organization.

Such optimistic views are tempered by the hope that world distribution of atomic energy raw materials may be fortuitous for those countries which do not themselves possess the technical and economic means for peaceful exploitation of the atom.

Mr. V. G. MELKOV (USSR) presented paper P/625 as follows: In prospecting for uranium and thorium deposits by plane and helicopter in the Soviet Union advantage was taken of two rock radioactivity manifestations occurring in the air at the altitude of flight: penetrating gamma radiation and general ionization of the air caused by the radiations emitted by the rocks and the gaseous radioactive emanations discharged. Accordingly, two methods of airborne prospecting for uranium and thorium deposits were devised and tried out—the ionization method and the gamma method. The ionization method has the fundamental advantage that it registers both the total radiation of the rocks and their emanating capacity. Its use is restricted in practice, however, as the radon and its decay products are dissipated by air currents, making it difficult accurately to relate the data obtained to particular geological objects. The gamma radiation of rocks, on the other hand, is closely associated with definite physical bodies, a fact which greatly facilitates the interpretation of the data obtained. For that reason the main practical method of airborne prospecting was based on the variations in intensity of the gamma radiation of rocks.

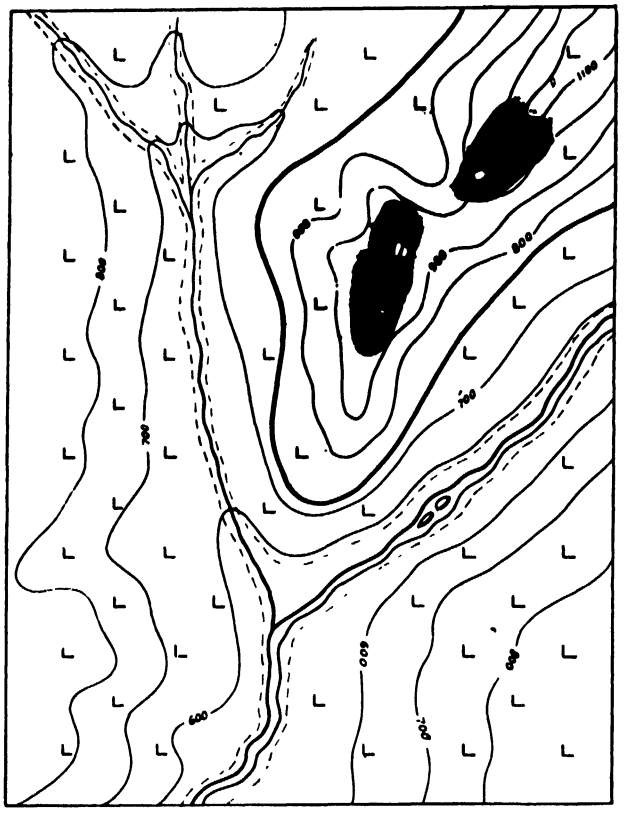
The geophysical principles underlying the airborne method of prospecting for deposits of radioactive ores are set forth in the paper, and will not be stated in this summary.

Modern geophysical instruments are sufficiently sensitive to register the gamma radiation of any rock. Accordingly, the basic methodological task in aerial prospecting for deposits of radioactive ores is to improve the accuracy with which aero-gamma-anomalies are determined and to elaborate methods of interpreting them. By anomaly we mean the deviation of the reading for the sum of the physical factors acting upon a measuring instrument from some figure that is normal for the survey area. The normal background is made up of cosmic radiation, the instrument's inherent background, and the gamma radiation of the rocks of the area concerned.

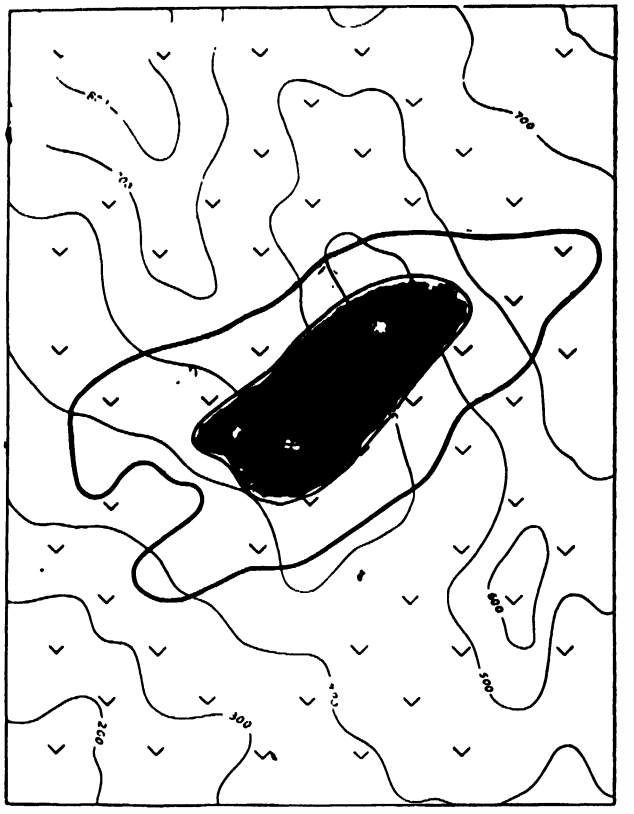
The content of radioactive elements is not the same in all rocks, so that the normal background is different for different areas. There is no such thing as a universal normal background. Accordingly, the first step in airborne prospecting is to measure the normal background over typical rocks of the survey area. The absolute magnitude of anomalies may vary within wide limits, from one or two to tens of microroentgens per hour.

Experience in industrial prospecting from the air has shown that even when flight altitude remained uniform the prospects afforded by aero-gamma anomalies cannot be evaluated on the basis of their intensity alone. In different geological conditions of practical interest, anomalies of widely differing intensity may occur.

It has been found in practice that a proper evaluation of aerial anomalies can be effected only by means of geological and geophysical ground work. It is of the utmost importance, therefore, to eliminate ano-



Slide 15. Anomaly in quartz porphyrite connected with outline of relief



Slide 16. Anomaly in diorite not corresponding to the relief outlines

malies which from various indications are known to offer no prospects and which do not require ground verification.

Generally speaking, anomalies cannot be rejected merely on the strength of geophysical evidence, such as intensity, shape, etc. The signs of anomalies not associated with deposits are determined by trial and error for each specific area, from both geophysical and geological data, during the actual process of airborne prospecting.

The following may be cited as examples of general signs that an anomaly offers prospects.

In mountainous regions, anomalies which follow the relief contours on the map (Slide 15) are often unpromising or false. On the other hand, anomalies which do not follow the topography (Slide 16) or are asociated with zones of tectonic disturbance (Slide 17) are more promising.

Anomalies whose mapped contours coincide with those of an outcrop of country rocks against a low general background of sedimentary cover may offer poor prospects (Slide 18).

In areas in which sedimentary rocks have developed, anomalies associated with a specific stratigraphical horizon usually offer good prospects (Slide 19).

In some regions, anomalies in the form of separate, narrow, local peaks corresponding to surface outcrops of small ore bodies are of practical interest. Peaks of the same shape and intensity, however, may be observed above outcrops of igneous rocks on a weakly active background. In such a case a substantial increase in amplitude in comparison with a large number of peaks of approximately the same height associated with outcrops of the region's normal igneous rocks may serve to indicate an ore anomaly worthy of verification. A distinctive sign of uranium mineralization may be found in the preponderance of uranium-series radiation in the total sum of gamma radiations. The nature of the radiation can be determined directly from the aircraft by the geophysical method, on the basis of the different gamma-ray spectra of the U and Th series.

