PAGES MISSING IN THIS BOOK

UNIVERSAL
LIBRARY

OU_158558

UNIVERSAL
LIBRARY

Outlines of Geology

A COMBINATION OF

OUTLINES OF PHYSICAL GEOLOGY By CHESTER R. LONGWELL, *Henry Barnard Davis Professor of Geology, Yale University*; ADOLPH KNOPF, *Professor of Geology, Stanford University, and* RICHARD F. FLINT, *Professor of Geology, Yale University*

AND

OUTLINES OF HISTORICAL GEOLOGY By CHARLES SCHUCHERT, *Late Professor Emeritus of Paleontology, and* CARL O. DUNBAR, *Professor of Paleontology and Stratigraphy, Yale University*

NEW YORK, JOHN WILEY & SONS, INC.
LONDON, CHAPMAN & HALL, LIMITED

PREFACE

Four years ago the two elementary textbooks, "Outlines of Physical Geology" and "Outlines of Historical Geology," were made available in one volume to meet a widespread demand from teachers of geology for a brief treatise covering the salient features of the entire subject. Thorough revision this year of both books makes it possible to offer an improved edition of the combination volume. In the work of revision the authors had as an important aim the welding together of the two parts into a more nearly unified whole. Physical geology is explained not merely as an end in itself but also as a key to the reading of geologic history. Throughout the revised treatment the attempt is made to give the student an appreciation of Earth-features as the results of processes that are still active. Practical and philosophical aspects of geology in relation to mankind are given special emphasis.

For a more detailed statement of the authors' objectives and points of view, readers are referred to the two separate Prefaces contained herein.

CHESTER R. LONGWELL
ADOLPH KNOPF
RICHARD F. FLINT
CHARLES SCHUCHERT
CARL O. DUNBAR

August, 1941

Outlines of Physical Geology

PHYSICAL GEOLOGY. *By* Chester R. Longwell, Adolph Knopf, *and* Richard F. Flint. Third Edition.

HISTORICAL GEOLOGY. *By* Carl O. Dunbar.

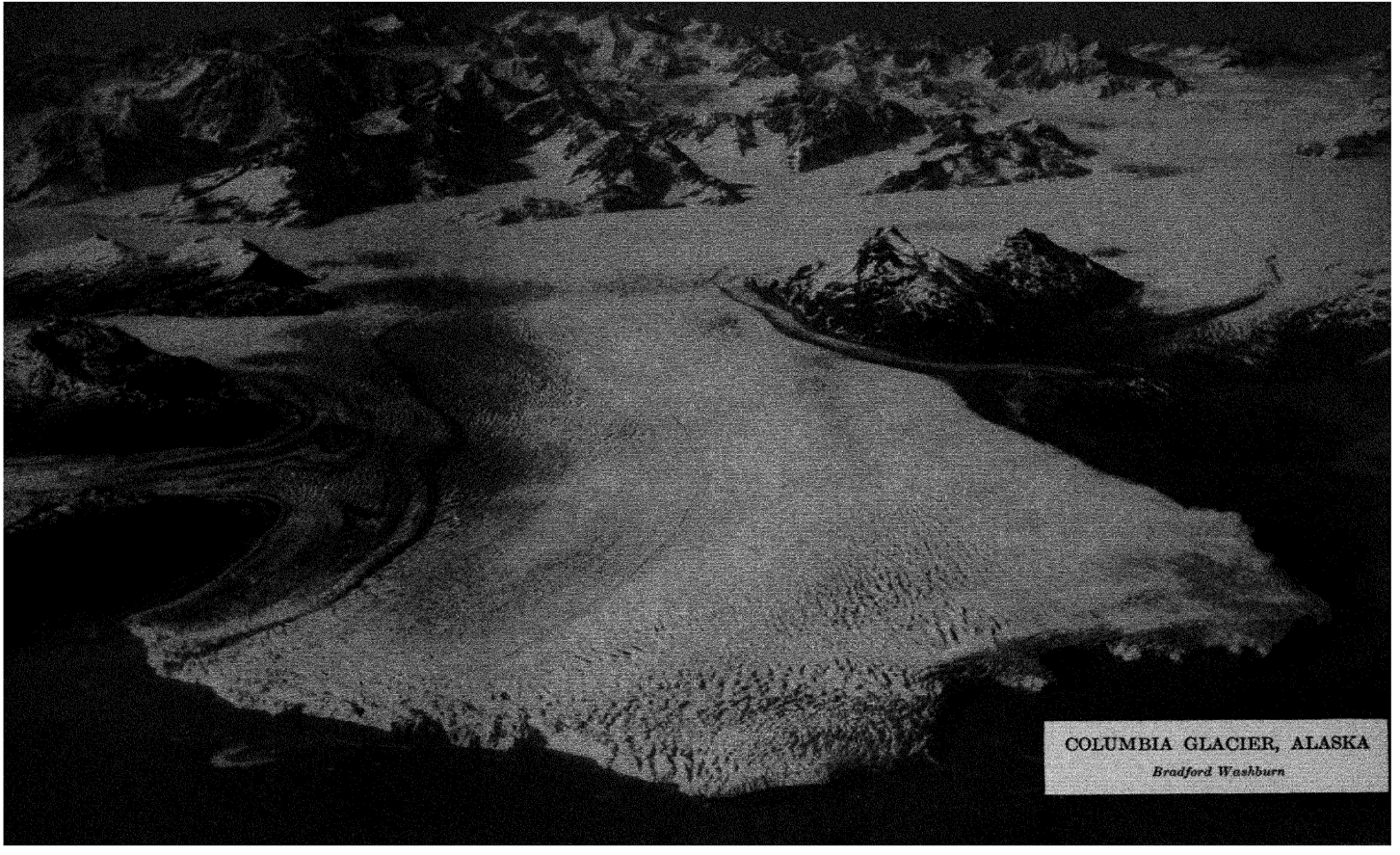
OUTLINES OF PHYSICAL GEOLOGY. *By* Chester R. Longwell, Adolph Knopf, *and* Richard F. Flint. Second Edition.

OUTLINES OF HISTORICAL GEOLOGY. *By* the late Charles Schuchert *and* Carl O. Dunbar. Fourth Edition.

OUTLINES OF GEOLOGY. OUTLINES OF PHYSICAL GEOLOGY and OUTLINES OF HISTORICAL GEOLOGY in one volume.

ROCKS AND ROCK MINERALS. *By* the late Louis V. Pirsson. *Revised by* Adolph Knopf. Third Edition.

GLACIAL GEOLOGY AND THE PLEISTOCENE EPOCH. *By* Richard F. Flint.



COLUMBIA GLACIER, ALASKA

Bradford Washburn

Outlines of
Physical Geology

By

Chester R. Longwell
Henry Barnard Davis Professor of Geology
in Yale University

Adolph Knopf
Professor of Physical Geology
School of Mineral Sciences
Stanford University

Richard F. Flint
Professor of Geology in Yale University

SECOND EDITION
Eighteenth Printing

NEW YORK, JOHN WILEY & SONS, INC.
LONDON, CHAPMAN & HALL, LIMITED

COPYRIGHT, 1934, 1941
BY CHESTER R. LONGWELL, ADOLPH KNOPF,
AND RICHARD F. FLINT

All Rights Reserved

This book or any part thereof must not be reproduced in any form without the written permission of the publisher

SECOND EDITION

Eighteenth Printing, November, 1955

Printed in U. S. A.

PREFACE

The first edition of this elementary textbook has been in use for seven years. Comments submitted by users of the book have convinced the authors of the need for further simplification of the treatment, in comparison with their larger book, *Textbook of Physical Geology*, which is designed for a longer and more thorough course. There have been requests also that the relation of geologic principles to practical human affairs be more strongly emphasized and illustrated. The present revision is an attempt to meet these suggestions, and at the same time to increase the teaching value of the book by inclusion of new factual material and improved illustrations.

The introductory chapter has been recast and rephrased in an attempt to make more understandable to elementary students the chief aims and the scope of geologic study. An orienting " preview " of this kind is highly desirable, but is difficult to present in terms that can be grasped in advance of any familiarity with the evidence on which geologic thought is based. The authors have no delusions that all the intended meaning of the new chapter will be obvious to the beginner on a first reading. It is our hope, however, that this preliminary charting of the way will prevent him from losing his bearings among the details of geologic features and processes, and will help lead him to the desired goal — a well-balanced concept of the Earth, with an understanding of present-day activities and surface features as keys to Earth-history. In an effort to insure this result of the study, a new final chapter refers back to the chief points in the introductory outline, gives a brief summary of geologic processes as agents of change, and emphasizes the historical nature of all geology. Thus, whatever the student may be unable to grasp fully in the " preview " will be brought to his attention afresh against the background of his newly acquired knowledge. It is believed that this device will tend to give a true perspective; it should help the student to realize that the facts of physical geology are not merely an end in themselves, but are necessary equipment for an understanding of historical geology.

A new chapter on minerals and rocks brings together materials that in the earlier edition are divided among several chapters and an appendix. Two features of the recently revised *Textbook of Physical*

Geology are incorporated in the present revision: The important processes of mass-wasting are given a prominent place, and the principles of stream action are treated separately from that part of land sculpture which is recognized as the joint effect of running water and mass-wasting. A new chapter, taking the place of two in the old edition, treats volcanoes and intrusive igneous bodies as allied subjects. Metamorphism, an extremely difficult subject for elementary students, is restricted to a brief discussion in connection with deformation of the crust. These several changes in organization are in the interest of simplification, which has been further served by drastically reducing the number of technical terms, and by concluding most of the chapters with summarizing paragraphs that emphasize the outstanding points of each major subject.

Attention of the student is called to numerous practical aspects of geology, such as soil erosion and conservation, floods and their control, problems of water supply, protection of shore property, relation of igneous activity to ore deposits, protection against damage by earthquakes. One of the longest chapters is devoted to nonmetallic and metallic mineral deposits, and a new chapter explains the value of geology in large engineering projects, such as construction of dams, aqueducts, and tunnels.

The three authors collaborated closely, but direct responsibility in preparing the chapters was divided as follows:

Chapters 1, 4, 5, 6, 7, 8, 10, and Appendix by Flint.
Chapters 2, 11, 12, 16, and 17 by Knopf.
Chapters 3, 9, 13, 14, 15, and 18 by Longwell.

Many illustrations in the first edition are replaced with new halftones and diagrams. Appropriate acknowledgment is made with each figure, but the authors take this further opportunity to express their gratitude for permission to use illustrative material.

C. R. L.
A. K.
R. F. F.

April 1, 1941.

CONTENTS

CHAPTER		PAGE
1.	Preview of Geology	1
2.	Minerals and Rocks	13
3.	Weathering and Mass-Wasting	43
4.	Running Water	68
5.	Sculpture by Streams and Mass-Wasting	85
6.	Subsurface Water	103
7.	Lakes and Swamps	117
8.	Glaciers and Glacial Sculpture	127
9.	Erosion and Deposition by Wind	156
10.	The Sea	169
11.	Sediments and Sedimentary Rocks	187
12.	Volcanism and Deep-Seated Igneous Action	207
13.	Bending, Fracturing, and Metamorphism of Rocks	244
14.	Earthquakes; the Earth's Interior	275
15.	Mountains and Related Land Forms	295
16.	Mineral Resources	319
17.	Geology and Engineering	346
18.	History the Central Theme of Geology	359
Appendix: Topographic Maps		368
Index		373

Outlines of Physical Geology

CHAPTER 1

PREVIEW OF GEOLOGY

WHAT GEOLOGY IS

Who can say just when it was that men first speculated about their Earth environment? When did they begin to wonder why this or that tract of land is barren of soil, why some rocks are full of sea shells, why water flows out of the ground as springs, why the ground sometimes violently trembles, why some mountains spew forth liquid rock? No doubt some of these thought processes began with the earliest of primitive men; they long antedate all written records. Curiosity is a human characteristic; and curiosity, among other things, has led mankind to find out much concerning the Earth he lives on, and to pass on his findings to later generations. Little by little the findings are sorted out, the false discarded and the true kept, and thus has accumulated a great body of Earth lore, the study and the development of which is geology. In terms of the other great branches of science, geology is the application of the facts and principles of physics, chemistry, and biology to the study of the Earth.

An advantage we moderns have over our predecessors is that we do not need to go back to the beginning and work through all the laborious thinking that has led to the present state of knowledge of our planet. By building upon these earlier labors we can summarize their chief results, and thereby quickly acquire a background of information to which we can bring new inferences and speculations. For we must not think that we have now learned all the Earth's secrets. Far from it. We have indeed built up gradually a fundamental body of working knowledge; but no matter in what direction we go outward from this body of knowledge, we soon come to questions that no one has yet answered. In all honesty we must reply " I don't know " and then set to work to find the answers, one by one. Each year many answers are found, but just as many remain elusive, while at the same time fresh questions arise, some of them out of the answers already secured.

The multiplication of questions is typified by the problem of the Earth's climates. As early as the eighteenth century it had been inferred that the Earth, in its infancy, had been very hot. From this primal heat it was deduced that the Earth must have been gradually cooling off, and that the Earth's inhabitants must therefore look forward to a progressive chilling that would ultimately destroy life. However, toward the middle of the nineteenth century Louis Agassiz demonstrated that the Earth had recently experienced chilling so severe that great glaciers had formed; in fact, as subsequently was discovered, had spread out over more than one-quarter of its land area. This recent chilling, from which the Earth has since largely recovered, showed clearly that our planet has not been cooling off steadily since its birth. The studies that began under the stimulus of Agassiz' discovery, however, led to complications. They revealed evidence of not just one chilling, but of several cold times, separated by intervals when climates were possibly even milder than they are at present. This startling fact raised a new question, namely, what can be the cause of climatic changes that go repeatedly from one extreme to the other, all within a few hundred thousand years — a brief span, as geologists reckon time? To this query, no one yet knows the answer.

No two people who have thought about the matter would agree as to just what should be included in a summary of basic knowledge about the Earth. But all would agree that it must include, first, at least a general description of the Earth and of the active processes at work upon and within it, and, second, at least a brief reconstruction of the Earth's long history as we have been able to read it from the evidence of the rocks. The first is the province of physical geology and the second (which can not be understood without some knowledge of the first) is the province of historical geology. They will be considered in separate volumes.

The Earth as a Planet

The Earth is one of a family of planets, all of which revolve around the Sun. It is not a particularly distinguished member of the family, being neither the largest nor the smallest, the lightest nor the most massive. Its chief claim to our special interest is that we live on it. For more than 150 years it has been recognized that the planets (including the Earth) were born of the Sun, and we now believe, on the basis of evidence from radioactive minerals in the Earth's rocks, that this birth took place at least 2000 million years ago. Throughout this stupendous period the Sun has been not only supplying the Earth with light and heat, but also doing this at a fairly uniform rate. The source

of this amazing output of energy has long been studied. It is now thought to lie within the atoms of the Sun's substance, either in the utilization of subatomic energy in building up heavy chemical elements from hydrogen, or in the annihilation of matter — the collision of electrons and protons, their mutual destruction, and their transformation into radiant energy.

As the Earth revolves about the Sun, it rotates on an axis of its own. Because of this rotation, it bulges slightly at its equator and is flattened slightly at its poles. The bulging amounts to a difference of 27 miles on a diameter of about 7900.

Atmosphere and Hydrosphere

The solid body of this planet has two fluid envelopes, both of which are of very great importance in geology. One of these, the *atmosphere*, consists of gases. It envelops the solid Earth continuously to a height of more than 100 miles, though in its outer or upper part the gases are extremely tenuous. Its importance lies in its chemical and physical activity. Without it the Earth's surface would experience little more change than our telescopes discover on the Moon.

The other envelope, the *hydrosphere* ("water-sphere"), includes the water of the sea, the lakes, and the streams, and, less conspicuously, the vast quantity of water below ground, filling openings in the soil and in the bedrock underneath. Although the hydrosphere is manifestly not continuous, there is so much of it that, if the inequalities in the Earth's solid surface were leveled off, there would result a universal sea more than a mile and a half deep. Fortunately for us, the leveling off is not likely to occur. The hydrosphere is physically and chemically just as important in geology as is the atmosphere; water plays a dominant part in the constant alteration processes to which the Earth's face is subjected.