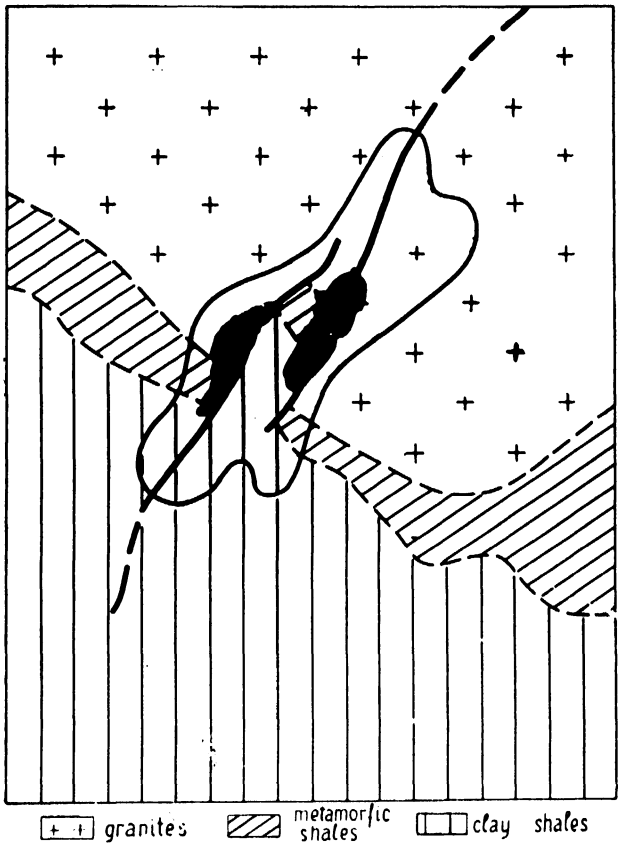
A number of industrially interesting deposits of uranium and thorium have been discovered by the airborne method.

DISCUSSION OF P/132 AND P/625

Mr. J. Lecoq (France): I have two questions for Mr. Bowie. First question: What is the cost of airborne scintillometer prospecting in the various countries in which this method has been extensively used?

Second question: Is it possible to establish a comparison between the respective costs in time and money of prospecting a new region by the airborne method and by the conventional ground methods?

Mr. Bowie (UK): I am afraid that I have no prices available with me in order to give a comparison. We have looked into this matter fairly carefully and have had figures from various countries in which airborne work has been carried out. Generally speak-



Slide 17. Anomaly connected with the tectonic zones

ing, the cost of the aerial survey work is roughly comparable with the cost of a preliminary geological reconnaissance on the ground. As to the time factor, I agree that it is possible to cover a much larger area in a certain time using a flying scintillometer, but it is necessary to check all the anomalies on the ground at a later date. Our general feeling is that if the survey is carried out on the basis of fundamental geological knowledge, then it can be extremely useful. One thing which we do not object to, but which we do not think is economic, is wildcat prospecting from the air. It will sometimes give results, just as results are sometimes obtained by untrained prospectors, but the results are probably not as good as if the work was carried out by geologists who know beforehand what they are aiming at.

The CHAIRMAN: The next two questions are from Mr. L. Page (USA). The first is "What magnitude of increase in gamma radiation warrants ground investigation?" I shall ask Mr. Melkov to reply.

Mr. MELKOV (USSR): The radioactivity which is registered by the instruments and which has to be interpreted in the light of the geological factors may vary in intensity, depending largely on the geological structure and on the particular characteristics of the processes of disintegration of the deposits which are anticipated in the survey area. It is not possible to state definite figures.

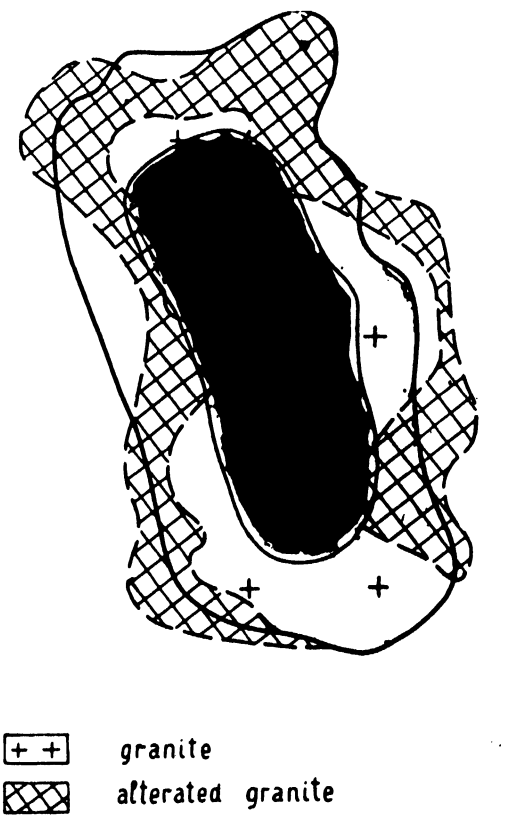
The CHAIRMAN: The next question, also from Mr. Page, is "What means are used to check anomalies by ground surveys?"

Mr. MELKOV (USSR): For the ground check of anomalies observed from the air, conventional prospecting procedures are usually employed. A ground reconnaissance is made of the areas in which the anomalies have been discovered, and large-scale, detailed exploration is undertaken by the usual methods, such as trenching, test drilling and the like.

The CHAIRMAN: I have another question from Mr. Lang (Canada) "Can Mr. Melkov tell us if airborne surveys in the USSR have resulted in the discovery of important uranium deposits?"

Mr. MELKOV (USSR): I have already read out, from the paper prepared by Mr. Baranov, the statement that a number of industrial deposits have been discovered in the Soviet Union by this method.

Mr. R. D. NININGER (USA): In the various papers referred to there is a difference of opinion on the efficiency of airborne exploration. The paper from Brazil and the paper from the Soviet Union indicated that this was a very useful method, but the representatives from Canada and the United Kingdom were not so favorably impressed. The position of the United States on this question has not been mentioned, so that I should like to say that we side with the Soviet Union and Brazil; we feel that this is a very efficient method of prospecting. It is not particularly expensive. We can operate a plane and crew for about $30,000 per annum, including the cost of amortizing the plane. It is inexpensive with low-level flying. It is true that high-level flying may be expensive, but it covers large areas quickly. To summarize, we feel that aerial survey-



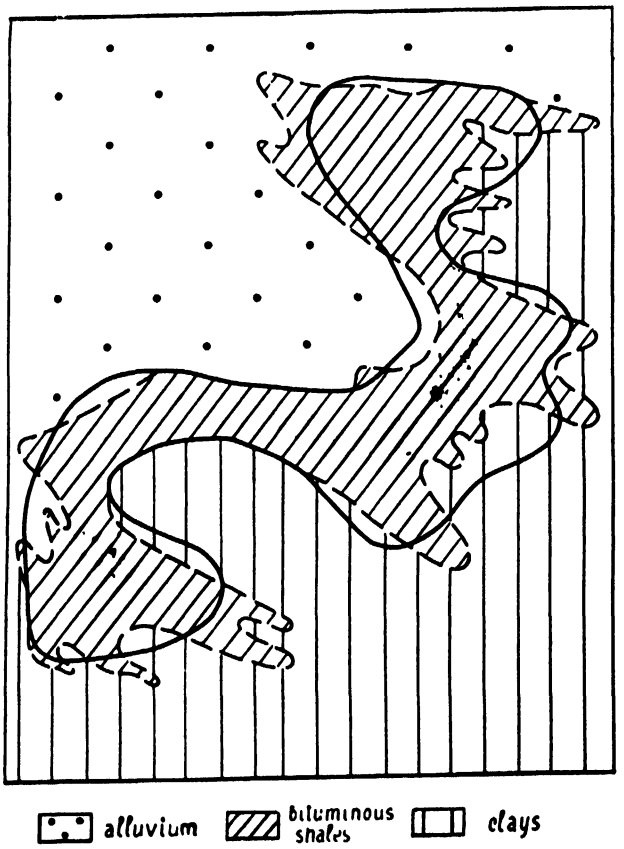
Slide 18. Anomaly limited by outcrops of country rocks

ing is a very important method of uranium and thorium prospecting.

The CHAIRMAN: Thank you very much; that is most useful. The next question is from Mr. Rahman (Pakistan) and is addressed to Mr. Bowie: "Would aerial survey be a feasible method of prospecting in areas of high relief?"

Mr. BOWIE (UK): Yes. You can use aerial prospecting anywhere, but I would say that in areas of high relief you have to pay much more attention to the interpretation of the results obtained. Aerial survey can best be carried out over relatively flat country or in country like the Colorado Plateau. Mr. Nininger can tell you more about this than I can, but there they do what is known as rim flying, flying a small aircraft round the walls of the canyon near where the uranium-bearing horizons outcrop. For this type of prospecting aerial surveys can be extremely useful.

I think that aerial surveying as described in Brazil is probably extremely useful, because the type of deposit is suitable for finding by aerial prospecting —generally speaking a large area of low grade deposit, such as monazite sand, and so on. I did not understand, in one of the pictures which Mr. Guedes showed, why the intensity of radiation is greater at a high altitude than it is at the surface. This is against all the known physical laws. If you have a small area outcrop, the falling off in intensity is inversely proportional to the square of the distance for the first 100 ft, and thereafter is a linear fall-off.



Slide 19. Anomaly connected with a certain stratigraphic horizon

Mr. GUEDES (Brazil): You have integration by measurement with the airborne equipment. In order to clarify the point raised by Mr. Bowie, I should like to say that the main difference factor lies in the use of two different instruments. The airborne scintillation counter is very big and is a more sensitive and advanced type than the other one, which is portable. That is the main factor. I should also like to clarify one of the anomalies associated with the isorads; the work done on the ground shows that in the case of airborne scintillation you have an integration of several veins, which are reported and detected in airborne work as one big vein, but when you come to do the ground work you detect several parallel veins. That is the reason I referred to the question of integration because airborne scintillation does not discriminate.

About the monazite problem, I should like to add that the work was carried out as a pilot project because the mineralization was known before. We carried out this work to prove what airborne scintillation could do in that condition. It proved, just as I mentioned, that somebody from the mining company had stored in his house a few bags of concentrate, which created a very embarrassing situation for him. Most of the work which we did, and which I demonstrated here, was carried out in intrusive rocks of alkaline syenites, and we have found that they all carry radioactive minerals with very little uranium on the surface, the uranium content increasing with depth.

Mr. R. D. NININGER (USA) presented paper P/503, as follows: The high degree of success achieved thus far in uranium exploration has been due largely to two factors: the importance attached to uranium, which has resulted in telescoping a century or more or normal exploration progress into one decade and, secondly, the natural radioactivity of uranium minerals. The latter is shared by thorium, and should its importance reach that of uranium, similar results may be expected.

Prospecting with radiation-detection equipment has been carried out extensively in the United States since 1944.

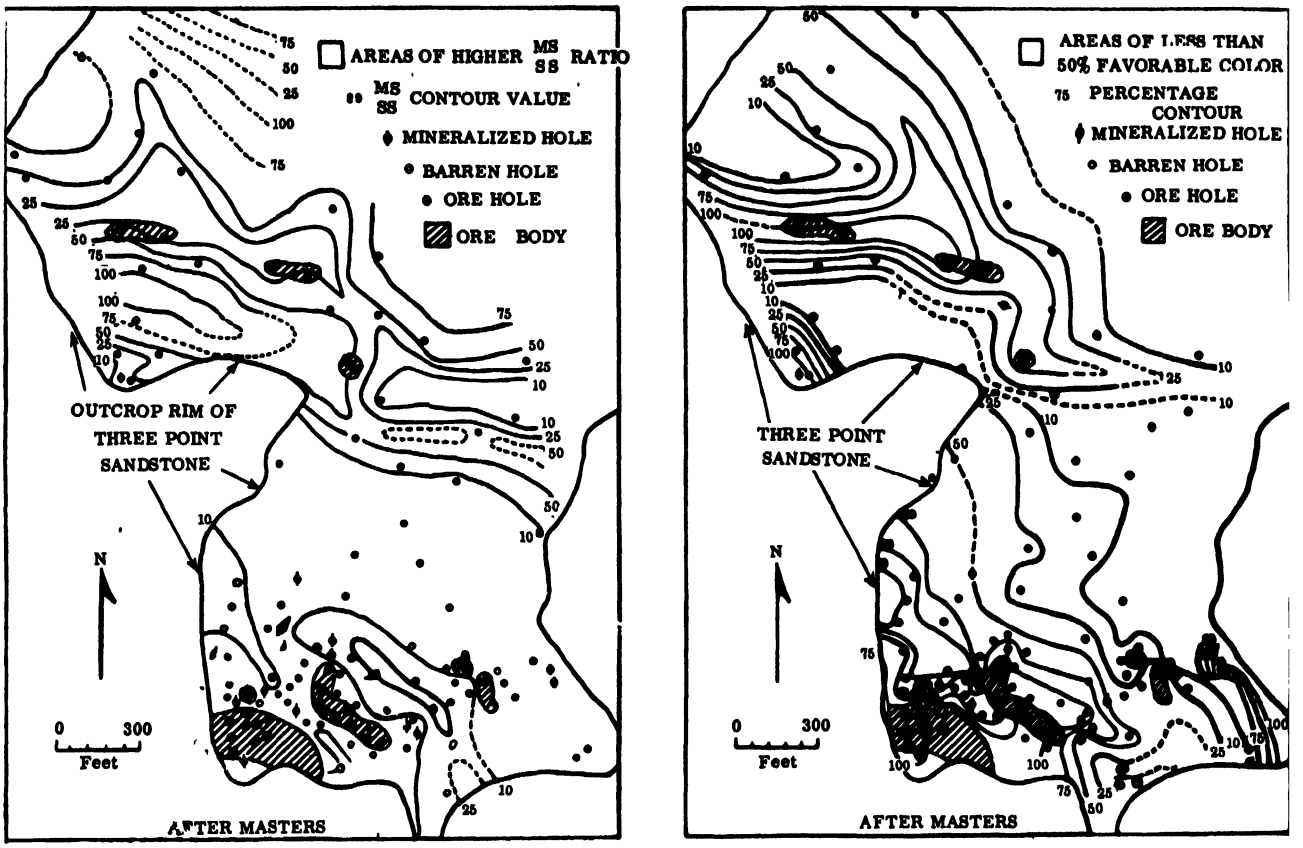
Geiger and scintillation counters and ionization chambers are now used routinely in surface, subsurface, and aerial exploration.

The development of small diameter scintillation and Geiger drill-hole probes and light, highly sensitive scintillation counters for aerial use, have perhaps been the most significant advances in this field.

In the future, successful prospecting for radioactive minerals will call for increased attention to the geologic, geochemical, geophysical, and engineering techniques on which exploration for other metals has had to rely.

Geologic Techniques

The use of the rapidly expanding knowledge of uranium and thorium geology to define potential



Slide 20. Three point sandstone, Lukachukai mountains, Arizona

metallogenic provinces, and to predict local favorability for deposits, is greatly increasing the rate of discovery of new mineralized areas and of new ore deposits within producing areas. Although important deposits have been found in environments which at one time were not believed to be favorable, virgin areas can often be evaluated in advance with a degree of assurance on the basis of present knowledge.