The Earth's Great Relief Features

The surface of the globe has a maximum *relief* (that is, difference in elevation between lowest and highest points) of more than 12 miles. A 12-mile ascent would be a challenge to any climber, but, when compared with the Earth's diameter of 7900 miles, this figure may seem disappointingly slight. However, the largest relief features (Fig. 1) consist of broad platform-like elevations (the *continental masses*), and even broader basin-like depressions (the *deep-sea basins*). The latter, which include the basin floors of the Pacific, Atlantic, Indian, and Arctic oceans, are full of water. In fact they are more than full, for

the water laps over on the margins of the platform-like continental masses as well. Upon these margins (the *continental shelves*) the water is comparatively shallow, but at some distance offshore the sea floor suddenly begins to slope more steeply into the great depths. These steeper slopes mark the true edges of the continental masses.

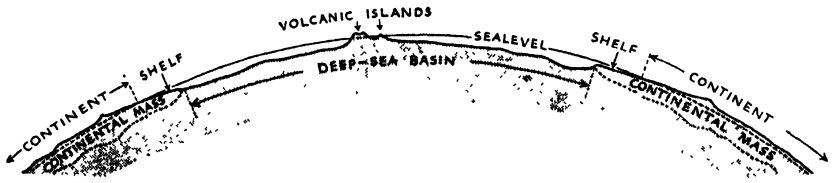


FIG. 1. Segment of the Earth, showing its great relief features. The vertical scale is much exaggerated.

The parts of these masses that stand above sealevel we call *continents*. Their shapes are familiar on all school geography maps: Eurasia, Africa, North America, South America, Australia, and Antarctica. The continents together constitute less than 30 per cent of the Earth's area: in other words, the seas exceed the lands by a ratio of more than 2 to 1. As the average height of the land is about half a mile, and the average depth of the sea is about 2½ miles, the average relief of the Earth's solid surface is only about 3 miles. Modeled to scale on a globe 100 feet in diameter, this relief would amount to less than one inch!

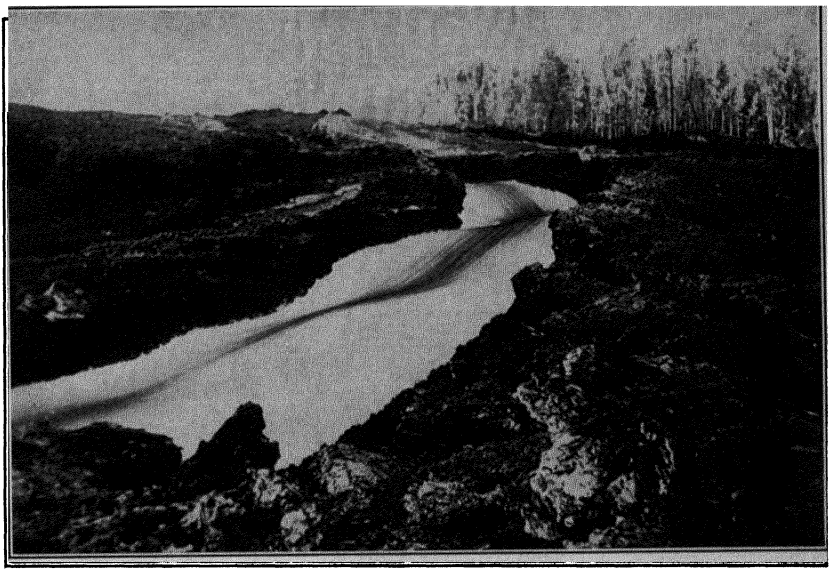
The deep-sea basins as well as the continental masses are diversified by lesser relief features. The deep troughs, ridges, and volcanic cones that accident the sea floor, as well as the plains, plateaus, and mountains of the continents, are relief features of the second order. Each of these is diversified by relief details of still lesser orders.

ROCKS OF THE EARTH'S CRUST

The outer zone of the Earth's solid body is generally spoken of as the *crust* — a term in good use although it is a relic of the now obsolete belief that all the Earth except a thin outer shell is molten liquid. The crust is composed of rocks and their constituent minerals. You need not have looked more than casually at the rocks and minerals exposed in valleys and cliffs, road cuts and tunnels, in order to realize that their variety is very great — perhaps discouragingly great. But a systematic study reveals the fact that all rocks fall into three general classes, each of which has fairly distinct characters by which it can be recognized.

THREE PRINCIPAL KINDS OF ROCKS

Climb the slopes of Italy's Vesuvius or Hawaii's Mauna Loa: you will see vast areas of dark, slaggy rock. Even if you are not fortunate enough to see fluid lava during an eruption, you can hardly fail to realize that this dark stuff once flowed down the volcanic slopes in red-hot streams of liquid (Fig. 2). "Fire-made" or *igneous* rocks such as those are common in many lands and have been formed at many different times. They are important constituents of the Earth's crust,

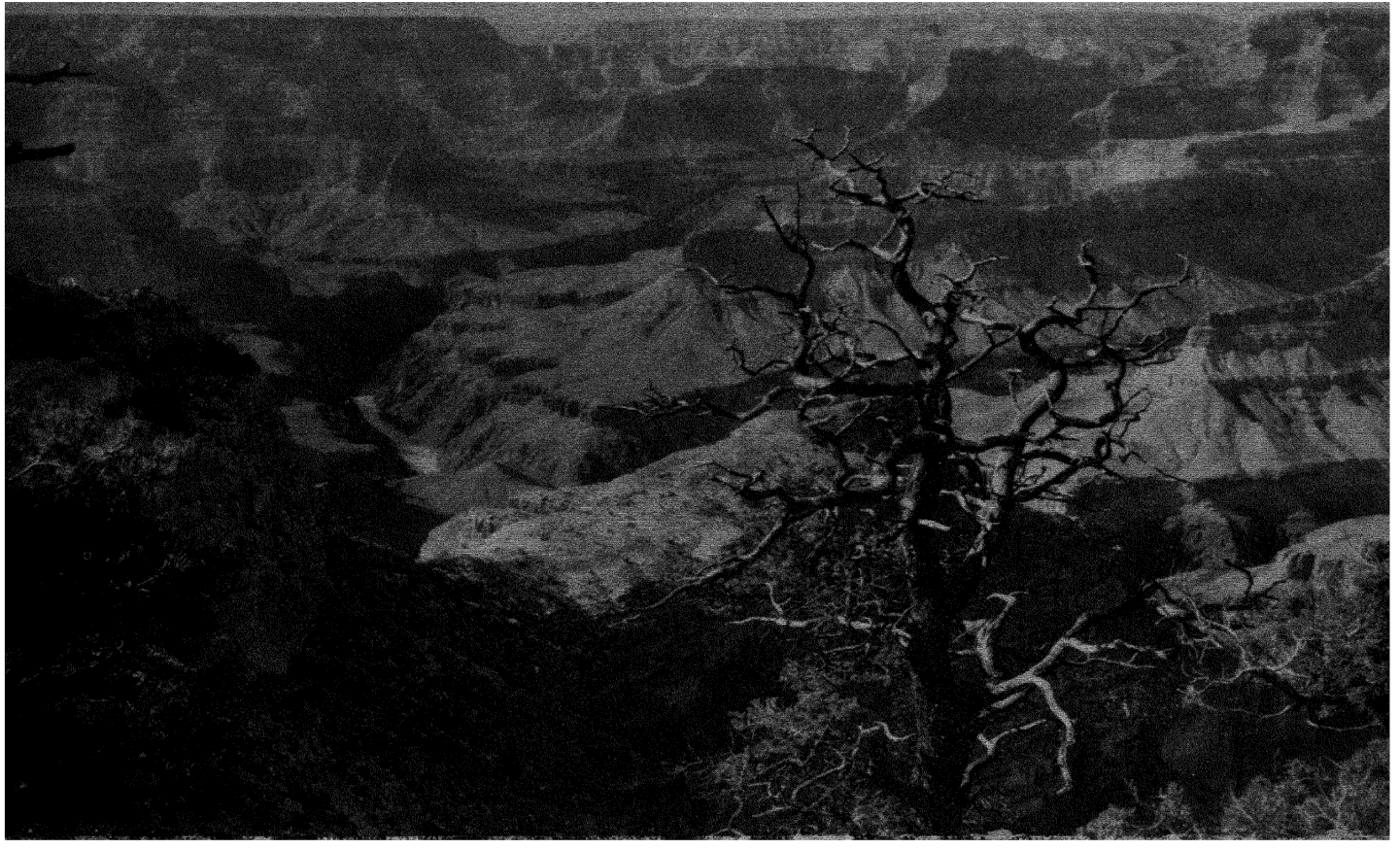


Hawaiian Volcano Observatory.

FIG. 2. Igneous rock in the making on the slopes of Mauna Loa. The dark-colored rock is solidified lava; the white band is a flowing stream of incandescent lava. (Alika Flow, 1919.)

though by no means all of them have been poured forth by volcanoes. On the contrary, *granite,* the chief foundation material of the continental masses, was made little by little by the very slow cooling of liquid rock material well beneath the Earth's surface. It has been exposed to view here and there by the gradual wearing down and washing away of the overlying rocks.

Stop at any highway cut in the great central region of North America, in which bedrock is exposed to view. The chances are good that the rock will consist of layers of hard, compacted sand and mud; and if you are lucky you may find that these layers contain sea shells. Except for their hardness they resemble the muds and sands of today's





KOLB BROS., GRAND CANYON, ARIZONA.

Fig. 3. North wall of the Grand Canyon of the Colorado. The inner gorge (of which only a short segment appears in the view) is cut into granite and metamorphic rocks; the higher part of the valley is cut through flat-lying layers of sandstone, shale, and limestone, most of which were formed on ancient sea floors. The steep cliffs are developed on resistant layers, and the gentler slopes on weak layers. The outer rim is several miles distant from the river and more than 6000 feet above it.

river deltas and sea floors. Water and wind are always on the move, carrying and dropping rock fragments or *sediments* which in the long course of time become compacted and cemented to form *sedimentary* rocks (Fig. 3; Chap. 11). Three-quarters of the Earth's land area is directly underlain by rocks of this kind.

From central Vermont are quarried large quantities of slate. This rock has a strong tendency to split into thin slabs. Vermont is part of an old worn-down mountain system, and the tendency of the slate and the neighboring rocks to split is the result of powerful pressures that were generated at the time the mountains were made. Slate is only one member of a large group of rocks that are alike in having had their original characters *altered* by great changes in temperature, pressure, and other factors, down within the Earth's crust. Hence they are called *metamorphic* rocks. All such rocks were either igneous or sedimentary before the changes occurred. We know this because some of them retain vestiges of their former character.

The Gradational Processes

A dusty wind, a muddy river, the surf flinging sand and stones upon the beach — all mean that pieces of rock, however small, are being shifted about over the Earth's surface. Kept on the move by energy supplied from the Sun, and aided by gravity, the three chief *gradational* agents — water, wind, glacier ice — are engaged in this never-ending job. Worked upon by the atmosphere, the firm rocks at the Earth's surface crumble and decay, and the waste products, as sediments, are cleared away by the gradational processes only to make room for more decay. Some of the sediments are carried uphill temporarily (watch the wind building a sand dune) — but their net travel is downward; they are spread out and dropped in all low places, including especially the sea floors.

The Upbuilding Forces

There is evidence that this business of gradation has been going on for many hundreds of millions of years; if unopposed it should have carried all the land into the sea long ages ago. But it is opposed — powerfully opposed. One clue to the nature of the opposition lies in the dark, slaggy lava-rock of Hawaii. Not only the surface but the whole vast body of each of the Hawaiian islands has been built up, layer by layer, by flows of lava welling upward from within the crust, and building new land.

Far more important than the restorative upbuilding of new igneous rocks are actual movements of the crust itself. One clue to these is

the presence, far above sealevel, of sedimentary rocks identical with the sediments of sea floors today, and containing sea shells. From such evidence, repeated in amazing variety, in every part of the world, we are convinced that the crust has been slowly upheaved again and again, now in one place and now in another. Every one of these upheavals has created more work for the gradational processes and has set them at it all over again. This is the main reason why the continents, after these millions of years, are now high and dry. To be sure, each of them has been worn low at times — great regions of North America have been awash more than once — but they have been renewed again and again.

Geologic Time

How long have these two opposing forces, the upheaval of the crust and its gradual wearing down, been struggling with each other? Until recently we could answer this question only by crude estimates. Now we know that the estimates, once regarded as unbelievably large, were wrong — they were far too small — and our present knowledge is based on sound evidence found within the rocks themselves. The evidence is this: Uranium and other radioactive chemical elements disintegrate continuously, at a rate that is measurable and that appears not to vary, regardless of changes in temperature and pressure. As soon as a mineral containing uranium has been formed in a rock, helium gas and other products that result from the disintegration of the uranium begin to accumulate. The end product of these radioactive changes is lead of a particular kind. With the passage of time, the ratio of this lead to the uranium steadily increases. Hence, after a chemical analysis has revealed the exact ratio of lead to uranium in a given uranium-bearing mineral (the apparently constant rate of change being accurately known), the age of the mineral can be calculated. It is as if a clock had been set going in each of these minerals at the moment of its origin; we are now able to read, on each of these clocks, the exact time. By this remarkable means, undreamed of a generation ago, we now know that the oldest rocks thus far discovered are more than 1500 million years old. The vast span of time that has elapsed since the oldest rocks were made we call *geologic time*. The figure 1500 million is not likely to mean much unless visualized in some concrete way: Let the height of the Empire State Building, dominating Manhattan's skyscrapers with its 1250 feet, mooring mast included, represent all of geologic time. The thickness of a dime laid on top of the mast will represent, in true proportion, the length of written human history.

Uniformitarianism

A hundred and fifty years ago it was customary to regard a canyon or other deep valley as a great crack in the Earth's crust, a rift suddenly opened overnight during some catastrophe that shook the world. It was customary to think of a range of jagged mountains as the jumbled wreckage of a vast and instantaneous cataclysm vaguely understood. Although today all this "catastrophism" has been tossed overboard, we must not judge our predecessors too severely; we must remember that they had no idea of the tremendous length of geologic time. Not only was the lead-uranium clock unknown to them, but they were strongly influenced by their understanding of the Book of Genesis, according to which the Earth is a very young sphere indeed.

At the turn of the eighteenth century, James Hutton of Edinburgh advocated a different way of looking at things. He showed that streams cut their own valleys little by little, and that, as a general worldwide rule, slow everyday processes operating through a sufficiently long time are quite capable of having produced all the features formerly thought to have resulted from sudden catastrophes. According to Hutton's view, the evolution of the Earth has been *uniform*. He did not mean by this that each process has operated at a uniform *rate*, but he did mean that no processes have ever operated in the past which are not somewhere in operation today. The present, he said, is the key to the past. The endless interplay of the two groups of forces of upheaval and wearing down he implied in the memorable phrase, "We find no vestige of a beginning — no prospect of an end."

Hutton's concept of uniform evolution, which has gradually become the basis of our modern thought, is widely known as the doctrine of *uniformitarianism*, a cumbersome word, but when its meaning is understood, an appropriate one.

Using the Present as the Key to the Past

The principal task of the geologist is to decipher the past, and to write a history of the Earth from its earliest discernible beginnings. For this task he has the following equipment: (1) knowledge of rocks and minerals, the primary documents with which he must work; (2) understanding of the gradational processes and the upbuilding forces — the activities that endlessly make and break rocks; (3) true understanding of the great magnitude of geologic time; (4) comprehension of the uniformitarian doctrine; (5) last, but not least, the ability to reason, in particular to draw sound inferences from specific evidence.

Thus equipped, the geologist begins the examination of his primary documents, the rocks. The character of a certain sedimentary rock

leads him to recognize it as part of a great deposit of sand and mud spread out by a stream where it discharged into the sea. The rock may provide him with a knowledge of the stream's source region, the depth of the water in which the sediment was deposited, the general position and trend of the seashore, and the length of time since the sea existed in that place. From a certain igneous rock occurring near by he learns that long after the stream had ceased to build its delta of sand and mud, a localized "hot spot" down within the crust caused the melting of a body of rock, some of which found its way upward and eventually poured out upon the surface as flows of lava. From the steeply inclined attitudes of some of the layers of sedimentary rock, and from the evident change of some of them into metamorphic rocks, he learns that, still later, forces within the Earth slowly buckled and pressed together the pile of rock layers already formed, gradually fashioning them into a chain of high mountains.

From the patient fitting together and overlapping of inferences such as these, there gradually emerges a connected story of the development of the Earth through geologic time. The story as we know it today is far from complete, but it constitutes much more than a good start, and year by year it receives important additions.