Prospecting for epigenetic deposits of uranium, whether of direct or indirect magmatic origin, should emphasize areas of deep-seated major structures, particularly those related to (1) near-surface intrusions, (2) basins containing terrestrial sediments, (3) areas of metamorphosed clastic sediments, and (4) granitic batholiths. Syngenetic deposits should be sought in (1) marine black shales and phosphorites, (2) terrestrial and marine placers, (3) alkaline igneous stocks, sills and dikes and, (4) granitic pegmatites.

Epigenetic deposits of thorium commonly occur in areas of metamorphic and igneous rocks associated with syenitic intrusions; syngenetic deposits are found in such rocks and in placers derived from them.

Within favorable terrains, specific stratigraphic zones; lithologic, mineralogic, and structural characteristics; and alteration phenomena, all of which are amenable to mapping, are the most important guides to ore.

Directional sedimentary features of paleo streamflow often control in detail the occurrence of uranium ore bodies in sandstones. Maps of such features as cross-bedding, lineation on bedding planes, logs, channels, scours, and ripple-marks are aids to exploration.

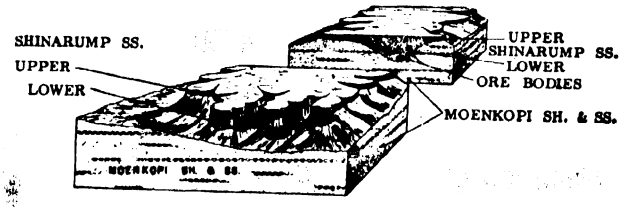
Around the Black Hills of South Dakota, the sandstone host rock is capped by impermeable beds. Structure contour maps on the upper surface of the porous sandstone have delimited favorable structures, such as anticlines, terraces, and zones of lithologic interfingering that have apparently controlled ore deposition.

Mapping of the ratio of mudstone to sandstone and of the degree of color favorability in the Jurassic Saltwash formation proved useful in a drilling project in the Lukachukai Mountains of the Colorado Plateau (see Slide 20).

Contours on the map on the left were drawn from data obtained from diamond drill cores in the initial phase of drilling. Most of the ore shown by cross-hatching was subsequently found to occur where the mudstone-to-sandstone ratio was less than one to ten.

Contours on the map on the right show the percentage of limonitic brown-stained sandstone in each core, a factor empirically considered favorable in this area. The bulk of the ore is in sandstone of which 50% or more is favorably colored. Some ore is found where only 25% of the rock is favorably colored, but there is no ore where the limonitic staining is absent.

The important uranium deposits in the Triassic Shinarump formation of the Colorado Plateau area occur where it fills channels in the underlying Moen-



Slide 21. Outcrop and cross section of paleostream channel incised in Moenkopi formation, filled by Shinarump sandstone

topi formation (Slide 21). The channel shown here s about 400 feet wide and 50 feet deep, and the ore commonly occurs near the base or on the sides.

Unusual thickening of the Shinarump as in Slide 22, or bleaching of the immediately underlying Moenkopi beds from dark red to light grey-yellow, indicates the presence of channels and the possibility of mineralization.

Maps of the lower surface of the host rock define the channels and the more favorable places for ore deposition (see Slide 23).

Iso-abundance maps of specified grain sizes, diagnostic heavy minerals, base metals and lithologic types have also been used as guides.

Contour maps of the water table, indicating the abundance of critical elements such as fluorine, in the water, are helpful in areas of caliche-type mineralization such as the schroekingerite deposits of the Red Desert region, Wyoming.

Mapping of clay mineral and hematitic alteration zones in proximity to veins in igneous and metamorphic rocks, as at Marysville, Utah, or associated with collapse features in sandstones as at Temple Mountain, Utah, has proved useful.

Geochemical Techniques

Geochemical prospecting techniques are rapidly being adapted to uranium exploration, and may prove useful in the search for thorium.

Relatively simple and inexpensive, but rapid and sensitive, field techniques can detect uranium anomalies directly, by chemical methods. Significant uranium concentrations in areas of sedimentary rocks may be as low as one part per million or 5 to 10 times background.

Anomalous concentrations of vanadium, molybdenum, selenium, zinc, copper, cobalt, and niobium, may also indicate uranium. Slide 24 illustrates the relation of uranium to three other elements in a surface anomaly at the Oyler mine in Utah.

The uranium and radon content of surface and ground waters may serve as an approximate index of the uranium concentration in the rocks with which the water has been in contact, depending upon variables of water pH, temperature and composition, and rock composition and permeability. Background for major streams in the United States is commonly about one-tenth part per billion, (or thousand million), that is 10^{9} power of uranium. The threshold of significance is 3 to 10 times background.

In the Florida phosphate area, the threshold of significance is approximately three-tenths parts per thousand million, and a content of 1 to 3.5 parts per thousand million is regarded as a strong indication of the presence of uraniferous phosphate.

In the Colorado Plateau area, the threshold of significance is about four parts per billion with a content of 5 to 12 parts per billion in uraniferous areas. Ground water is usually much higher in uranium content: about 1 to 10 parts per billion in barren aquifers and 5 to several hundred parts per billion in mineralized aquifers.

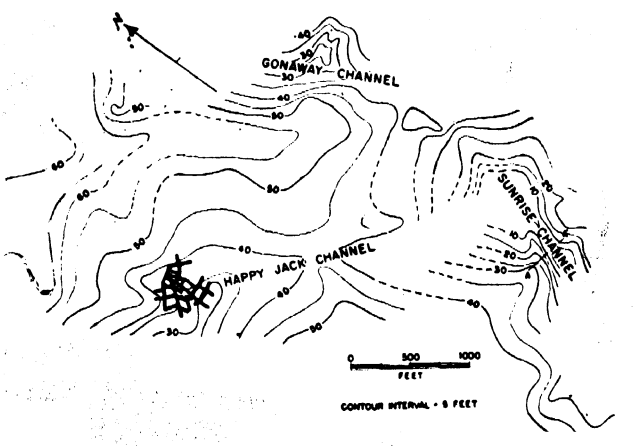
Water seeps and springs in the Black Hills area of South Dakota and Wyoming contain 10 to 250 parts per billion of uranium in mineralized areas and have led to the discovery of ore deposits in areas not otherwise thought to be favorable.

Geobotanical prospecting has shown that uranium deposits under as much as 20 meters cover may be reflected chemically in surface vegetation.

In semi-arid country, trees or deep-rooted shrubs that are absorbers of uranium, show differences in uranium content which may indicate the presence or absence of ore. The uranium content of the ash of plants growing in unmineralized sandstone is generally less than 1 part per million; a content of several parts per million is common in the ash of plants rooted over ore.

Sampling of indicator plants has also been used. Carnotite and other oxidized uranium ores contain

Slide 22



Slide 23

appreciable amounts of selenium and sulfur. The distribution patterns of plants requiring one of these elements in quantity may indicate favorable ground.

The two block diagrams in Slide 25 show the agreement of geobotany with radiometry at the Annie Laurie prospect, Arizona. The upper block shows by height of vertical lines the radioactivity, in counts per hour, of the ash of the leaves of oak trees. The lower diagram shows the radioactivity of a shallow-rooted shrub, the mimosa. Highest counts are concentrated within the area of highest surface radioactivity as indicated by the radioactivity contours.

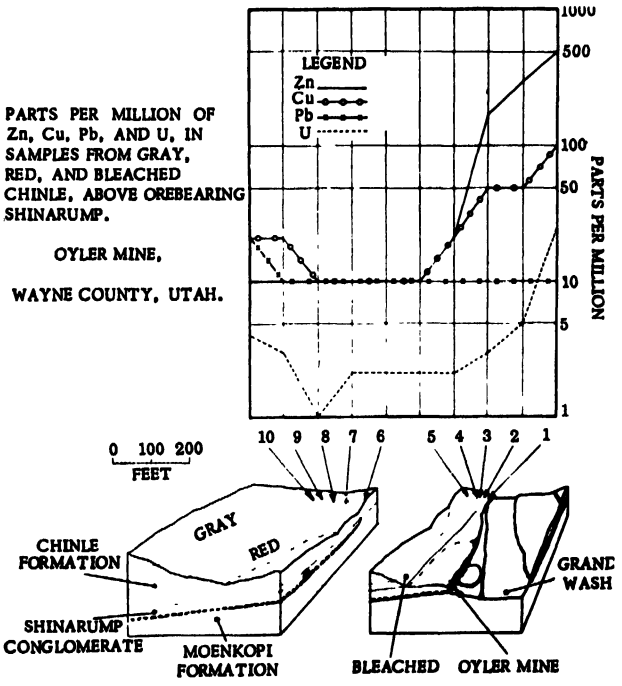
Geophysical Techniques

Uranium deposits have not proved susceptible to direct detection by geophysical means. Some geophysical methods have proved to be of great value, however, in the detection and delimitation of geologic features which localize ore, even though, in some cases, these features may be obscure.

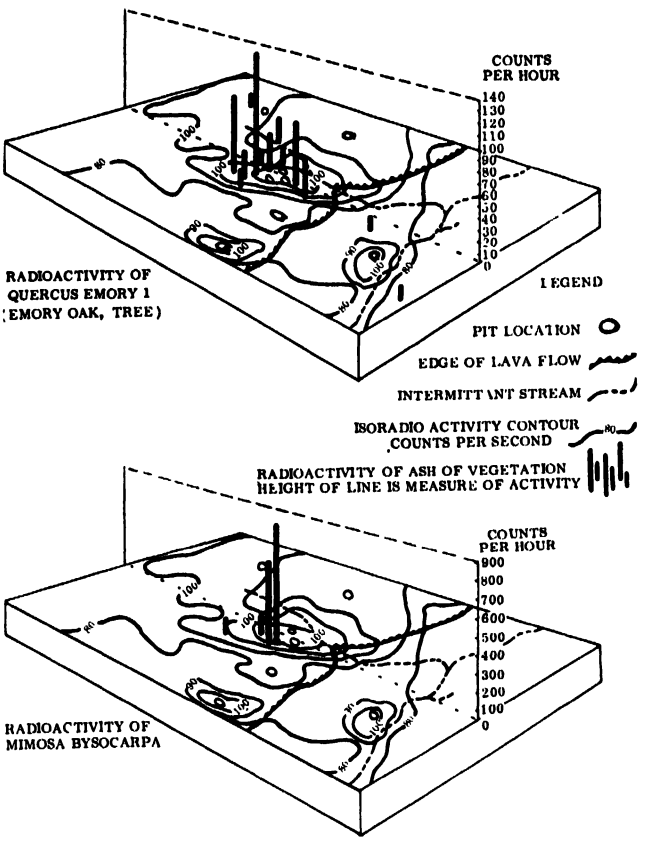
There is no recognizable difference in electrical resistivity of sedimentary formations attributable directly to uranium minerals that may be present.

However, resistivity highs have been found associated with carnotite-type mineralization in South Dakota, and low resistivity has indicated uranium carbonate and phosphate-type mineralization in Wyoming.

Formational irregularities such as paleo-channels favorable for uranium have been successfully located by continuous profiling with reversed shots using standard seismic refraction equipment. The shallow reflection method, using continuous velocity logging in conjunction with high-resolution seismic equipment, also offers promise.



Slide 24. Parts per million of Zn, Cu, Pb, and U, in samples from gray, red, and bleached Chinle, above ore-bearing Shinarump. Oyler mine, Wayne County, Utah



Slide 25. Radioactivity of vegetation at the Annie Laurie uranium prospect, Santa Cruz County, Arizona

Channels have also been located by a combination of vertical and horizontal resistivity profiling.

The routine use of electric logging in conjunction with gamma-ray logging, on drilling projects, has substantially improved sub-surface lithologic information. Formation resistivities can be determined with accuracy by using single-point, in-hole equipment. A new type of electrode which provides a rolling, wet contact with the dry rock has been developed for logging dry holes.

Engineering Techniques

Lastly, as a result of the unprecedented scale of uranium exploration activity in the United States and the very large requirements for subsurface information, great advances in drilling techniques have been made. Several drilling methods are used. All equipment is mobile—jeep or truck-mounted.

The standard mining diamond drill is the most versatile and gives the greatest amount of information, providing rock cores as required. It is also the slowest and most expensive method used, although drilling rates up to 30 meters per 8-hour shift have been achieved in shallow holes.

The operating cost of larger diameter, non-core oilwell drilling equipment is ½ to ⅙ that of the standard diamond drill, and it is 3 to 8 times more rapid. Rates up to 400 meters per 8-hour shift have been obtained. Samples of sludges or cuttings may be collected, but radiometric and electric logging of holes provides more reliable information.

Percussion air-drilling is a rapid, economical method feasible at depths up to 75 meters in dry rock. Samples are collected as in dry rotary drilling and the information confirmed by radiometric and electric logging. Cost and speed are equal to rotary drilling but cost of equipment is much less.

The techniques of exploration for radioactive minerals, briefly described, are but a few of those that have resulted from the remarkable exploration effort of the past ten years. Progress in the future will, I am certain, be even more rapid.

Mr. A. P. VINOGRADOV (USSR) presented paper P/626 as follows: In recent years, wide use has been made in the Soviet Union of the hydrogeochemical method of prospecting for uranium deposits, which is based on the migration of natural waters containing in solution both uranium itself and its decay products, radon and radium.

The method is used in conjunction with other methods. It is very simple and enables preliminary explorations of large territories to be carried out.

It is based upon the occurrence of dispersion halos in waters which, in their course, wash uranium deposits; these halos are characterized by an anomalously high content of uranium (or of its decay products) in comparison with the average background content of these elements in waters of the same region which occur in similar geochemical and physico-geographical conditions but do not traverse uranium deposits.

The hydrogeochemical method of prospecting for deposits is designed to reveal anomalies of this kind, and it comprises three kinds of operation: (1) sampling the water, (2) determining in these samples the uranium, the pH and the ionic composition, and in many cases the radon and radium also, and (3) interpreting the data obtained.

Samples of water are taken, so far as possible, from all springs, streams, wells, boreholes and other water sources throughout the survey area. If necessary, borings are made to give access to subsoil waters.

Extremely sensitive and simple methods are used to determine uranium in natural waters, based on the adsorption of uranium by some adsorbent (such as carbon), followed by the determination of the uranium by the luminescent or colorimetric methods; special field laboratories make it possible for mass water-sampling to be carried out on the spot by prospecting and survey parties.

The most complicated part of the hydrogeochemical work is the interpretation of the water-sampling data. Appropriate geochemical studies were carried out in this connection which shed light on certain regularities in the behavior of radioactive elements in different natural waters.

Large number of analyses carried out in the USSR, amounting in the case of uranium to many thousands, have shown that radioactive elements are present in all the natural waters investigated; their concentrations vary sharply, however; for uranium, for example, they lie between $n \times 10^{-6}$ and $n \times 10^{-2}$ gm/l.

Natural waters derive uranium from various types of rocks and from uranium-bearing deposits occurring in the latter. The uranium content in natural waters is the result of equilibria set up in the system: rocks (deposits)–water–gases. It depends in the first place on the concentration of uranium in the surrounding rocks. These concentrations vary. Where uranium deposits occur, the uranium content rises sharply, and this is reflected in the formation of anomalous concentrations of uranium in the natural waters.

The uranium content in the waters is also dependent to a large extent upon the form in which the uranium occurs in the rocks, which determines its ability to enter into natural solutions of uranium. Mobile forms of uranium are the most readily soluble; investigations have shown that in different rocks the quantity of such relatively readily soluble uranium accounted for from a few per cent to 90% of the total amount of uranium in the rock. Much less readily soluble is uranium occurring isomorphously at intersections of the crystal lattices of various minerals which usually yield with extreme difficulty to the action of natural solutions.