This study naturally requires a division of labor among specialists; therefore a group of special branches of geologic investigation has grown up. Among them are (1) the age relations of rocks (*stratigraphy*), (2) the fossils preserved in the rocks (*paleontology*), (3) the character and origin of rocks of all kinds (*petrology*), (4) the minerals of which rocks and ores are composed (*mineralogy*), (5) the deformation of rocks (*structural geology*), (6) the land forms fashioned by the gradational processes (*geomorphology*), and (7) the mineral veins and other deposits of economic value (*economic geology*).

Although each of these branches constitutes a special field, all are parts of a related whole, a whole that grows through co-operative effort.

Applied Geology

Most of the special branches of geologic study named in the preceding section aim at adding to the sum of human knowledge by producing as complete a history of the Earth as possible. This objective is philosophical rather than material. But the seventh and last-named branch — economic geology — has a quite different objective. It aims at increasing man's material wealth in a hundred different ways by applying the body of knowledge embraced by all the other branches to the specific tasks of getting useful mineral deposits out of the ground

building dams, bridges, and other structures, and last, but by no means least, protecting and conserving our agricultural soil and our water supplies. The basic facts and principles used by geologists in carrying out these material tasks are precisely the same as those used in the historical effort. But the facts and principles are *applied* by them to economic rather than philosophical problems. Hence economic geology in its broadest sense is often called *applied geology*.

What Is to Follow

This chapter has given a preview of what the book as a whole contains. We shall begin (Chap. 2) with an examination of the rocks and minerals that constitute the Earth's crust, for without some knowledge of these we can not hope to understand the geologic processes. Then we shall describe (Chaps. 3–15) the gradational processes and the upbuilding forces at work upon the crust, and shall indicate some of the chief features by which the work of each is recognized. Finally we shall show (Chaps. 17, 18) how geologic information is applied to economic ends. All of this is physical geology. Volume II deals with historical geology — the measurement of geologic time, the fossils entombed in the rocks, and the history of the Earth from the earliest decipherable time up to the present, as read from the record of the rocks themselves.

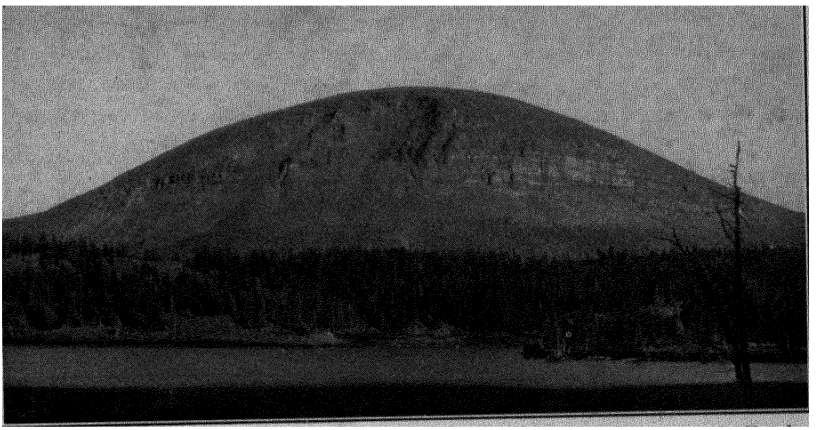
What We Do Not Know

Much of the information contained in this book is within the well-lighted zone of proved fact. But no one ought to embark upon a study of even the elements of geology without realizing that we quickly pass from fact into a twilight zone of inference in which we can say, not "This is true," but only "Probably this is true," and that thence we pass into a region of darkness lit here and there by a guess, by speculation. Speculation is a legitimate and desirable thought process just as long as the thinker fully realizes that he is only speculating. But when he speculates, and at the same time persuades himself (and also, alas, his listeners) that he is drawing sound inferences, then knowledge does not progress. The reader of this book should remember at every page that fact, inference, and speculation are three wholly different things, that "We do not know" must be said or implied at nearly every turn, and finally that *what we do not know at present* would fill an indefinite number of volumes, many of which, we hope, will in the course of time be written.

CHAPTER 3

WEATHERING AND MASS-WASTING

Bedrock and Mantle. Examine any deep excavation made for the foundations of a building, for a road grade on a hillside, or for the burial of a water pipe. Typically, in a moist climate, the upper part of such a cut reveals dark-colored soil containing plant roots. At a depth that may be only a few inches, or possibly many feet, the soil



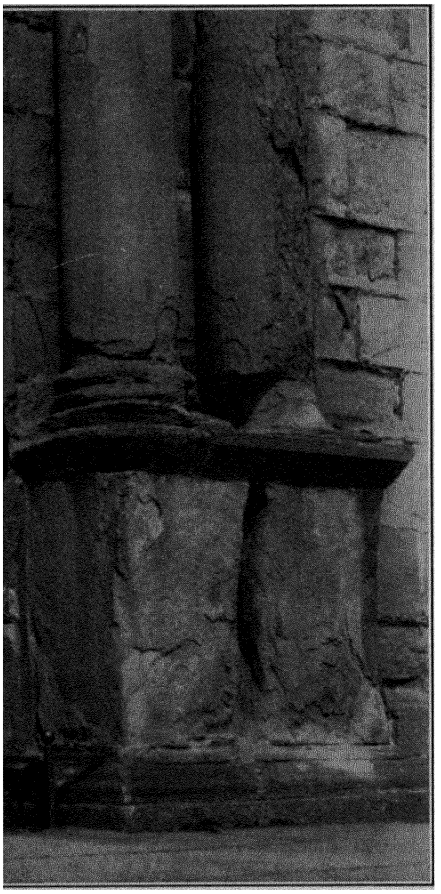
A. P. Church.

FIG. 18. A rounded mountain summit partly covered with mantle formed by weathering of the bedrock. Some of the more resistant rock layers are not covered; they form prominent outcrops on the mountain side. Northeastern Utah.

grades into infertile clay or sand, usually lighter in color than the topsoil. If the cut is deep enough, it may penetrate broken and partially decayed rocks, and, still lower, enter firm, fresh bedrock. Locally, as in cliffs or in the channels of brooks, the bedrock forms natural *outcrops* at the surface; elsewhere, drilled wells go through loose material tens or even hundreds of feet thick before bedrock is encountered.

The widespread cover of loose material on the bedrock is the *mantle* (Fig. 18). Pebbles and other coarse pieces of material in it are readily identified as fragments of rock or of individual minerals; and a powerful microscope shows that tiny rock particles, some fresh and others very much altered, make up a large part of the fine material also. In

some places all the recognizable particles consist of minerals found in the fresh bedrock directly beneath. In other places, however, most or all of the constituents in the mantle are not related to the underlying rock. We infer that the mineral fragments in the mantle have resulted from breaking up of bedrock, and that much of the debris has been moved from its original site. Many flat areas are covered with *residual* mantle, which has remained essentially where it was formed. On the other hand, the "bottom lands" bordering the Mississippi and other large rivers are underlain by *transported* mantle, a large part of which was washed tens or even hundreds of miles from its place of origin.



C. R. Longwell.

FIG. 19. Sandstone columns beside a doorway of Durham Castle, England, showing effects of exposure to the weather for several centuries.

Erosion in General. Durham Castle in northern England is a stone structure built centuries ago near the top of a steep slope. Today its walls show remarkable effects of long exposure to the weather. Each sandstone block has been worn back, bit by bit; but the mortar between adjacent blocks, more resistant than the stone itself, has yielded more slowly. As a result, the face of each block is deeply dish shaped, and the protruding pattern of mortar gives the walls an extremely ragged, weather-beaten appearance. Some columns in the building have been considerably reduced in size by the attack of the weather (Fig. 19).

The old castle has suffered also in another way. For a long time there have been conspicuous cracks in the walls, and a few years ago some of the cracks had grown so wide that partial collapse seemed to

be threatened. On investigation it was learned that the foundations of the castle did not extend into bedrock but rested entirely in the deep soil and other loose materials that mantle the hillside. During the centuries this loose mantle, urged steadily by gravity, has been creeping slowly down the slope and striving to carry the castle with it. As the rate of movement was not everywhere the same, the walls of the castle were being twisted and ruptured. The danger has been removed, with considerable difficulty and at large expense, by strengthening the foundations and extending them to bedrock.

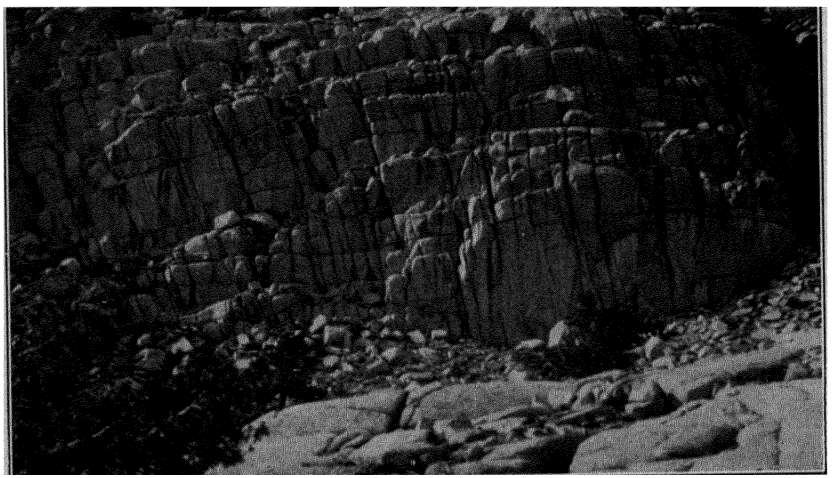
The experience of Durham Castle, in the few centuries of its existence, illustrates what has been happening through the ages on the entire land surface of the Earth. However strong and durable they may be, rocks exposed to the weather are slowly crumbling, and the resulting fragments are being moved by various agents. The general process of loosening and removing rock material at the Earth's surface is *erosion*. An important part of erosion is *weathering*, a rather complex set of processes by which rock material is loosened and softened and thus made more susceptible to the attack of streams, the wind, and other eroding agents. Aside from its fundamental position among geologic processes, weathering is of vital importance to the human race because it produces soils, the basis of all life on the lands.

Weathering and Its Results

Agents of Weathering. The chief agent of weathering, as of the weather, is the atmosphere, which uses energy derived from the heat of the Sun. Although it is for the most part invisible, the atmosphere is responsible for vast changes on the Earth. By carrying moisture from the sea and precipitating it on the continents, the atmosphere makes possible the formation of streams and glaciers, which are powerful eroding agents. Winds, by blowing dust and sand, accomplish some erosion directly, and by generating waves on the sea they cause marine erosion of the coasts. Therefore the greater part of erosion is chargeable either indirectly or directly to the atmosphere. For the present, however, we shall consider only its part in the weathering of rocks.

The important geologic activities of the atmosphere depend upon its peculiar physical and chemical properties. Since it is a gas it penetrates readily into all crevices and other openings that lead down from the Earth's surface, and so comes into contact with much of the bedrock in addition to exposed surfaces. About three-fourths of the atmosphere consists of the gas nitrogen, which is not chemically active, although with the aid of certain plants and bacteria it enters into

some important reactions in the ground. Oxygen is enormously more active chemically and plays a large part in the attack on rocks. Water vapor is a highly variable constituent of the air, but its geologic role is large. Precipitated as rain or dew, it moistens the rocks, dissolves some of the minerals directly, takes an essential part in many chemical reactions, and assists in mechanical changes also. Carbon dioxide, which normally forms only 3 parts in 10,000 of the atmosphere by volume, has an importance out of all proportion to its rank in



G. K. Gilbert, U. S. Geol. Survey.

FIG. 20. Fractures in the bedrock which aid weathering by allowing entry to water, air, and plant roots. The rock is granite, in the Sierra Nevada, California.

quantity. Aside from its vital function in supplying carbon to growing plants, carbon dioxide combines with some of the elements in rocks and so brings about radical changes.

Water, after it is precipitated and is no longer part of the atmosphere, continues to be a prime factor in weathering so long as it remains on the surface or at shallow depths in the crevices of bedrock and in the pore spaces of the mantle.

Break-up and Decay of Rock. Whatever the original nature of the rock, it may be disrupted mechanically. This reduction of rock to smaller pieces, with or without some chemical alteration, is described as *disintegration.* On the other hand, the composition of the constituent minerals is changed by chemical attack, resulting in *decomposition* or " rotting " of the rock. Disintegration and decomposition usually proceed together and are so interrelated that they can

not be distinguished clearly as due to wholly different processes. However, under certain conditions one effect predominates over the other. Disintegration and decomposition of bedrock are facilitated by the presence in nearly all rocks of numerous cracks and crevices (Fig. 20) which allow ready entrance of air, water, and other weathering agents. Even some of the mineral grains have cleavage planes or minute cracks which admit some moisture. By weathering processes these original openings are widened and others are formed. The loose arrangement and high porosity of the mantle make it especially susceptible to continued weathering.

CHEMICAL DECAY OF ROCKS

Mechanical breaking-up of rocks makes decomposition much more effective, since the chemical agents can attack each newly made fragment from all sides simultaneously, and can descend ever deeper into bedrock as new cracks are formed or old ones are extended. However, since decomposition is directly responsible for some of the mechanical disruption, it is advisable to consider the chemical aspect of weathering first.

Chemical Processes Involved. A piece of bright new steel exposed to the weather becomes coated in a short time with yellowish-brown rust. If the exposure is continued for months and years, scales of rust fall from the surface of the steel, and finally the entire piece can be crumbled into brown dust. The iron of which the steel was chiefly composed has reacted with oxygen and water to form a new substance, hydrous iron oxide, corresponding to the mineral *limonite,* in a soft, earthy form.

A piece of bright copper treated in the same way keeps its original appearance longer than the steel, but eventually acquires a coating of soft green material from the union of the copper with carbon dioxide and water in the air. A lump of rock salt placed in the rain quickly disappears through *solution,* another process by which mineral substances are slowly changed.

Rocks exposed at the Earth's surface consist of various minerals, and these react to the chemical agents of weathering differently and at very different rates. Iron in such minerals as black mica in a granite or pyroxene in a basalt unites slowly with oxygen and water to form limonite, which makes a brown stain on the surface of the rock. Other chemical reactions occur, the net result of which is softening and partial or total disruption of the mineral grains, not only at the surface but also along any crevices into which moisture can penetrate.

Water further aids in decomposing the rocks by removing certain

minerals in solution. Only a few common minerals are soluble in pure water (common salt is one), but many others dissolve in carbonic acid which forms when carbon dioxide unites with water. For example, the mineral calcite (calcium carbonate) is only slightly soluble in pure water, but carbonic acid converts it into calcium bicarbonate, which is dissolved and carried away by water percolating through the pores and crevices in the rock. Limestone consists chiefly of calcium carbonate, and vast quantities of this rock have been carried away in solution (Chap. 6). Other less-soluble mineral grains common in some kinds of rocks dissolve very slowly; but their partial removal weakens the rock and provides more openings to be used by chemical reagents.

Effects on Feldspar and Other Minerals. Since feldspars are the most abundant rock-making minerals, their response to weathering merits particular attention. When feldspar decomposes in a moist, temperate climate, the chief product is the substance ordinarily called clay, which is of great importance because it plays a large part in the formation of soils and also because eventually it goes into the formation of shale, the most abundant type of sedimentary rock. Other common minerals that contain aluminum also yield clay when they are decomposed. Several of these minerals contain some iron, which commonly forms limonite, and thus the clay acquires a yellowish color.

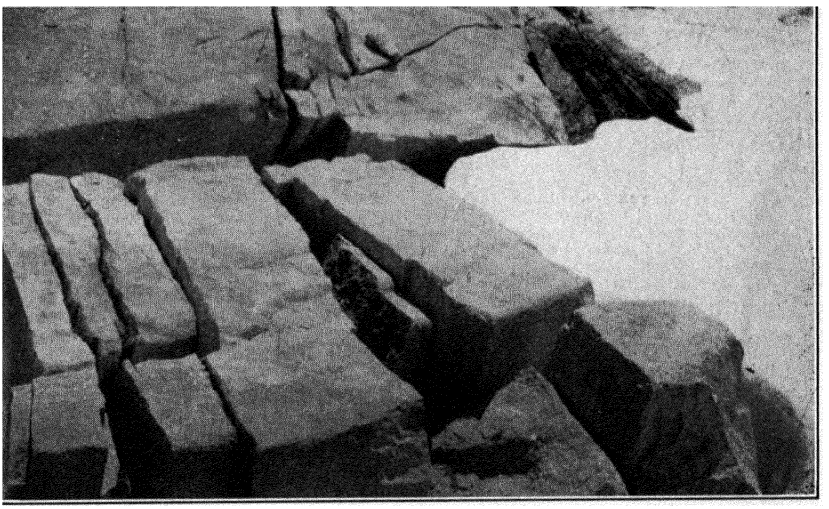
Quartz resists chemical weathering more successfully than any other common mineral in the rocks. Therefore when feldspar and other minerals in a rock decay, the associated grains of quartz remain essentially unchanged. As quartz is hard and has no cleavage to form planes of weakness, the grains also resist mechanical wear by wind, streams, and waves, and become concentrated as the less-resistant mineral grains are destroyed. Therefore sand and gravel come to consist largely of quartz particles.