As experimental data and direct observations on deposits have shown, almost all the uranium in uranium deposits passes on the whole fairly readily into natural aqueous solutions, creating anomalous concentrations within the halos.

The transfer of uranium to the water depends on the characteristics of the ores themselves—on their mineralogical composition, texture and structure; compact pitchblende ores, for example, enrich underground waters with uranium to a much lesser extent than loose amorphous oxide ores.

The concentrations of uranium in natural waters depend on the chemical characteristics of the waters themselves, and particularly on their oxidation-reduction potential: the presence of free oxygen in the waters increases the solubility of the uranium, as it converts the element into the hexavalent form; on the other hand, strongly reducing conditions convert compounds of hexavalent uranium into compounds of the tetravalent element which are not readily soluble; in similar conditions (for example, in the presence of petroleum or bitumens) the waters are not enriched with uranium even if they pass through an actual deposit; on the other hand, they become enriched in radium and radon, and this, too, in such circumstances, is a valuable criterion for prospecting purposes.

The content of uranium in the waters also depends on the time during which the waters are in contact with the rocks or ores, i.e. on the rate of flow of the solutions, this in turn being a complex function of the geomorphology of the region, the degree of permeability of the rocks, the nature of the routes taken and other hydrodynamic characteristics of the solutions.

The natural background characterizing the average uranium content in the waters of a given territory changes significantly (sometimes several times) in the course of the year, depending on the season and the amount of precipitation associated with it. As is well known, climatic conditions greatly affect the uranium content of the waters, and this fact must be borne in mind when interpreting the data.

Waters circulating through uranium deposits are, as a rule, considerably enriched in radioactive elements; thus, the uranium concentrations in them frequently amount to $n \times 10^{-4}$–$n \times 10^{-2}$ gm/l, i.e., they exceed by tens and hundreds of times the natural background for the waters of the same region. The waters richest in radioactive elements are those close to the actual deposit; as the waters move away from the deposit the concentrations of these elements decline through dilution with poor waters from non ore-bearing rocks, adsorption of uranium and radium by highly dispersed systems along the path of flow of the solutions, and a number of other causes.

It follows from the foregoing that the degree of anomalousness of the waters caused by the presence of uranium deposits may be different in different natural conditions. In the case of particularly marked anomalies, when the uranium content in the waters of the dispersion halo is hundreds and thousands of times greater than the natural background, their interpretation presents no special difficulty; as a rule, they indicate the presence of uranium concentrations. The task is considerably more complicated in the case of less striking anomalies, as it is also possible that these anomalies may not be caused by the presence of uranium deposits, and may result from other causes. Among the latter, the following call for mention: non ore-bearing rocks relatively enriched by highly mobile forms of uranium; the possibility of subsoil-water evaporation in a desert climate, and so forth.

It was pointed out that in prospecting for uranium deposits the best and most readily interpretable results are usually afforded (except in strongly reducing conditions) by a study of the dispersion halos of uranium itself; radium and radon usually play an important but nevertheless secondary part, as their behaviour in natural waters differs materially from that of uranium. High concentrations of radon indicate the proximity of actual deposits, since radon quickly decays and cannot migrate far.

The data obtained are, as is the usual practice in geology, transferred to a map. The uranium isoconcentration lines plainly delineate a prospect area.

Application of the hydrogeochemical method in conjunction with other geological and geophysical methods has led to the discovery in the Soviet Union of new ore districts and deposits, and of new ore bodies in deposits already known.

In principle, the hydrogeochemical method can also be used in prospecting for deposits of other elements, including copper, lead and zinc.

Its potentialities are particularly promising in areas in which especially marked water anomalies are typical, i.e., more especially, in regions with a relatively dry and hot climate. Regions of broken topography are suited to the application of this method, as they generally abound in natural outlets of underground waters in the form of springs of one kind or another.

The hydrogeochemical method makes it possible to detect not only deposits cropping out directly on the surface, but also—what is particularly important—deposits that are masked by thicknesses of bare rocks or alluvium, i.e., it permits prospecting at depth.

Mr. K. G. VOHRA (India) presented paper P/869 as follows: Investigations on the radioactive content of air in Bombay have suggested a technique for the remote location of uranium and thorium mineral deposits. It is based on the study of the radioactive composition of the air blowing over mineral deposits and reaching a remote place at a subsequent time. I shall briefly describe the mechanism.

Mineral deposits of uranium and thorium constantly produce radon and thoron gases due to radioactive decay of uranium and thorium. A fraction of these gases is ejected into the atmospheric air due to daily variations in the atmospheric pressure and diffusion.

Radon and thoron are dispersed in the air by the following processes: (1) mixing in the lower layers of the atmosphere is caused by turbulence; (2) vertical transport of radon and thoron is caused by convection; and (3) winds move the radioactive matter to great distances horizontally.

Radon and thoron decay during the mixing and movement processes, as discussed in the paper. Short-lived products RaA, RaB, RaC and ThB and ThC are produced and subsequently decay in the air, whereas the long-lived products D, E, F and G get attached to the dust particles in the atmosphere and are brought down to earth by gravity or rain.

Now consider a mass of air blowing over a mineral deposit. This air mass carries with it radon and thoron. Its radioactive composition will be different at different times due to the different decay rates of the products. Analysis of the radioactive content of this air at a remote place will give the time of origin of radon and thoron. This time has been called the "age" of the air. Knowing the "age" of the air and trajectories of the winds and velocity of the air, we can obtain information about the deposits.

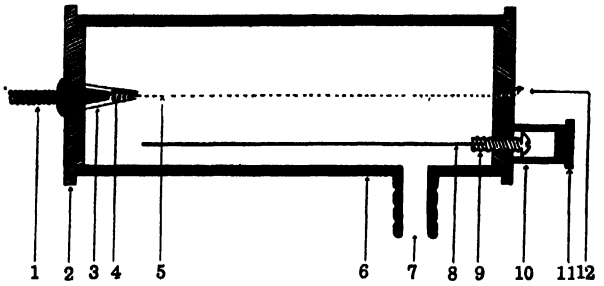
In the present experiments, the radioactive matter is collected from the air as follows:

During the processes of alpha and beta decay the decay products of radon and thoron in the air are left positively charged by recoiling.

These charged atoms (or ions) can be collected on a negatively charged electrode exposed in the air.

In the present experiments, this is done in an ion collector shown in Slide 26 (Fig. 1 of P/869).

The wind tunnel is 80 cm long and 8 mm in diameter. The collecting rod is a steel rod 8 cm



Slide 27. The proportional counter; 1. Anode terminal; 2. Perspex cap; 3. Glass sleeve; 4. Phosphor bronze spring; 5. Anode wire; 6. Cathode; 7. Filling tube; 8. Source rod; 9. Supporting screw for the source rod; 10. Bakelite tube; 11. Sealing cap; 12. Peg for supporting the wire

long and 1.5 mm in diameter. Air is drawn along by means of a fan. On the left-hand side there is an exponential horn coupled to the inlet to get a streamlined flow of air. The air is drawn at a rate of about 8 litres per second.

This arrangement concentrates the radioactive matter from a very large volume of air. About 30 million cubic centimetres of air are drawn per hour.

Alpha activity of the deposit obtained on the rod is measured in a proportional counter (Slide 27).

The rod carrying the deposit is mounted inside the counter, and then the counter is evacuated and filled at the desired pressure.

A theory has been developed for the analysis of the deposits obtained by ion collection. I shall give a brief sketch of the theory. The cases of radon and thoron will be treated separately.

Suppose a number of atoms of radon are introduced into a volume of air at time $\tau = 0$. The number of ions of RaA, RaB, and RaC in this volume of air at a subsequent time T have been computed for $N_0 = 10^6$ and are shown in Slide 28 (Table I of P/869).

λ' is the recombination constant for the ions in the air. Two values of λ' have been compared.

If we now assume that a volume of air which contained 10^6 atoms of radon at $\tau = 0$ passes the ion collector per minute, the values in Table I give the rates of collection for different ions. If the collection is made for a sufficiently long time to give equilibrium deposits, the numbers of atoms of RaA, RaB and RaC present on the collector at the time of stopping are given in Slide 29 (Table II of P/869).

These are the total amounts of RaA, RaB and RaC collected at equilibrium. This table shows that the decay-product activity increases with the "age" of the air.

The decay curves of these deposits have been computed and are given in Slide 30 (Fig. 2*B* of P/869). The activity is plotted against time in minutes.

These are the curves for two extreme values of τ, the age of the air. The rest of the curves lie between these two extremes. These decay curves are not sensitive to the age of the air. Another method of age determination has been developed and suggested in the full paper but cannot be discussed in this short time. Theory relevant to the present experiments only will be considered now.

The decay curves are similar for the two values of the recombination constant considered. However, there are two features of these curves which make them distinctive of radon: (1) the activity at 60 min is nearly half of the activity at 20 min; and (2) this part of the curve is almost linear.

Let us consider the case of thoron contamination.

1. Most of the thoron picked up by the air breaks up into its decay products within a few minutes (half-life 54.5 sec).

2. Air which has freshly acquired thoron will therefore contain ThB ions (ThA is unstable).

3. If the air is old, it will contain ThB atoms, since the ions have a very short life.

4. Decay of ThB will give ThC ions. Consequently, only ThC ions will be collected in an ion-collector. Air which has freshly acquired thoron will give ThB collection.

5. Computations have been carried out in the same way as in the case of radon, and the deposits of ThB and ThC on the collector and ThB/ThC ratio for a collection time of 8 hours are shown in Slide 31 (Table IV of P/869).

6. ThB/ThC ratio shows a rapid decline with the age of the air N_B is the number of atoms of ThB on the collector and N_C the number of atoms of ThC. The table shows that the ThB to ThC ratio increases with the "age" of the air.

7. Using this ratio as a convenient parameter, theoretical decay curves for different ThB/ThC ratios are shown in Slide 32 (Fig. 3*B* of P/869).

Activity is plotted on a log scale against time for three different values of ThB/ThC ratio, viz, ThB/ThC = 1, 5 and 10. The slope of these curves gives ThB/ThC ratio.

We shall now discuss the experiments and compare the results with theory.

1. Experiments were actually designed for studying the seasonal variations of the radioactive content of the air. The experiments were carried out in Bombay (India) during 1952–53.

2. Collections were made from two places at heights of 60 to 70 ft above ground.

3. Forty collections were made, mostly during the summer and winter monsoon winds.

4. Decay curves were obtained for each of the collections. Only α activity was measured for these collections, by mounting the collecting rods inside the counter.

Analysis and Results

The decay curves of these collections fell into two distinctly different groups. One group referred to the months of January, February, and March. These are the months of winter monsoon in Bombay. The second group covered July, August and September. These are the months of summer monsoon in Bombay.

The curves of winter monsoon months showed very little residual activity due to ThB. A typical decay curve is shown in Slide 33 (Fig. 4 of P/869). These curves were found to be similar to the theoretical radon decay curves.

The curves for the months of July, August and September showed appreciable residual activity due to ThB. A typical decay curve is shown in Slide 34 (Fig. 5 of P/869).

In this case the activity after 14 hours is as large as the residue after 1 hour for the winter monsoon curves.

The two cases have been analysed individually.

1. The average concentration of radon in the winter monsoon season is found to be 128 atoms per litre of the atmospheric air. Calculation shows that if 10% of the atoms of radon from the uppermost cm^3 of soil having its normal uranium content, are injected in the air per day, and if this is mixed in a vertical column of air of 1 km thickness, the observed value of radon content is fully accounted for. Since the winds during these months blow over large areas of land in the north and northeast of Bombay, it is inferred that these land areas do not contain any extensive surface deposits of uranium over a distance of a few hundred miles.

2. For the summer monsoon collection, the air "age" is estimated to be 5–10 minutes. This shows that thoron is freshly picked up. The only possible source of fresh thoron was the coastal regions. This was established by collecting deposits from the air that was passed over a bed of sand from the local coast in a long box. These deposits gave much stronger collections and large ThB/ThC ratios.

I shall now say a few words about a simple Geiger counter device recently developed for carrying out these measurements in the field.

Ion Collection on Geiger Counter

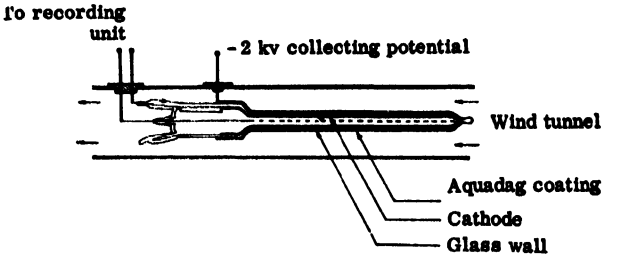
The proportional counter technique used in the earlier experiments is not suitable for large-scale field experiments due to the bulky associated equipment it requires.

In the new technique, the collection is obtained on the walls of a thin-wall Geiger counter and β-activity of the collection is studied. The arrangement of the counter in the wind tunnel is shown in Slide 35.

The counter has a glass wall of 15 mg per cm^2. The cathode is silvered on the glass wall. The counter wall is 8 cm long and 8 mm in diameter. The outer surface of the wall is coated with a thin layer of Aquadag. The counter is placed in the wind tunnel and a collection is obtained on the Aquadag coating.

The results obtained by this technique confirm the results of the earlier experiments done with the proportional counter. This arrangement will be specially advantageous for field investigations.

In conclusion I would like to say that the technique of ion-collection and especially the collection of ions on the walls of a thin-wall Geiger counter can be very successfully used to estimate and analyse



Slide 35

the decay products of radon and thoron in the air. With the standardised apparatus the measurements could be carried out at fixed stations in a selected area, along with the relevant meteorological measurements. These measurements taken over a long period of time will tell the general nature of the radioactive minerals in the surrounding areas. New stations could then be established in the areas found suitable for detailed prospecting and location of deposits could be predicted within a distance of a few miles.

DISCUSSION OF P/503, P/626 AND P/869

Mr. H. S. BROWN (USA): On the basis of what we have so far heard from our distinguished geochemical colleagues from the Soviet Union it would appear that an intensive geochemical and biogeochemical prospecting program has been followed with far greater practical results in the Soviet Union than in other countries which have reported here today, and my colleagues and I would be most interested to hear as time goes on more complete details of these important and very interesting developments.

I have two questions concerning this. Mr. Vinogradov has indicated that substantial uranium deposits have been found by utilizing botanical prospecting, and I would like to ask were these previously completely unknown deposits or had preliminary evidence for their existence been obtained by other than botanical or geochemical means?

Secondly, I would like to ask whether geochemical and botanical methods of prospecting have been utilized successfully for the discovery in the USSR of important deposits of elements other than uranium, and if so is it possible that we might hear something about that?

Mr. VINOGRADOV (USSR): It would give me much pleasure to reply in great detail to Mr. Brown's questions, but time compels me to answer very briefly.

1. It is a fact that the geochemical method is very often, indeed constantly, used in the Soviet Union, especially for the interpretation of data. I should mention that various methods—aerial surveying, radioactive well logging and the biogeochemical method—are used in conjunction with one another: that is how it is done in our country. Actual practice indicates the respective advantages of each method according to circumstances. I should point out that the radiometric method is sometimes applied in a

differentiated manner in order to determine uranium separately from thorium. The main point is that we use the methods in combination. The radiometric method will be reported on by Golbek.