DISINTEGRATION OF ROCKS

Disruption by Freezing Water. When water freezes it expands by about one-tenth of its volume, and if it is in a closed vessel the pressure on the walls is very great. In the days of muzzle-loading cannon this principle was often utilized to destroy captured enemy artillery. Rocks are disrupted by repeated freezing and thawing of water in cracks and pore spaces (Fig. 21); the process is aptly called *frost wedging*. The effect is confined to a shallow zone, and is most noticeable near the edges of cliffs, where blocks are poorly supported. In high mountains, freezing at night occurs even during the summer

months, and there the results are especially conspicuous. Probably the wedging-apart of minute rock scales or mineral grains is as important in the long run as the dislodging of large blocks.

Supposed Direct Effects of Temperature Changes. The heat of a forest fire causes large flakes to break from exposed surfaces of granite and other rocks. Unlike iron and most other metals, rock is a poor conductor of heat; fire heats only a thin outer shell, which expands and is disrupted by the stresses that result.

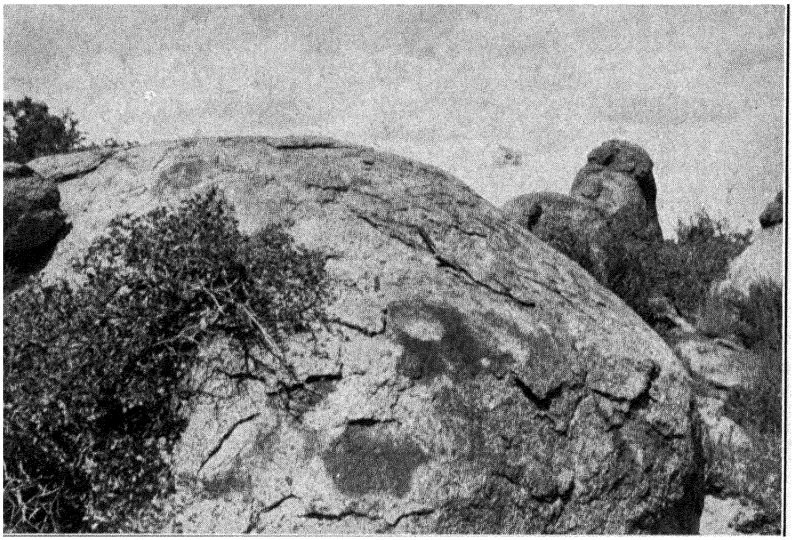


F. E. Matthes, U. S. Geol. Survey.

FIG. 21. Blocks of granite sprung apart by frost wedging. Sierra Nevada, California.

The theory is commonly held that the smaller changes in temperature between day and night also cause slow disintegration of rocks, especially in arid regions, where the daily range in rock temperatures is sometimes more than 100° F. Disintegration is conspicuous in such regions. The mineral grains in granite and similar rocks become loose and fall apart, and it is argued that this effect is produced by minute stresses set up between mineral grains owing to unequal expansion and contraction of feldspar, quartz, and other minerals when they are heated and cooled. The spalling-off of thin flakes and slabs from rock surfaces, an effect that is more common in moist than in dry climates, has been ascribed also to expansion and contraction through repeated heating and cooling. This theory has been tested by laboratory experiments, in which temperature ranges considerably greater than those recorded in any desert have failed to cause the slightest breaking of

rock samples. In some recent experiments the changes in temperature have been repeated thousands of times by an automatic mechanism, to test the possibility that fatigue is caused in the rock by repetitions of small stresses for a long time. No specimens subjected to such treatment have shown any changes detectable under powerful microscopes; hence it is not probable that temperature changes play any large part in weathering, except in connection with freezing water. It is highly probable that slight chemical changes, discussed below, are responsible for many effects that have been attributed to temperature change.



C. R. Longwell.

FIG. 22. Exfoliation of a large granite boulder. Scale indicated by hammer near middle of boulder. The locality — near Prescott, Arizona — is in a mountain district, where rainfall and temperature are moderate.

Disintegration Caused by Decomposition. Many chemical changes produce swelling of the parts of the rock affected and therefore set up stresses. The outer surface of an exposed rock dries rapidly; but moisture that penetrates into minute crevices remains until some decay is effected. Slow increase of volume at slight depth finally disrupts the rock, and pieces that are quite or nearly undecomposed are broken off. *Exfoliation,* the spalling-off of flakes and of comparatively thin concentric shells (Fig. 22), probably is due at least in part to such chemical effects, although many observers have attempted to explain it as caused entirely by temperature changes. It is significant that exfoliation is common only in regions where moisture is fairly abund-

ant, and not in deserts where rapid changes in temperature are most extreme.

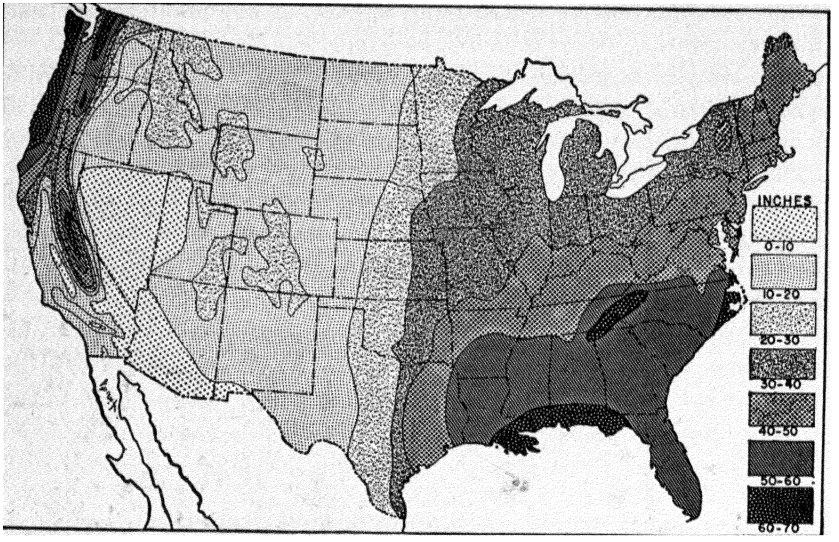
The slow disintegration of granite into its constituent mineral grains probably results in part from chemical changes in microscopic crevices, even in the driest regions. In Egypt the surficial disintegration of granite blocks and monuments is more pronounced in shaded places where the moisture is conserved than it is on the sides most exposed to sunshine.

Disruption by Plant Growth. The wedging-apart of rocks by the roots and trunks of growing trees has considerable importance in weathering. Shrubs and smaller plants also send their rootlets into tiny crevices of the bedrock and slowly enlarge the openings. In the course of time, the amount of disintegration accomplished in this way must be large, but much of it is obscured by chemical weathering which takes advantage of the openings as soon as they are formed.

CAUSES OF VARIATIONS IN WEATHERING

Climatic Effects. Pronounced contrasts in climatic conditions are accountable for striking differences in the rate of weathering and in the effects produced. Since warmth and abundant water are essential to effective chemical change in rocks, this form of weathering proceeds very slowly in Arctic regions even if moisture is plentiful, and in arid lands even if temperature is high. Decomposition progresses most rapidly and reaches to greatest depth in moist tropical lands; it is highly effective also in temperate regions that have abundant rain.

The controlling influence of rainfall appears convincingly in a comparison of the rainfall belts of the United States (Fig. 23). Soil and other decomposed mantle form a thick cover in most parts of the southern Mississippi Valley and of the South Atlantic States. In the southern Appalachians, where rainfall is exceptionally heavy, the mantle extends to remarkable depth, and decomposition of its constituents is extreme. At the same latitude but with only one-fourth as much rainfall, the "panhandle" regions of Texas and Oklahoma have thin, stony soils and numerous exposures of bedrock. In the arid region of southern Nevada and southeastern California, true soil is almost absent, and over great areas the bedrock either is exposed at the surface or is veneered only with coarse rock debris which appears fresh or only slightly decayed. In all moist regions of the temperate zones the luxuriant growth of vegetation is an indirect but powerful ally of the ordinary chemical processes. From dead plants there is developed in the soil organic matter, or *humus,* which forms acids that are very effective in leaching the soil and decomposing the bedrock.



U. S. Geol. Survey.

FIG. 23. Rainfall map of the United States. Conventional patterns show average annual rainfall in the several belts.



C. R. Longwell.

FIG. 24. Sliderock forming slope below a high cliff in the Wind River Mountains, Wyoming. The base of the slope is about 10,000 feet above sealevel.

It is evident that decomposition is dominant in the humid parts of the country, and disintegration in the arid regions. This does not mean that forces causing mechanical break-up are absent or of small consequence in areas where rainfall is large. Disintegration is very effective in such areas so long as bedrock is exposed; but the results are partly obscured by chemical decay, and, as a thick decomposed mantle develops, the bedrock beneath becomes more and more immune to mechanical disruption. In an arid region the forces causing disintegration may be less powerful, but the products accumulate and become conspicuous because the pieces of broken rock do not decay chemically.

Variations with Altitude and Slope. As a general rule, high altitude and steep slopes favor disintegration of rocks, for several reasons. The average temperature decreases with increase of altitude; hence frost action is effective in high mountains even in warm zones. Because of the steep slopes most of the loosened debris falls, rolls, or is washed to lower levels, and thus fresh surfaces are exposed to the attack of the weather. At the bases of high cliffs the fallen blocks accumulate to form masses of *sliderock* (Fig. 24). Such deposits develop below cliffs in nearly all regions that have rugged relief, whatever the nature of the climate. Their presence is evidence of fairly rapid disintegration of the rocks above them.

Rolling topography at a moderate elevation offers the most favorable opportunity for decomposition to great depth (Fig. 25). Vegetation protects the soil from rapid erosion, and, as the upper part of the mantle decays more and more, the chemical reagents penetrate to greater depth. There is a limit to this penetration, because below a certain depth all the openings are filled with water which moves very slowly or is almost stationary. In a low plains country this depth is not far below the surface, and weathering is confined to a rather shallow zone, even if climatic conditions are especially favorable for weathering and the rocks near the surface become thoroughly decomposed.

Variations with Rock Composition. Rocks vary greatly in their susceptibility to weathering under different climatic conditions. Quartz is one of the most stable minerals, and rocks composed almost wholly of it, such as quartzite or siliceous sandstone, are especially stubborn in their resistance. Granite yields much more easily in any kind of climate; in a humid region the feldspar decomposes to form clay, and in an arid region the grains of feldspar and quartz fall apart. The actual rate at which these changes occur, however, is slow as judged by human standards. Granite has a long life in buildings and in monuments.



I C. RUSSELL, U S. GEOL. SURVEY.

Fig. 25. Rounded hilltops and smooth slopes characteristic of a region with a moist climate Deep soil mantles most of the surface. The small terrace-like features in left foreground are paths made by generations of grazing animals. North of Luray, Virginia. Note contrast between this landscape and the one shown in Fig. 62, p. 95, which is characteristic of a semi-arid climate.

Limestone is dissolved wherever there is sufficient water; caverns and sinks are formed (Chap. 6), and the limestone finally disappears, leaving only the small amount of clay, sand, or other insoluble impurities that may have been contained in it. In a humid climate, therefore, limestones are weathered faster than most other rocks and tend to form lowlands; but in arid lands extensive solution can not occur, and there limestone is one of the most resistant kinds of rock. In many parts of Nevada and adjacent States, thick series of limestone layers make the highest mountain ridges and peaks.

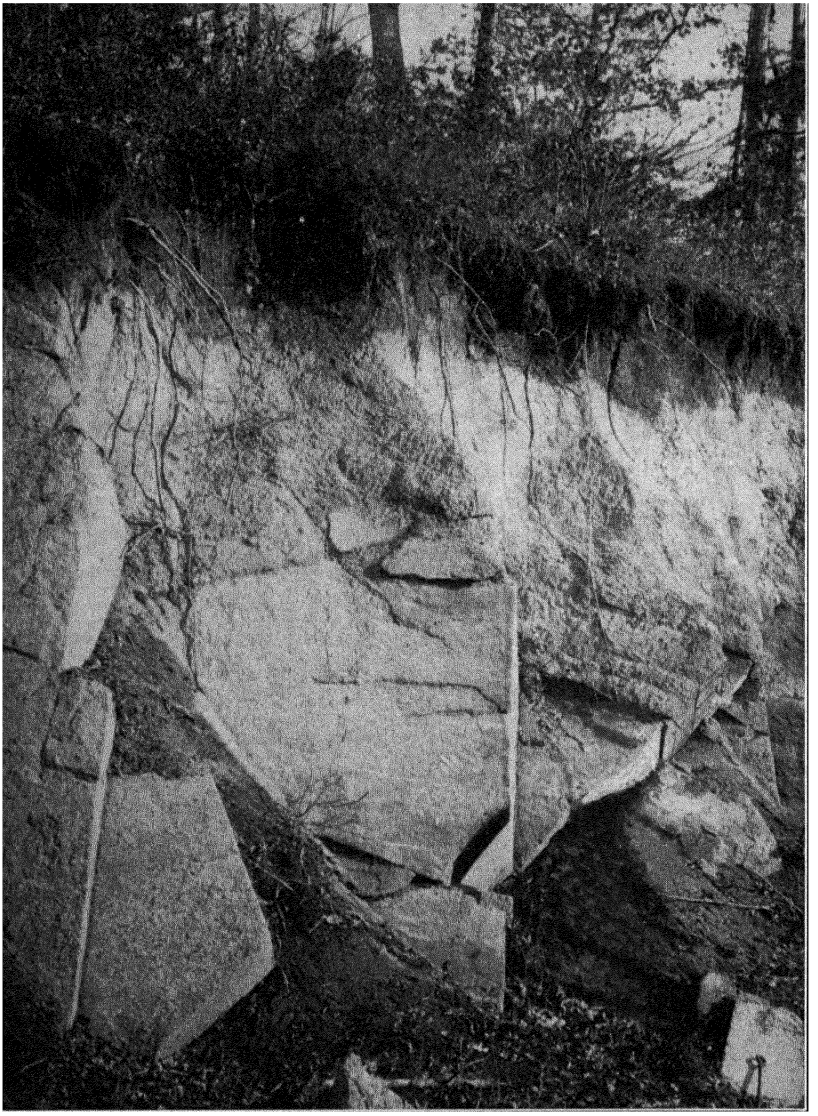
Ordinary shale consists chiefly of clay which was the product of chemical weathering in some earlier geologic period. Further weathering can not cause much additional change in composition, but shale disintegrates easily into plastic clay, especially if it becomes thoroughly soaked with water. In regions of old mountains like the Appalachians, where the rocks are steeply tilted sedimentary strata, the resistant sandstones come to form the high ridges, whereas the weaker shales and limestones underlie the valleys and plains.

DEVELOPMENT OF SOIL

Residual Mantle. Wherever weathering occurs, part of the resulting debris is carried away by running water, wind, or some other transporting agent. In some places the loosened material is removed as fast as it is formed, and the bedrock remains exposed (Fig. 18); in other places transported material is dropped and builds up a thick mantle; in many areas part of the weathered rock is removed, by solution or otherwise, but a residue accumulates. In regions with plentiful rainfall the upper portion of residual mantle normally consists of soil, and there is a gradual change downward through clay that contains some rock fragments into more or less rotten rock (Fig. 26). This evident relation to the underlying rock, shown by almost insensible gradation into it, is characteristic of mantle formed in place.

Formation of Soil. The term *soil* is sometimes applied erroneously to mantle of any kind, but properly it refers only to the part of the mantle which has been so decomposed and otherwise modified that it supports rooted plants. Development of a good soil is an extremely slow process. First the upper part of the mantle, whether residual or transported in origin, becomes sufficiently decayed to yield plant food, and some vegetation takes root. Ordinarily the soil at this stage is scanty and poor in quality and contains large quantities of rock fragments little altered. As the plants die and partially decay they contribute some organic material (humus), which contains carbon extracted from the air by the growing plants; this material gives the topsoil — the layer at the immediate surface of the ground — its dark color. Bacteria multiply in the soil, and some of these serve highly important functions, such as taking nitrogen from the air and combining it with other elements to make available food for plants. The decaying vegetable matter furnishes carbon dioxide and acids that help to decompose the mineral particles in the mantle and dissolve some substances, carrying them to lower levels. Thus the composition of the soil changes continuously, though slowly. Gradually the soil grows deeper, and as it loses all except the most insoluble of the original mineral particles it becomes *mature*.