2. Our basic procedure is as follows: we first locate the dispersion halo by any method; then, using geochemical methods, knowing the paragenetic interrelationship of uranium and other elements, we compile data of practical use on the dispersion halo.

3. I refer now to the geochemical method. Our main line of approach is to evolve sound methods of detecting uranium at depth by interpreting the data and applying our knowledge of the laws of uranium migration. This is the basic approach in the Soviet Union at present. In setting up our field parties we attach geochemists to the prospectors to assist them with geochemical data and data obtained by various methods. In practice, these geochemical methods are applied by field parties in the USSR in prospecting not only for uranium, but also for very many other chemical elements.

As regards the biogeochemical method, I shall be glad to present Mr. Brown with a synopsis describing how the method is applied—not only in the case of uranium, but in that of many other elements as well, and indicating where it is suitable and where unsuitable.

I have yet another question, namely, how the hydrogeochemical method is used in our country. This method is in very wide use. Every field station always has a laboratory and uses this method. We constantly use it for the purpose of discovering dispersion haloes.

Mr. A. LENOBLE (France): I should like to learn from Mr. Vinogradov at what stage of exploration hydrogeochemical methods are applied in the USSR. In other words: is this kind of prospecting carried out before geological prospecting to determine favorable zones, or is it used only to define uranium-bearing zones in regions already recognized as favorable?

Mr. VINOGRADOV (USSR): The hydrogeochemical method is used as the primary method of exploring unfamiliar territories.

Mr. J. LECOQ (France): My question is addressed to Mr. Nininger. Is there, to his knowledge, any instrument for gamma-ray drill logging with which it is possible to distinguish between an anomaly created by an isolated uranium-bearing mineral bed of small size intercepted by drilling, and an anomaly created by diffuse mineralization over a larger area?

The second question is this: what is the diameter of the probe used in such an instrument?

Mr. NININGER (USA): The bore-hole counter which we use is such that if the hole penetrates the ore so that on all sides of the hole there is ore, the counter will tell you, if it has been sufficiently calibrated, whether you have a high-grade or a low-grade deposit, whether you have a large, very long intercept of low grade or a narrow intercept of high grade, given experience of the area and proper calibration. It will not as yet tell you whether you have just passed the edge of a deposit, so that the ore is only on one side of the hole. This will give you a result which will be a half or some other fraction of the result if the hole were entirely surrounded by core. We are working on a directional mechanism which will take care of that.

The size of the probe is about 2 in.

Mr. LENOBLE (France): Could Mr. Nininger tell me whether resistivity methods have been successfully used elsewhere than on sedimentary formations to determine favorable structures?

Mr. NININGER (USA): Because our important deposits in the USA, with a very few exceptions, have been largely in sedimentary areas, we have done little or no work on resistivity methods for finding veins in igneous rocks.

The CHAIRMAN: There are two questions on paper P/869, read by Mr. Vohra. The first is from Mr. Nininger (USA): "Do you believe that such a deposit, averaging 0.2% and covering 10,000 m², would be detected by the method which you have described in an area of high background?"

Mr. VOHRA (India): The method suggested by me is especially useful for extensive areas of uranium deposits. With a deposit of the type in question, if the measurements are made at a number of stations in the area over a long time, and if the winds are studied during the time of the measurements, by a correlation of the results it should be possible to detect, or rather to predict, a deposit of this type. In fact the method is particularly useful for low-concentration extensive areas having surface deposits of uranium and thorium.

The CHAIRMAN: The second question is: "What in your opinion would be the most economical way of prospecting inaccessible areas such as the higher Himalayas?" This question is put by Mr. Rahman (Pakistan).

Mr. VOHRA (India): The first step should be to obtain and study geological information on the Himalayas in sufficient detail. This programme could be carried out simultaneously with the remote location method just discussed by me. Due to the large number of rivers and streams in the Himalayan regions, radio-hydro-geological methods will also be very useful.

Additional Comments

Mr. MELKOV (USSR): I am very grateful for the opportunity given me to report a few particulars concerning new uranium minerals discovered in the Soviet Union. Our mineralogists will be very pleased if this information proves helpful to our colleagues in their scientific research before such time as our data, which have been prepared for the press, are available for perusal. The minerals on which I wish to report, and also minerals which have been discovered in the Soviet Union and information on which has been published, can be seen at the Soviet Union's Scientific and Technical Exhibit.

Among the new uranium minerals discovered in the USSR are oxides, hydroxides, silicates, phosphates, arsenates, phosphato-arsenates, molybdates, titanates and tantalates.

Oxides and hydroxides comprise hydronasturan and black oxides of uranium. These minerals contain variable amounts of tetravalent and hexavalent uranium. Hydronasturan is a hydrated mixed oxide of uranium and occurs as black compact, brittle substance with a glassy lustre, appearing dirty-green against the light. Black oxides of uranium are black or dark-grey, usually friable, earthy substances with a dull lustre, and are chiefly found in the cementation zone of uranium deposits.

Hydronasturan and residual black oxides of uranium are products of the partial oxidation of nasturan and uraninite, occurring in alkaline and acidic conditions respectively.

Regenerated black oxides of uranium separate out of weakly alkaline or neutral solutions containing hexavalent uranium in the presence of reducing agents such as ferrous iron, hydrogen sulphide, etc. They occur in the cementation zones of uranium deposits, especially in those enriched with disulphides of iron.

Two minerals of the silicate category have been discovered: nenadkevite and orlite. Nenadkevite, a hydrous silicate of uranium, magnesium, calcium, thorium and lead, contains varying proportions of tetravalent and hexavalent uranium, and varying proportions of magnesium, calcium and lead. This mineral separates out of hydrothermal solutions in the form of veins.

Orlite is a hydrous uranyl silicate of lead and differs from kasolite in structure, composition and other characteristics. It is found in the oxidation zone of uranium veins comparatively poor in iron disulphides.

A number of minerals of the phosphate and arsenate category have been discovered. One mineral of tetravalent uranium only, called yantinite, is described in the literature. A second such mineral, lermontovite, has been discovered in the Soviet Union; it is a hydrous phosphate of tetravalent uranium with an admixture of calcium and rare earths. It is characterized by the botryoidal and nodular character of the aggregates; it is grey-green in colour, and it is stable in reducing conditions. It is found in veins below the level of subsoil waters.

Soviet mineralogists have discovered some additional varieties of micaceous uranium ores, in which the part of ordinary cations is played by hydrogen and sodium. To this group belong H-otenite, H-uranospinite and Na-autunite.

In addition, a hydrated uranyl phosphate of lead has been discovered, and given the name of przhevalskite. It is a neutral, not basic, salt of the dewindtite and dumontite type. Various micaceous uranium ores of mixed composition have also been discovered, i.e. ores which include arsenic and phosphorus, and also copper and calcium, in addition to uranium.

Two new molybdates of uranium have been determined: a yellow molybdate in powder form—irigi-nite, occurring as a hydrous molybdate of hexavalent uranium, and a black molybdate in the form of porphyritic crystals in albitite—moluranite (a hydrous molybdate of tetravalent and hexavalent uranium). Both are as yet of scientific interest only.

Three minerals have been identified in the category of the titanates and tantalates. Of great scientific interest is the discovery in hydrothermal veins of a titanate of tetravalent and hexavalent uranium with an admixture of thorium, given the name of lodochnikite, and also the discovery in pegmatite veins of a titanate of iron, rare earths and uranium, called ufertite; lastly, mention should be made of the discovery of a tantalate of yttrium, uranium and sodium, which has been given the name of obruchevite.

PEACEFUL USES OF ATOMIC ENERGY:

Proceedings of the International Conference in Geneva, August 1955.

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