So long as a soil developed on residual mantle is immature it reflects the character of the underlying bedrock. An immature soil on granite (Fig. 26) is rich in clay formed from the weathered feldspar, and it contains numerous bits of quartz and other constituent mineral grains of the granite, set free but unaltered. A soil formed from a mixture of shale and limestone contains clay and is rich in calcium carbonate. However, as these unlike soils mature under similar climatic conditions



G. P. Merrill, U. S. Nat. Museum.

FIG. 26. Residual mantle on bedrock. The material grades from firm rock below through rotten rock into a mixture of clay and rock fragments, and finally into soil made dark by its humus content. Near Washington, D. C.

the differences disappear, and eventually it becomes difficult to distinguish between them.

Some appreciation of geologic time is necessary for a proper perspective of weathering processes and effects, and for full realization that the soil is mankind's priceless heritage from past ages. Even after the bedrock has been broken up and decomposed, thousands of years are required for the development of fertile soil a few inches thick. Countless generations of plants must live and die, myriads of bacteria must run their life cycle, to supplement the physical and chemical weathering of rock material in the preparation of an agricultural soil. Once the humus-laden topsoil is swept away from a field, there is no way to repair the damage quickly, even with the most laborious and expensive addition of prepared fertilizers. The careless and ignorant waste of good soil in large areas of this country is appalling. Recent widespread interest in soil conservation is a hopeful sign that a concept of the soil as a precious and perishable national asset is growing in the public consciousness. Some of the methods used in soil conservation are described in Chapter 4.

Mass-Wasting at the Earth's Surface

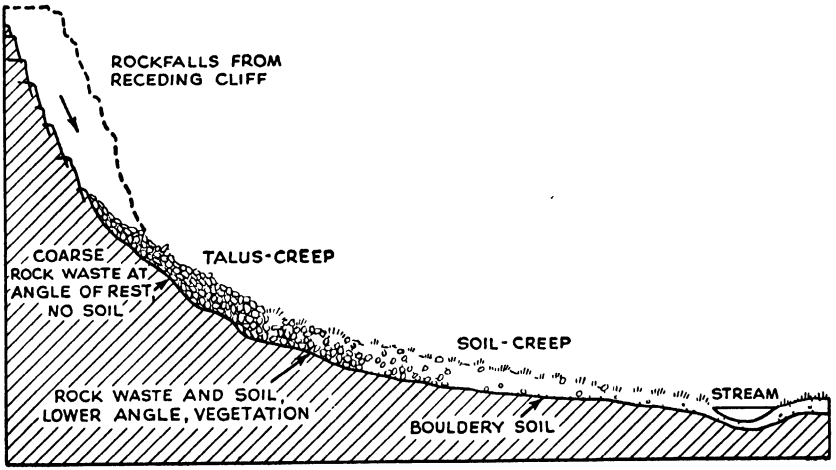
Weathering is essentially a static process; that is, the weathered materials remain where they are formed, unless they are removed by other agents, of which the most prominent are running water and the wind. However, there are important movements of the mantle, for the most part slow but locally rapid and even catastrophic, which are not directly dependent on the ordinary transporting agents and are closely related to the continued action of weathering. These movements, which are controlled directly by gravity, in large part escape notice because their average rate is imperceptibly slow; nevertheless they account for a large and essential part of erosion. Because the movements affect large masses of material as units, and because they are part of the general wasting to which all the lands are subject, the entire process including these movements is called *mass-wasting*.

Sliderock and Talus. When fragments are loosened on the face of a cliff they fall to the slope beneath, and by rolling or sliding reach a position of rest on the slope or at its base. There results a heap or sheet of waste called a *talus* (Fig. 27). This term applies to the entire body of rock fragments, as a unit; the material composing the talus is sliderock. Typically, the profile of a talus is a curve concave upward, steepening at the top to the maximum angle at which the sliderock will lie. In the upper part of a steep growing talus the fragments lie in

such delicate equilibrium that the weight of a climber may precipitate violent sliding.

In general, the freshest blocks of rock lie in the upper part of the talus. In time they are broken up and decayed, and the resulting fragments slowly migrate down the slope. In a moist climate the lower part of a typical talus merges into a soil-covered slope set with vegetation (Fig. 27).

Creep of the Mantle. As we look at a soil-covered slope closely set with grass or other vegetation, it is difficult to believe that anything is lost by erosion except for some mineral matter dissolved by water



Modified from Sharpe, "Landslides and Related Phenomena," Columbia University Press.

FIG. 27. A talus in typical relation to bedrock and lower soil-covered slope. The creeping mantle is slowly carried away as it reaches the stream, at the right.

percolating beneath the surface. Without first breaching the protective armor of plants to form gullies, running water can not begin an attack. Nevertheless the mantle under every such slope as this is moving downward, carrying the cover of vegetation with it. Usually the movement or *creep* is so slow as to be imperceptible, and the entire sheet of mantle moves essentially as a unit so that no breaks appear in the surface. The moving force is gravity. On even a moderate slope the weight of the loose material creates a tendency to slide downward. When the soil is soaked with rain the water in the pore spaces adds to the weight and also lubricates the mass, thus decreasing the friction. The force of gravity acts continuously, and, even if movement is almost infinitesimal in the course of a year, the cumulative results are very large. Our attention is forcefully drawn to the importance of the process whenever a building, like Durham Castle described previously, is endangered or destroyed by the movement.

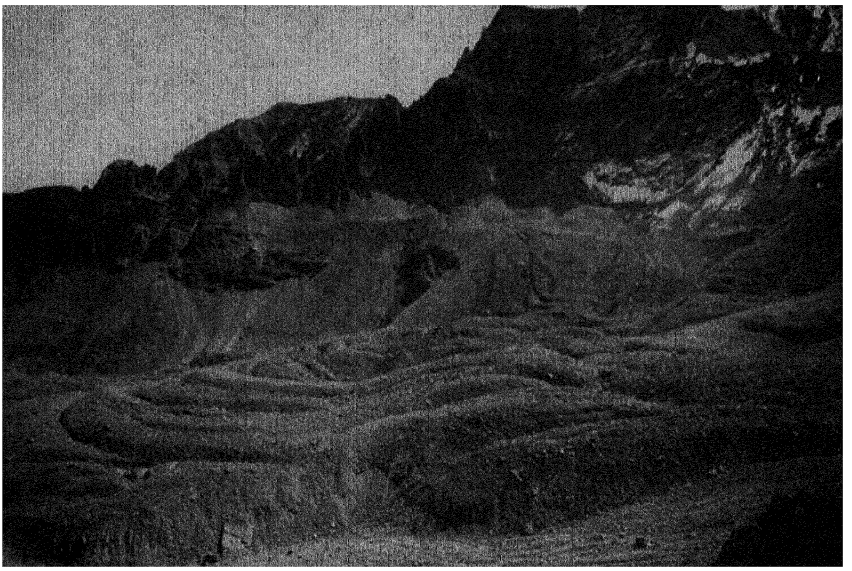
Soil-Flowage. A special form of creep is common in Arctic regions and in high mountains, where the ground freezes to great depth. In summer the upper part of the mantle thaws, while the lower part remains solidly frozen. Since the surplus water has no opportunity to drain downward, the upper unfrozen layer of soil, ranging in thickness from a few inches to several feet, becomes so saturated that it flows under its own weight, like a stiff liquid. This type of movement is called *soil-flowage*. One result is the mixing of soil with coarse rock fragments to form an unsorted mass of debris (Fig. 28).



R. F. Flint.

FIG. 28. Characteristic unsorted debris on a slope subject to soil-flowage. South side of Calispell Peak, northeastern Washington, at altitude 5000 feet. The section shown here, exposed in a recent road cut, is about 10 feet long.

Rock Glaciers. At the bases of exceptionally steep mountain slopes, sliderock accumulates rapidly, and in favorable locations masses of the debris take the form of rather definite "streams" that move slowly down slopes or valley floors. Freezing and thawing of water in such masses help the action of gravity in producing movement. From their general resemblance to valley glaciers (p. 130) these streams of rock fragments are called "rock glaciers." They are especially numerous in the San Juan Mountains of southwestern Colorado (Fig. 29).



WHITMAN CROSS, U. S. GEOL. SURVEY.

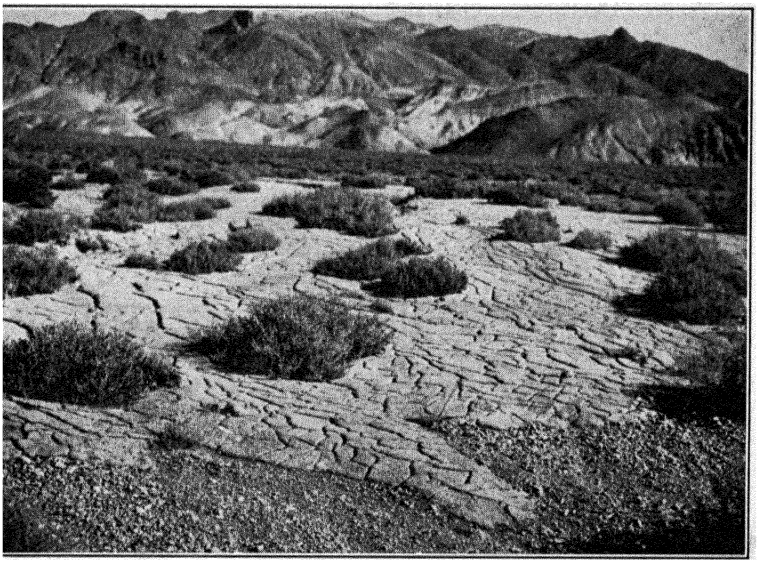
Fig. 29. A rock glacier in Silver Basin, Colorado. Slow movement of the rock debris is indicated by the pattern of ridges on the surface of the mass.

Mudflows. In arid and semiarid regions, fine rock debris becomes water soaked on steep slopes after heavy rains, and moves downward as *mudflows* (Fig. 30). Whenever such a flow originates in a narrow mountain valley, the forward part continues to gather debris until it becomes a stiff mixture incapable of rapid motion. This frontal portion acts as a slowly moving dam retarding flow of the more liquid upstream part of the flood, and the entire mass moves along haltingly, giving out a strange roar from the grinding and bumping of boulders carried in the muddy matrix. When a mudflow of this kind passes abruptly from the confining walls of a narrow valley into a much wider valley or onto a piedmont slope, the pent-up liquid behind the moving frontal dam breaks through with a destructive rush, and the slimy mass of debris spreads into a wide sheet, ruining fertile fields and wrecking houses. Boulders many feet in diameter are carried along, " bobbing like corks in a surf," and some of them reach isolated positions far from the mountain front.

Immense quantities of material have been spread out on lowlands by mudflows in rugged parts of Arizona, Nevada, and other western States. Recent mudflows in southern California have caused serious damage to farmlands and towns located on slopes near the mountains.

Landslides. On June 23, 1925, a mass of earth and rock estimated to have a volume of 50,000,000 cubic yards suddenly rushed down the

steep slope of Sheep Mountain, in the Gros Ventre Mountains of Wyoming, and formed a great dam across the Gros Ventre River 2000 feet below (Fig. 31). The impounded water of the stream rapidly formed a lake several miles long and 200 feet deep. Conditions on the south side of this valley favor landslides, several of which are known to have occurred at near-by localities before 1925. Water from rain and melting snow, sinking through the mantle and along cracks and pore spaces in the underlying sandstone, encounters a bed of shale



Eliot Blackwelder.

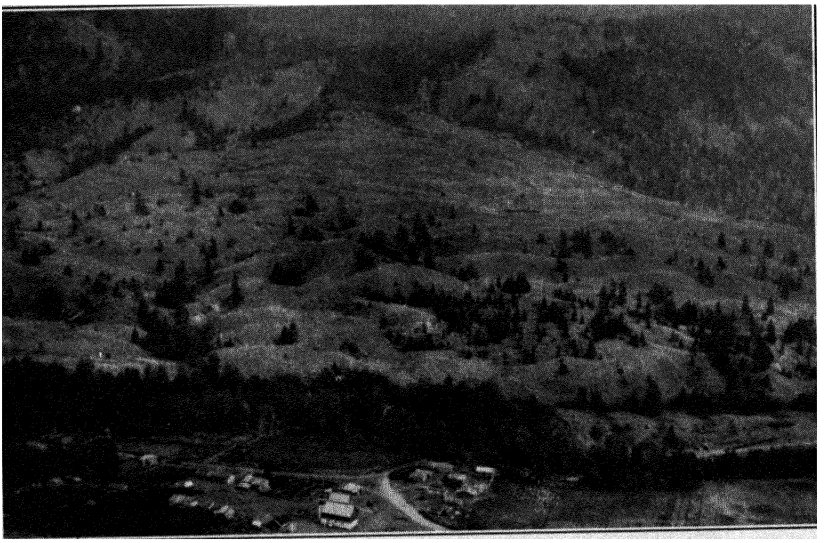
FIG. 30. Marginal part of a fresh thin mudflow. East base of the Stillwater Range, Nevada.

which is inclined toward the valley. Since the shale is impermeable, the water collects along the upper surface of the bed and softens the shale to form slippery clay. Locally the support is finally weakened, and a great mass of mantle and bedrock slides down along the well-lubricated bedding plane. Similar conditions have caused destructive slides in other mountainous regions. At Frank, Alberta, in 1903, a mass consisting of about 40,000,000 cubic yards slipped from the top and flank of Turtle Mountain and rushed to the floor of the adjacent valley. The mass of rubble spread entirely across the two-mile-wide valley, obliterating the town of Frank and killing 70 people. Similar disastrous landslides have occurred in the Alps, Himalayas, and other high mountains.



C. R. Longwell.

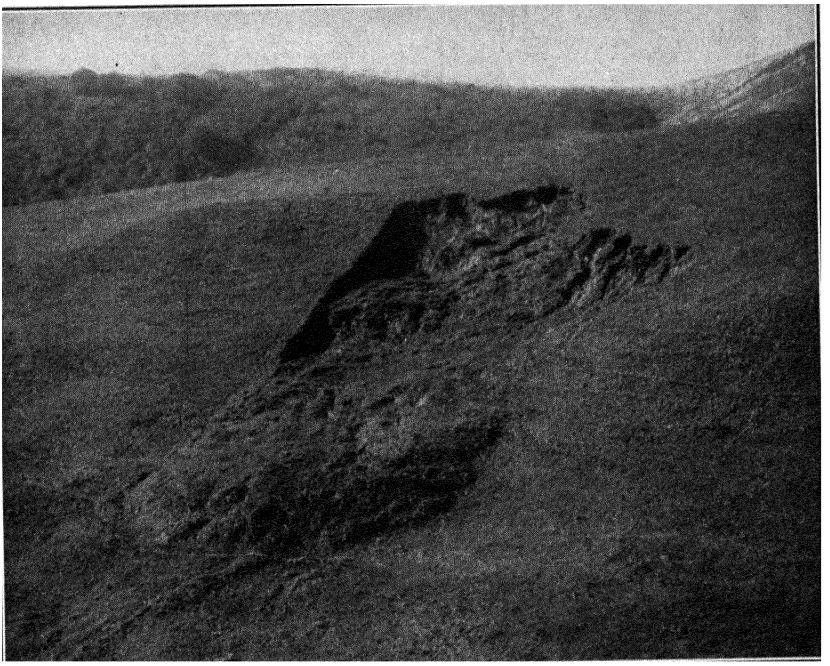
FIG. 31. The 1925 Gros Ventre slide, Wyoming, as seen from a point about 2 miles upstream. The head of the slide, just out of view at the left, is 2000 feet vertically above the valley floor. Momentum of the down-rushing mass carried its front far up the right side of the valley. The lake impounded by the slide, originally more than 200 feet deep, later had its surface lowered 60 feet as flood water cut a trench through part of the natural dam; the original higher shoreline is best shown on the far side of the lake, at the left.



Geol. Survey of Canada.

FIG. 32. Landslide topography along the Fraser River, Pavilion, British Columbia. The hummocky surface is a common feature of large slides.

Some great landslide masses move slowly and spasmodically for many years and cause little or no destruction. Exceptionally heavy rains or water from melting snow saturate the mass, adding greatly to its weight and decreasing friction by converting all clay and silt into mud. Such masses move by localized flowage at varying rates, and perhaps also by some sliding of the entire body of material. Trees



G. K. Gilbert, U. S. Geol. Survey.

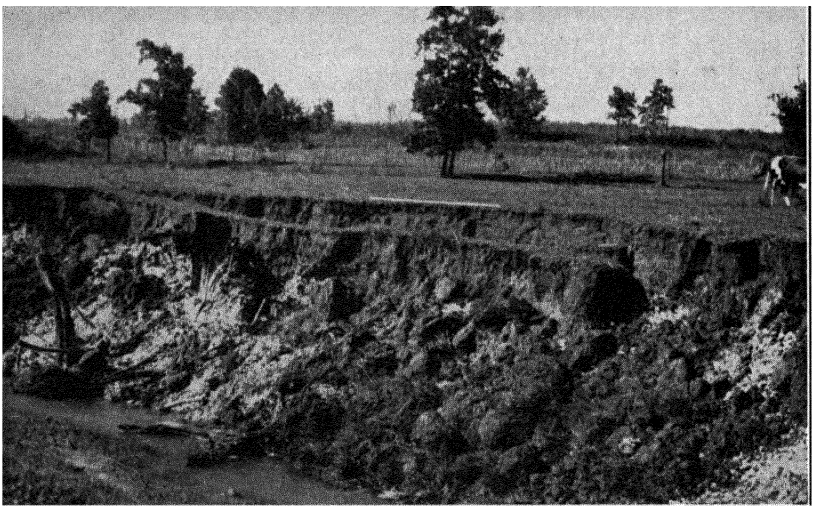
FIG. 33. Result of earth-flowage on a steep grass-covered slope after thorough saturation by heavy rains. Note the downslope bulge of the surface, compensating the depression made farther upslope. Berkeley Hills, California.

growing on one of these "chronic" landslides are likely to be tilted at various angles, and much of the surface has a characteristic hummocky topography (Fig. 32).

Other kinds of mass-wasting are more or less closely related to true landslides. Grass-covered soil on steep or moderate slopes sometimes starts flowing beneath the sod after thorough and deep saturation by water. Large bulges are formed downslope, and removal of support causes abrupt slumping, with breaking of the sod, on the upslope side (Fig. 33). Slumping of soil masses is a common occurrence along

stream banks that become steepened and perhaps undercut by flood water in the stream (Fig. 34).

Mass-Wasting and General Erosion. The evident net effect of mass-wasting in all its forms is to decrease the relief of the lands. In a general way the entire mantle of weathered material on all parts of the continents is sliding or creeping steadily from higher to lower



C. F. Stewart Sharpe, U. S. Soil Conservation Service.

FIG. 34. Slumping of subsoil and soil in the bank of a stream, near Spartanburg, South Carolina. The bank was undercut when the stream was in flood.

altitudes. The rate of this movement is greatest in the high, rugged mountains, least on the low, gently sloping plains; but the tendency is everywhere the same.

The several agents of erosion work together and react on each other in an intricate way. Most of the material moved in mass-wasting — sliderock, clay, soil, and other debris — has been produced by the weathering of bedrock. Break-up and decay continue while the debris is in transit, and in many ways these weathering processes contribute to the mechanism of movement. On the other hand, many of the movements in mass-wasting increase the efficiency of weathering. Migration of the mantle formed on hillsides exposes new bedrock to mechanical and chemical attack. Rock fragments moved in mudflows or landslides are broken by impact and grinding, and thus fresh surfaces are exposed. When great masses of bedrock are moved and broken up,

as in the Gros Ventre and Frank landslides, immense quantities of new material are made available to active weathering.

There is also a reciprocal relationship between mass-wasting and the work of streams. When gullies are cut into slopes, many of the steep banks slump, and creep is promoted in the adjacent mantle. The most active mass-wasting, by sliding and creep, takes place on the sides of deep mountain valleys that have been formed by stream cutting (supplemented by glacial erosion, p. 135). On the other side of the

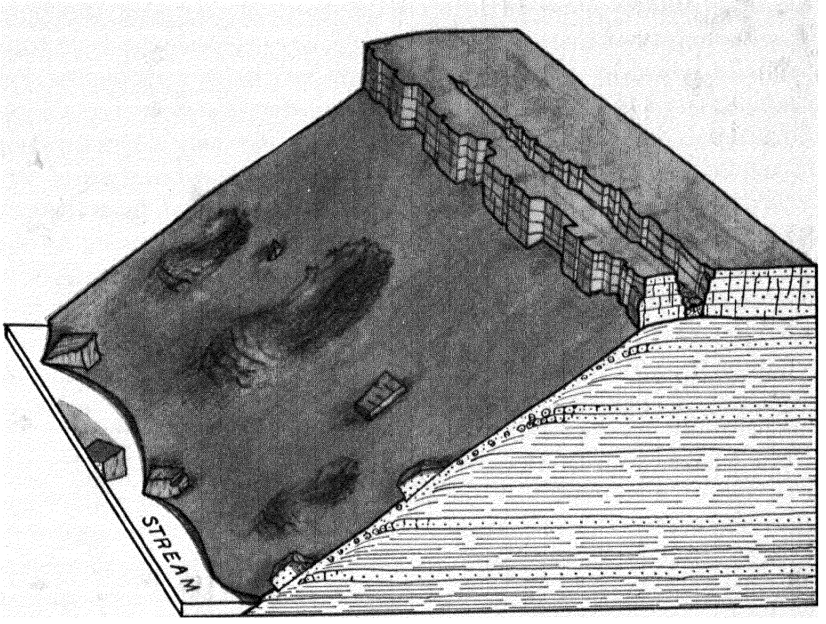


FIG. 35. Segment of one side of the Cheat River valley, West Virginia. The steepness of the slope causes exceptionally active creep of the mantle, with local sliding and flowage. The thick sandstone layer at the top is weakened by vertical joints parallel with the valley. As the mantle moves away from the base of the cliff and the weak shale directly beneath is softened by water, long blocks of the sandstone separate along joints and move slowly outward, tilting more and more with the slope. Smaller blocks are detached from time to time, and many of them roll down to the stream. As the creeping mantle reaches the foot of the slope it is carried away by the stream. The slope is not gullied because it is protected by a dense cover of vegetation, not represented in the sketch. (Not drawn to scale.)

ledger, a large part of the mud, sand, and gravel carried by streams and ultimately spread out on the sea floor is delivered to the streams by creep and other forms of mass-wasting. The supplementary action of the several agents is readily seen in any deep, narrow valley (Fig. 35). Mantle moved down the valley side by creep, slumping, and soil-flowage is cut away and removed as it reaches the stream. As this action continues, the slope becomes longer and less steep. Thus mass-

wasting is an important agent of valley widening, a process in which the stream also takes part by its lateral cutting (p. 88).

Mass-wasting is further explained and illustrated in connection with processes discussed in following chapters.

Practical Aspects of Mass-Wasting. Great quantities of rich soil are lost every year through the combined operations of mass-wasting, running water, and wind. Soil conservationists find it simpler to check the destructive effects of slope wash and gullying than to control the large masses of earth involved in creep, sliding, and slumping. There is hope that some of the most immediate problems can be at least partially solved by combination of direct and indirect methods. For example, in parts of the semiarid West and Southwest overgrazing of range lands has greatly increased the frequency and destructiveness of mudflows, which not only strip the topsoil from large areas but, after mixing this soil with unproductive clay and gravel, bury the rich topsoil of lower areas under the infertile mixture, thus ruining all the ground affected by the movement. The only effective remedy is to restore the protective sod, a remedy that requires a comprehensive program to prevent the recurrence of overgrazing. Slumping of farm lands adjacent to deep gullies can be checked by measures, now extensively practiced, leading to gradual filling of old gullies and prevention of further gully development (p. 82).

Knowledge of principles governing mass-wasting is essential in the selection of successful sites for large buildings, dams, and other engineering works. The St. Francis dam in California, which failed with appalling loss of life and property (p. 352), had one of its abutments in ground subject to sliding — a fact that should have been recognized at the time the dam site was selected. Some engineering works have to be constructed in spite of difficulties from mass-wasting. Landslide masses are sometimes stabilized by piercing them with drainage tunnels to remove water that plays an essential part in the movement.

Private companies and governmental bureaus are put to enormous yearly expense in repairing and rebuilding railroads, highways, aqueducts, and other large works that are injured by landsliding and creep in rugged country.

Summary

All rocks at the Earth's surface are subject to break-up and decay by weathering. Part of the resulting debris remains essentially in place for a long time; but much of it is carried far away by water, wind, and other agents of erosion. The most important part of the mantle, from the human viewpoint, is soil, which develops very slowly through

extreme decomposition of rock material, aided by contributions from plants and from bacterial action.

Climatic conditions have a strong influence on the rate of weathering and on the nature of the resulting products. In arid, arctic, and high-altitude regions disintegration of rocks is effective, but there is little decomposition. Humidity and warmth are essential for development of abundant good soil. Nature of the bedrock and relief of the land are other important controls of weathering.

Aside from transport of mantle by water, wind, and other common agents of erosion, there are movements, in large part almost imperceptible, affecting large bodies of debris *en masse*. Creep, landsliding, and various types of earth-flowage are the chief forms of this mass-wasting, which plays a large part in reducing the height and relief of land masses. Weathering and mass-wasting are closely interrelated with streams and glaciers in the task of eroding the lands.

Chapter 4

RUNNING WATER

Streams Cut Their Own Valleys. Stand on the brink of the Grand Canyon of the Colorado, and look down at the winding river a mile below. The rock-walled canyon is impressively vast, and, by contrast, the stream at its bottom seems puny. So large is the canyon that those who first speculated on its history thought that the river had found this low-level course already prepared for it by a great gash or rift earlier opened by some cataclysm in the Earth's crust. But today we are convinced that the Colorado once flowed through a shallow trough at the level of the canyon's brink. We can see that very gradually the sediment-laden water cut down through the underlying rocks, sawing ever more deeply. As it did so, waste crept and was washed down the sides of its valley, making the valley wide. In the course of time these processes dug a trench a mile deep and eight miles wide at the top.

The key to the matter is the tremendous load of sediment carried by the Colorado. Although the river looks like a bright ribbon from the canyon brink, a closer view shows it to be very muddy. In addition to the mud there are stones rolled along the river bed, and also dissolved solids which are hidden from the casual visitor. All these solids taken together add up to more than 11,000 tons per hour, 24 hours a day, 7 days a week, year in and year out. An endless train of gondola cars, each loaded with 25 tons of sediment, moving past the Kaibab Trail crossing at the rate of one car every ten seconds, would hardly be able to keep up with the Colorado as a carrier of mud and stones.

Where does this vast quantity of sediment come from? It has crept and been washed off every hillslope within the whole vast area of 230,000 square miles drained by this river and its network of tributaries. Every hill is being continuously weathered, and the resulting rock waste is imperceptibly creeping toward the Colorado. If we calculate the volume of sediment carried off by the river each year, and apply it to the entire area drained by the river system, we find that the whole surface of this 230,000 square miles of country is being lowered at the average rate of one inch every 440 years. To be sure, this period amounts to many times the span of life of one man. That this fact must be pointed out merely shows what an egocentric point

of view most of us have. The significant thing is that the whole Colorado River valley system — not only the mile-deep main canyon itself but every tributary valley throughout the whole vast drainage area — could, at such a rate, have been excavated well within the last million years, and that the Earth is thousands of times older than that.

Next, from your observation point on the brink, look at the intricate pattern of canyons and subcanyons which, arranged like the veins in a leaf, join the main valley, most of them entering the main stream at its own level. Such relationships could not have developed by chance; they must have grown up by systematic evolution, in obedience to a definite set of natural laws. This must indeed be the case, for the same relationships are found again and again in stream systems large and small throughout the world.

How Streams Begin. Rain (together with snow) falling on the land is the ultimate source of stream water. The amount varies greatly from place to place — 2 inches in a year at Death Valley, California, 30 inches at Chicago, 40 inches at New York City, 500 inches on the southern slopes of the Himalaya Mountains — and the number of streams and their flow vary correspondingly. Of course not all the fallen rain flows off at once as surface streams. Part of it evaporates and part of it percolates into the ground; its travels underground are described in Chapter 6. But some of it starts off down the surface slopes, beginning as thin sheets of water (*rainwash*) and soon concentrating into little rills and then into sizable streams, each occupying a valley either excavated or modified by itself.

Stream Flow. Every *stream* (defined as water and rock waste streaming toward the sea along a more or less definite course) occupies a channel in the floor of its valley. The amount of water that flows through it is controlled by its gradient (rate of downstream slope) and by its size and shape. Furthermore, the gradient, size, and shape of the channel are themselves influenced by the amount of water in the stream, so that all four factors may be truly said to be not only related to each other, but also mutually adjusted to each other. This explains why nearly all rivers have slight flow and small channels in their headwater areas, and large flow and capacious channels near their mouths.

Not only does a stream adjust its channel from place to place; it also has to alter its channel from time of rain to time of drought. Detailed measurements show that in the Mississippi River, just downstream from the mouth of the Ohio, the *normal* rise of the water surface during spring floods is about 40 feet! At such times the river greatly lowers its bed by scour; so the actual increase in channel size is much greater than this water-surface measurement alone would indicate. The flood

itself is essentially an upward bulge of the stream's surface analogous to the bulges in the surface of the sea caused by the tides (p. 171). This is clearly shown by government-maintained stream gages installed along a river. Each rises gradually to a high point as the crest of a flood passes it, and then it slowly descends.

A stream channel therefore behaves somewhat like an accordion of unusual shape, as it expands and contracts in delicate response to the changing flow of water through it.

Stream Erosion and Deposition

Forces at Work. If we watch attentively a stream at work on the rock fragments of all sizes that fall within its grasp, we can resolve its activity into four separate though related factors:

1. The *hydraulic action* inherent in its flowing motion is able to churn up and wash away loose fragments, their size depending on the strength of the stream.

2. The hydraulic churning causes rock fragments to rub, knock, bump, and scrape each other, and to scour the rocks in the stream bed. This is *abrasion;* it wears down the rock fragments, making them gradually smaller, smoother, and rounder (Fig. 155). A conspicuous effect of abrasion consists of bowl-shaped or cylindric *potholes,* ranging from a few inches to many feet in diameter and depth, in the rock beds of many swift streams. Most potholes are excavated by rock fragments swirled about by eddies that stay in the same positions for considerable periods of time.

3. The water in a stream causes some *solution* of the rocks — especially limestone — with which it comes in contact. However, only a little of the matter dissolved in stream water has been dissolved by the streams themselves. By far the greater part of it was dissolved by subsurface water (Chap. 6) which later percolated into the surface streams.

4. The rock waste carried by the stream — the stream's *load* — is in *transport,* and this is another aspect of the stream's hydraulic action. To watch a stream is to notice at once that its flow is turbulent, greater near the center than near the sides, and always including numerous cross-currents and eddies. Therefore loose rock particles on the bottom are lifted and kept in suspension by repeated tossing as they are carried forward. The smaller and lighter particles are tossed up more easily and frequently, and so travel farther downstream than the larger and heavier pieces. The largest are slowly rolled or pushed along the stream bed. The result is that the distance through which a rock fragment is transported by a stream depends chiefly on its size and weight. This brings about a sorting of the deposited load of a

stream (p. 195), and constitutes one of the reasons why the beds of some streams are stony near their heads and sandy or muddy near their mouths.

Transport and *deposition* go on simultaneously in every stream, and, although it is easy to recognize them as distinct factors, it is simpler to think of them as together forming a continuous single activity.

Velocity, Erosion, and Transport. Having in mind the above four factors that operate in every stream's handling of its load, let us see what happens when velocity is increased in times of flood. Under ideal conditions, doubling the velocity may (1) increase abrasive power about 4 times; (2) increase the capacity to transport rock fragments of a given size by as much as 32 times; or (3) increase the volume of the largest piece of rock the stream can push along its bed by as much as 64 times.

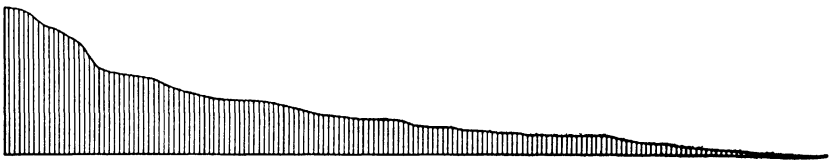


FIG. 36. Long profile of the Lehigh River and its continuation through the lower Delaware River to the sea, illustrating the general concave-up form of its curve. Baseline = sealevel. Long dimension, 120 miles. Elevation of stream at top of profile, 820 feet. Vertical exaggeration, 132 times. The irregularities in the profile are caused by unequal resistance of the rocks to erosion and possibly by other factors.

These powers are calculated to result from merely doubling the velocity. Actually the Mississippi, in flood, more than doubles its velocity at many points. Under flood conditions, other large streams are known to increase their mean velocities ten or twenty times! From this it is clear why flood damage is great, and why most streams perform the great bulk of their eroding and transporting chiefly during floods, and most of their depositing as the floods subside.

Baselevel. A stream continues to erode its bed until it reaches the sea. Here its current is checked, preventing further downcutting. The sealevel, therefore, is a level below which, in general, streams can not cut; and this level, projected inland as an imaginary plane beneath the surface of the land, is termed *baselevel,* because it is the base that limits the deepening of valleys by streams.

Long Profile. The continuous curve formed by the slope of a stream from source to mouth is its *long profile.* Although the long profile of a newly formed stream is the profile of the land surface itself, the long profile of a well-established normal stream is a curve concave up (Fig. 36). This curve results from adjustment of each part of the

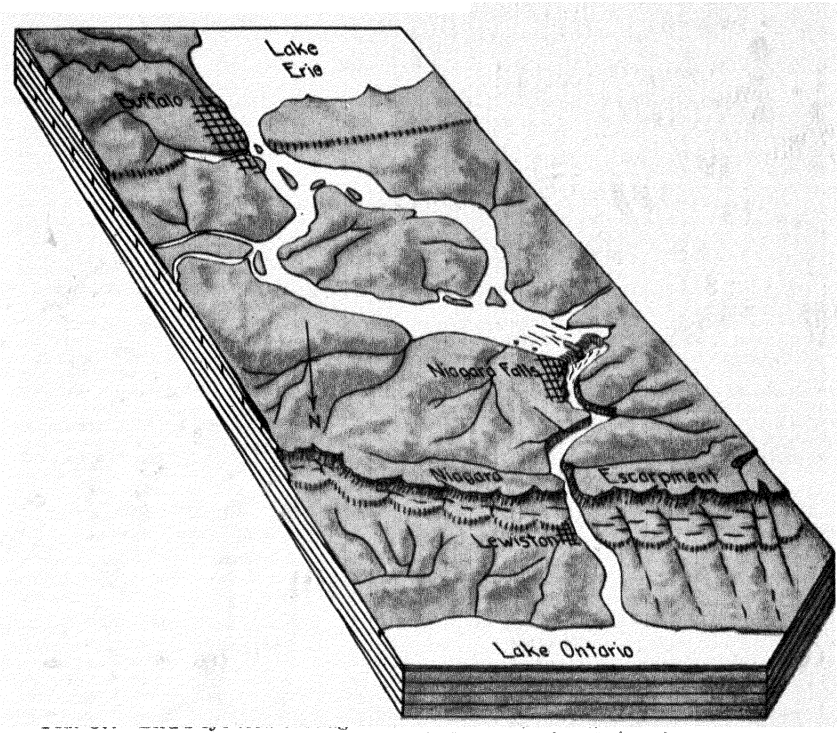
profile to the conditions in the corresponding part of the stream. In its upper course the amount of water in the stream is relatively small, but, owing to the usually steep initial slope of the land, the gradient is steep. The stream is not fully loaded; hence most of its energy is applied to downcutting. In its lower course the amount of water is much greater; for this reason and because the load is finer grained, the stream can move its load on a gentler gradient, and downcutting is at a minimum. Intermediate conditions obtain at intermediate points; hence the gentle slope downstream gradually becomes a steep slope upstream. Of course the long profile becomes gradually less steep throughout its length as the stream cuts down toward baselevel.

The Graded Stream. The energy inherent in a flowing stream is used up in eroding its bed and in transporting its load. But as the stream lowers its bed by erosion during the earlier stages of excavating its valley, two things happen: The load is gradually increased, requiring additional energy for its transport, and (because baselevel at the stream's mouth is a fixed point) the gradient is reduced, thereby decreasing the energy of stream flow. The inevitable result is that erosion of the stream bed is retarded just enough to enable the stream to transport its load on a smooth gradient. The stream is then said to be *graded,* and, if no drastic changes upset it, this condition will be maintained indefinitely, as the stream very slowly reduces its gradient.

When a part of a main stream reaches the graded condition, the tributaries soon become graded with respect to it. This is because the main stream acts as a kind of temporary baselevel, below which the tributaries can not cut. When downcutting by the main stream slackens, downcutting by its tributaries has to slacken also.

Falls and Rapids. Falls and rapids in a stream are clear evidence that the stream is not graded. They occur at points where a stream's gradient is abruptly steepened, either where the stream falls over a previously existing cliff, or where it passes from resistant rocks on to weak rocks that are easy to erode. Niagara Falls, for example, was formed by a river that fell over a ready-made cliff (p. 154). The Niagara River, originating as the outlet of Lake Erie at Buffalo, flows over a plateau that ends near Lake Ontario in an escarpment (Fig. 37). At the surface of the plateau are layers of resistant dolomite, and underneath are weak, easily eroded shales (Fig. 38). When the river came into existence by the overflow of Lake Erie, it flowed across the plateau and tumbled over the escarpment at Lewiston, forming a falls. As the falling water gradually undermined the weak shale at the base of the cliff, the resistant dolomite above was left projecting as a lip, which, left unsupported and penetrated by cracks and fissures, fell

away block by block. Through long continuation of this process the falls perpetuates itself and gradually retreats upstream, leaving a great gorge downstream to mark its path. It has now moved 7 miles back from its original position and is still visibly retreating. Thus on January 17, 1931, a large mass of rock at the lip of the American Falls



of block, 35 miles. (Vertical exaggeration, 2 times.)

was undermined and fell, leaving the lip greatly altered. Similar masses weighing thousands of tons fell from Horseshoe Falls on August 13 and December 5, 1934, and in September, 1938.

Not all falls, however, were formed by ready-made escarpments. More rapid erosion in weak rock than in resistant rock lying immediately upstream will result, at the contact, in a steepening of the gradient that may become a falls.

It is worth repeating that falls and rapids occur only where streams are not graded. When a stream becomes graded, sharp irregularities in its long profile, such as falls and rapids, are necessarily smoothed out and destroyed.

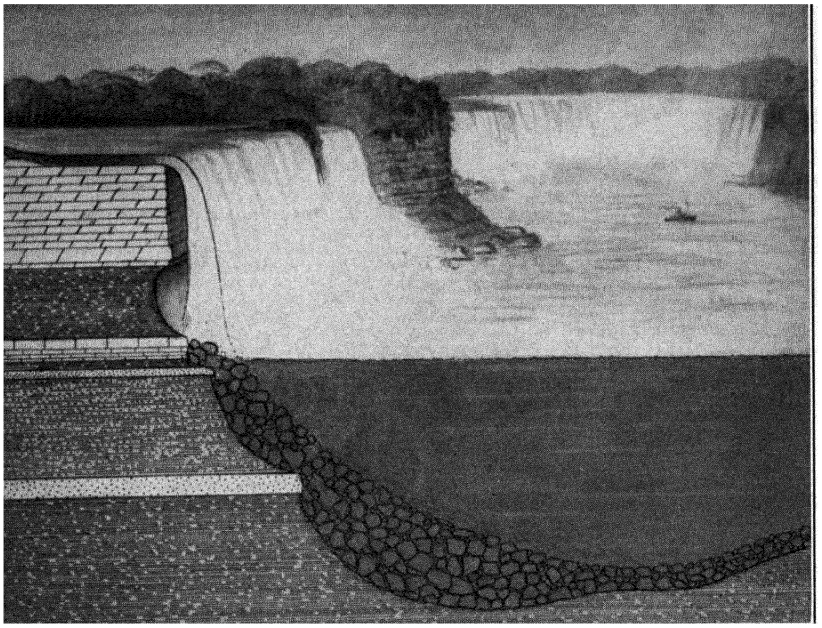


FIG. 38. Relation of Niagara River to bedrock at the Falls. Section shown is on the northeast edge of the American Falls. Goat Island in middle distance; Horseshoe Falls in background. Conditions below surface of Niagara River are partly inferred; probably the gorge was excavated chiefly by the Horseshoe Falls rather than by the smaller American Falls. The overdeepened part of the valley is a *plunge basin*, excavated not by the comparatively weak American Falls but by the more powerful Horseshoe Falls before it had receded to its present position.

STREAM DEPOSITS

Stream deposits (or, as they are often called, *alluvial deposits* or *alluvium*) are of many different kinds, even along a single stream. They are of great importance to geologists and engineers concerned with river navigation, flood control, power dams, and similar projects. Stream deposits are closely studied for another purpose: Similar deposits that have become buried and converted into firm rock, thereby constituting an integral part of the Earth's crust, can be recognized and identified as having been made originally by streams; this leads toward an understanding of the geography of the time when such a deposit was made.

In the study of a stream deposit two main things are determined: (1) the external form and position of the deposit as a whole, and (2) the internal character of the deposited sediments.

Position and External Form of Stream Deposits. In the slack water just inside a bend in a stream, deposition occurs, thereby narrowing the channel and causing the current to erode the opposite bank at the outside of the bend. Continuation of this process results in shifting of the bend and spreading of a veneer of deposits, which in

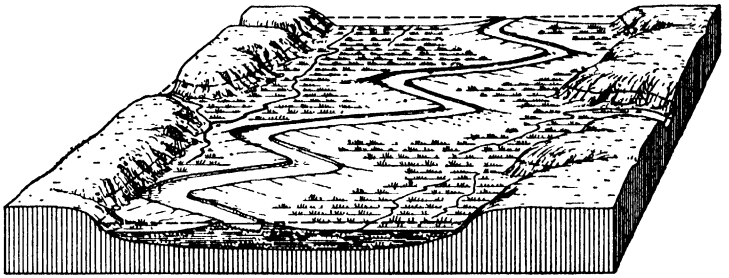
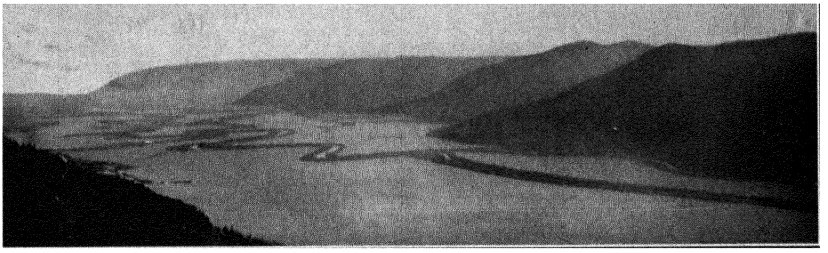


FIG. 39. Valley floor with natural levees bordered by swamps. The vertical scale is exaggerated, and the stream and levees are shown larger in proportion to the width of the valley than they would normally be. Dashed line shows position of water surface in time of great flood.

time may cover the entire valley floor. Such deposits are no thicker than the stream is deep.

A stream that overflows its banks in seasonal floods deposits sediments in another way. The overflowing water rapidly becomes shallow, and its velocity is quickly reduced, causing deposition of sand



Geol. Survey of Canada.

FIG. 40. Valley of the Kootenay River, British Columbia, during a great flood. The valley floor is entirely under water except for the trees growing on natural levees along the main channel.

and silt (p. 190) along the immediate borders of the flooded channel. These deposits consequently take the form of low ridges (natural levees, Figs. 39, 40) that remain after the flood has subsided. The ridges have heights of 4 or 5 feet up to 15 feet or more, and, although they are the most pronounced visible features of some valley floors, their heights

are small compared with the depths of the channels. In the course of flood deposition the valley floor becomes covered by a thin mantle of fine sediment deposited from the somewhat lake-like shallow flood water. Such deposits as a rule form very fertile soil.

The part of a valley floor that is subject to floods is termed a *floodplain.* The Mississippi River has a floodplain which, including the natural levees and the low swampy lands beyond their outer slopes, formerly covered an area of 35,000 square miles, but has been reduced by artificial means to about 25,000 square miles.

During the low-water stage, many streams heavily loaded with fine sediment, or losing volume by evaporation or by percolation into their beds, choke up their channels with deposits; they then overflow and cut new channels, which in turn become rapidly choked. This process is termed *braiding,* because it develops an intricate network of shallow channels that form a complex pattern on the valley floor. Many streams in dry regions (for example, the South Platte River in western Nebraska) and streams of glacial meltwater heavily loaded with sediment are intricately braided (Fig. 107). The fact that a stream fills its channel with deposits at low water does not imply that the valley floor as a whole is being built up, because during a flood stage the stream may remove more rock waste than it deposits during a low-water stage.

Deltas. As the current at the mouth of a stream is checked by the standing water of the sea or a lake, the load drops to the bottom, gradually building an embankment that grows outward like a railroad or highway fill made by dumping. As the fill is built up close to the water surface, deposits usually encroach upon it from upstream, are distributed outward, and gradually cover it, making a crudely triangular area of new land with one apex pointing upstream. From this shape resembling the Greek letter Δ (*delta*), the deposit derives its name (Fig. 41).

The stratification of an ideal delta consists of three units which are shown best in small deposits built in relatively deep water. Here deposition is most rapid on the outer slopes, forming thick *foreset beds* sloping outward (Figs. 41, 42). Fine sediment is carried farther out and forms thin *bottomset beds.* Along the top, where erosion and deposition alternate as the stream current fluctuates, thin *topset beds* are laid down.

A stream that rises in flood and spills over the natural levees is likely to break through them at weak places. The current at the breakthrough flows down the outer slopes of the levees (these slopes are much steeper than the gradient of the main channel) and continues

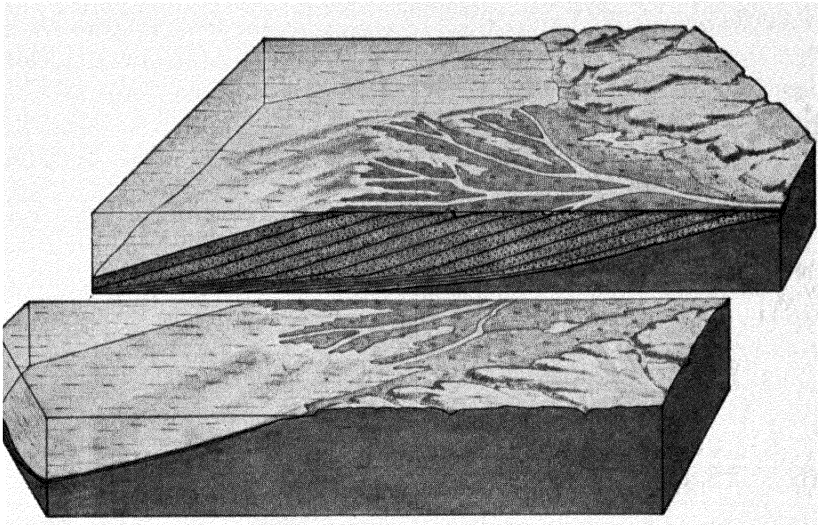
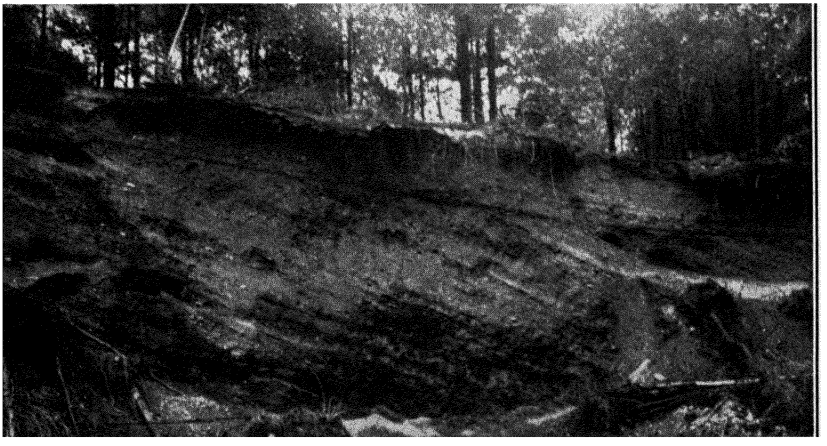


FIG. 41. Ideal small delta in three-dimensional view. On the surface appear " delta fingers " formed by deposition from distributary streams. The block has been cut in two and the pieces pulled apart to reveal a vertical section of the delta. Thick, inclined foreset beds are underlain by bottomsets and overlain by topsets. The topsets are represented only by the thickness of a single line, because they are commonly very thin. The slope made by the uppermost foreset bed is shown in phantom view, through the water. (Vertical scale greatly exaggerated.)



R. F. Flint.

FIG. 42. Section of small delta deposited in a glacier-dammed lake that existed during the Ice Age. Shows foresets and topsets only. Parkhill, New Hampshire.

along new routes, leaving the old channel with diminished flow. New channels repeatedly formed make a branching system of *distributaries* that give the delta its characteristic shape. Between the distributaries lie shallow basins which fill with fine sediment during floods and are thus converted into low land.

The Mississippi Delta, one of the greatest in the world, is in reality a complex of several coalescing deltas that have been built successively and continuously during the last several thousand years. The building

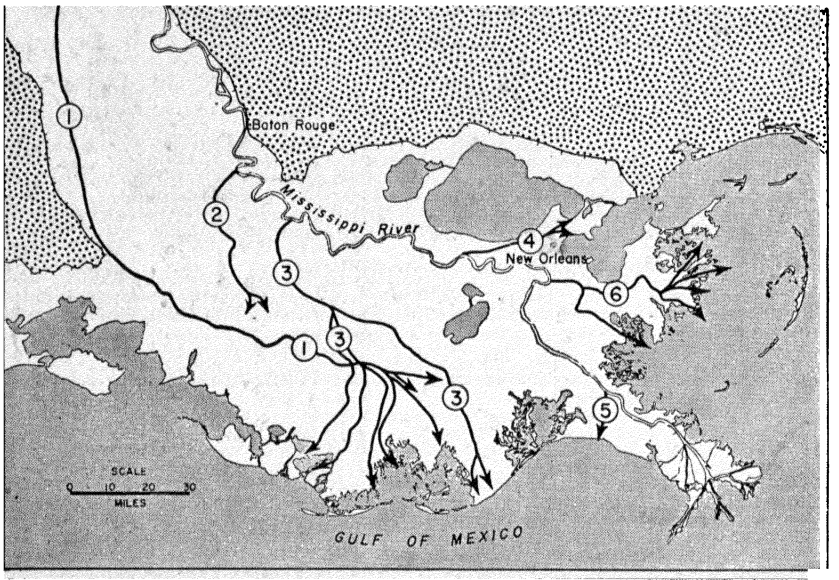


FIG. 43. The Mississippi delta and its surroundings, in Louisiana and Mississippi. White area represents delta and floodplain. Heavy-stippled areas are higher lands. The numbers refer to successive distributary routes used by the Mississippi River during the last several thousand years, as interpreted by R. J. Russell.

of each individual unit was begun at the time of some break-through and diversion that became permanent. Figure 43 shows the sequence of main distributaries inferred mostly from abandoned systems of natural levees.

Fans. When a swift stream flows down from high land on to a wide and nearly level valley floor, the abrupt change in its gradient causes it to deposit immediately the greater part of its load. In this way a *fan* is built up, radiating outward from the point at which the stream emerges (Figs. 44, 45).

The fan acquires its shape because of the nearly uniform distribution of rock waste over its surface by the stream that builds it. The stream



SPENCE AIR PHOTOS.

Fig. 44. Fans being built out into Death Valley, California, from Black Mountains (left). View south from Furnace Creek Ranch (right foreground), showing Death Valley, a closed basin with a white salt-incrusted playa, and the Panamint Range inclosing the basin on the west (right). The relations shown here are essentially those portrayed in Fig. 66.

repeatedly chokes up its channel, overflows, and forms new distributaries, just as in the braiding process. When one sector of the fan has been built up, the stream shifts to another and lower sector, and builds that up. In this way the entire surface becomes covered by deposits laid down by the stream, and the fan as a whole is remarkably symmetrical.

Upbuilding of the fan steepens a part of the long profile of the tributary stream. This continues until the gradient has been made steep enough to enable the stream to transport its load down the fan. The radiating profiles of the fan thus become graded profiles.

Fans are larger and more common in regions of high relief at points where streams emerge from very steep slopes on to plains than in regions of low relief and gentle slopes. In the mountainous parts of western North America some of the fans are tens of miles in radius and hundreds and even thousands of feet in thickness. East of the Rocky Mountains, fans are less conspicuous and are confined chiefly

to the bases of very steep slopes such as the sides of valleys that have been kept steep through lateral cutting by their streams.

Internal Character of Stream Deposits. Whatever their original shapes, stones and smaller particles transported by streams become rounded (Figs. 122, *C*; 155) through the abrasion they undergo as they are rolled and tumbled by the shifting currents. Rock fragments handled by the wind and by sea waves are likewise rounded, and for the same reason; consequently the fact of rounding does not necessarily imply stream origin.

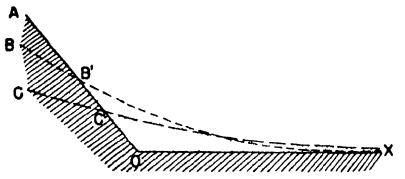


FIG. 45. Vertical section showing growth of a fan. Bedrock is shaded; stream deposits are stippled.
AOX = Profile of surface before fan deposition.
BB'X = Long profile of stream at an early stage of fan building.
CC'X = Long profile at a later stage, after the stream has become graded. In the grading process, the stream has cut away the original upper part of the fan, in addition to cutting away much bedrock upstream from the fan.

Because of the delicate adjustment of transporting power to the sizes and weights of the rock fragments that form the load, stream deposits are sorted according to size and weight (and therefore composition) of the rock fragments (p. 195). Layers of pebbles of various sizes are usually separated from layers of sand, and these in turn are sorted out from layers of silt and clay. No one layer extends far, however, because the variability of stream currents, repeatedly changing the conditions of deposition, results in thickening and thinning of the layers, and causes them to lie at angles inclined to each other (Fig. 105). This arrangement gives rise to one kind of *stratification* (p. 195).

Lake currents, sea waves, and flowing air (*i.e.*, wind) likewise stratify the sediments that move. However, the varieties of stratification are many, and, with some exceptions, those varieties produced by streams can be identified as such.

THE PROBLEMS OF SOIL EROSION AND FLOODS

Soil Erosion. Of the agricultural land in the United States, nearly one-third has lost much of its topsoil, an additional third has lost all its topsoil, and one-eighth has been wholly destroyed by erosion. These are staggering figures, not only because of their size, but because they refer to the nation's basic natural resource — the soil. After two decades to two centuries of cultivation (depending on the location) man has destroyed much of what had been built up by natural processes through thousands of years. The big rivers had always carried sedi-

ment to the sea, but at a rate that was balanced by the slow creation of soil by weathering.

Then came the pioneer. He — and his successors — cut down forests, drained swamps, plowed the sod. The rain battered the ground unimpeded by the protecting leaves of trees, and ran down bare slopes no longer checked by grass. The whole complex process of moving the rainfall to the sea was sped up and made disastrously rapid, as increased velocity increased the capacity of the running water (Fig. 46).



U. S. Soil Conservation Service.

FIG. 46. In this field near Bethany, Missouri, corn was planted in rows that ran downslope instead of along the contour. After a heavy rain gullies developed, 4 to 5 inches deep, through which the field as a whole lost an average of 2 inches of topsoil. Such damage can be prevented by proper methods of cultivation.

But the damage does not end on the hillslopes. Its effects are felt far beyond the places where the trouble begins. The great quantity of sediment washed into the streams buries agricultural bottomlands, silts up reservoirs, destroys fish life, and pollutes water supplies; and the too-rapid runoff of rainwater, no longer adequately delayed by percolation through the ground, heightens floods on the big rivers to disastrous figures.

Soil erosion can be checked, and the normal conditions that existed before the damage began can be restored, by widespread adoption of conservation measures, among which are the following:

1. Retirement of lands which should never have been deforested or plowed, and which must be returned to their former condition without delay.

2. Soil-protection measures, aimed at slowing down the flow of water on slopes. These include:

a. Terracing the slopes.

b. Plowing and cultivating "row crops" such as corn and cotton only *along* the contour — not up and down the slope.

c. Planting strips of thick-growing crops (hay or grain) alternately with row crops along the contour, and staggering the seeding dates so that the entire slope is never bare.

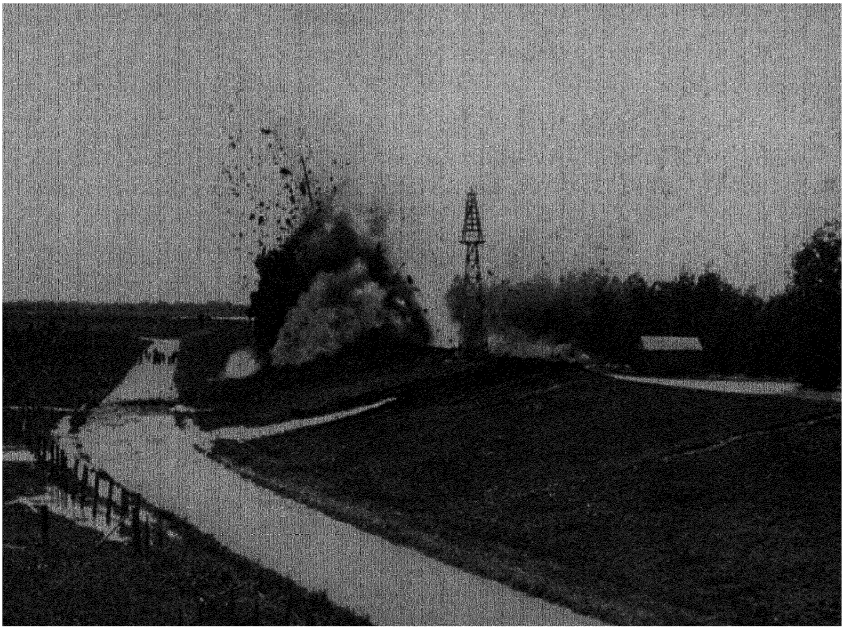
d. Rotation of thick-growing crops with row crops so as to permit small gullies to heal.

3. Curative measures, such as the healing of gullies by planting quick-growing vines and the building of check-dams, and the proper draining of roads on slopes.

Destructive Floods. Prior to the settlement of North America, the Mississippi and other large rivers were subject to annual floods that inundated broad areas beyond the immediate stream channels. Early in the eighteenth century attempts were made to confine the flooded Mississippi to its channel in order to protect new settlements and to

U. S. WEATHER BUREAU.

. 47. *Dynamiting an artificial levee on the flooded Mississippi River at aernarvon, Louisiana, in order to give an additional outlet to the river to reduce he flood height. River is shown at right; the road and lowland on the left were mmediately inundated.*



reclaim for agricultural purposes the floodplain. These attempts took the form of stout embankments (artificial levees, Fig. 47) which were built on the tops of the natural levees. Now if a given flow of water is confined to a narrowed channel and is thus prevented from normal flood-time spreading, the depth of the channel must be increased. Much of this additional depth is attained locally by increased erosion of the bed, but part of it is attained by rise of the water surface. Hence whenever a new levee is put in, those already in existence must be raised. The first levee, built at New Orleans, was 4 feet high. Today the average height is 18 feet. In 1902 there were 1300 miles of these levees along the Mississippi; in 1927 there were more than 1800. The river at flood stage is gradually rising higher above the adjacent basins, so that when breaks occur they are correspondingly more destructive. Witness the disastrous flood of 1927 in which the swollen river broke through the levees in 225 places and inundated 18,000 square miles of inhabited land.

Through more than 100 years each big flood on the Mississippi has been more disastrous than the last. It seems probable that this is largely the result of deforestation, artificial drainage, and improper agricultural practices throughout the huge region from the Appalachians to the Rockies that contributes water to the Mississippi. Even if such evils were not enormously harmful in themselves, the protection of the lower Mississippi basin would be sufficient reason for curbing them. Levees can not be built to withstand floods of ever-increasing magnitude, but probably they are capable of confining the normal floods which we could expect once again if drastic and far-reaching conservation measures were applied to the tributary region. In the meantime the extensive flood-control plan now under way recognizes the need of additional means of combating floods, among which are the building of dams on tributary streams, and the establishment of permanent overflow channels along old delta distributaries, to act as safety valves for regulating the height of flood stages.

Summary

Streams are the product of rainfall. They cut their own valleys, and by erosion, transport, and deposition they continuously adjust their channels and their long profiles to ever-changing conditions. Because increased velocity enormously augments their power, they do the bulk of their work during floods. They are unable to deepen their valleys below their baselevel, the level of the sea.

Stream deposits are stratified. According to their stratification and

their form and position, they are classified into distinctive groups such as deltas, fans, and natural levees.

The principles of stream work are applied to the supremely important problem of protecting agricultural soil against excessive erosion, and to the complementary problem of protecting valley bottomlands against excessive floods.

Chapter 5

SCULPTURE BY STREAMS AND MASS-WASTING

How Valleys Are Made

Beginning of a Valley; Consequent Streams. On a new land surface, such as one just emerged from beneath the sea, the first rains wash away loose particles and carry them down the nearest slopes in broad sheets and in rills. Joining at the bases of converging slopes, two or more rills combine, and the increased volume greatly increases the eroding ability of the flowing water. With increasing erosion, the rills become larger (and of course fewer), and the larger they become, the more water they carry. Each rill first excavates a *gully* (Fig. 48). Erosion at its head lengthens the gully, and the water washing down its sides widens it. At the same time, it is being deepened. Undergoing continued enlargement, the gully grows into a valley.

Streams that follow (*i.e.*, that are "consequent upon") the pre-existing slopes of the land in the manner described are said to be *consequent* streams.

Intermittent and Perennial Streams. At a very early stage the valley is likely to carry water only during and after rains, so that its stream is intermittent. As erosion deepens the valley, however, more and more of the rainfall that enters the ground directly has opportunity to emerge again along the valley sides, thus contributing water long after the rains have ceased. Eventually the valley is excavated to the depth at which all openings in the rocks are permanently filled with water. From this time on, water seeps uninterruptedly into the valley, forming a perennial stream.

Tributaries. Many of the tributaries of a consequent stream system are formed simultaneously with the main stream, by rills flowing down the pre-existing slopes. Additional tributaries begin by flowing down slight irregularities in the sides of the main valley, cutting gullies whose heads grow upslope away from it (Fig. 48). Once begun in this way, the tributary gullies are extended headward at the same general angle to the main, because the growth of each is guided by adjacent tributaries developing under the same control. The pattern made by the whole branching system resembles the trunk and branches of a tree.



BRUBAKER AERIAL SURVEYS.

Fig. 48. Consequent system of gullies growing headward up a gentle slope underlain by silt. Horse Heaven Hills, north of Pendleton, Oregon. View from the air.

Divides. As a stream system continues to grow headward up the slope of the land, its headwaters approach those of another stream system draining in the opposite direction. The line separating the two watersheds is a *divide;* it is gradually lowered as the watersheds are reduced by erosion. At the same time it is shifted laterally, because no two stream systems perform equal erosion and the resulting greater rate of erosion on one slope shifts the divide slowly against the weaker system. The shift becomes increasingly slow, partly because gradients normally decrease as streams continue to erode the land, and partly because the rates of erosion on the two drainage areas gradually approach equality.

In both stream systems each tributary has a rate of erosion that differs from that of each immediate neighbor. Therefore the intervening divide is shifted unequally along various parts of its course, and

so it gradually assumes an irregularly zigzag pattern (Fig. 49). Where two opposed valleys head directly against each other, a sag develops in the divide.

Stages in the Growth of a Valley. A valley once formed in a land area standing moderately above baselevel goes through a fairly definite series of changes, each of which merges with the next, to form an unbroken chain. In crude analogy with living organisms, valleys are said to be young, mature, and old, the characterization emphasizing their *stage of development* (Fig. 50) rather than their absolute age in years.

The ideal *young* valley has a V-shaped cross profile (Fig. 50) and its floor is scarcely wider than the channel of the stream it contains, because downcutting by the stream is dominant over valley widening by mass-wasting.

SPENCE AIR PHOTOS.

Fig. 49. Land mass in early-mature stage of the fluvial cycle. Note the intricate maze of valleys, and the zigzag pattern of some of the divides. Poso Creek district, Kern County, California.



Lateral swinging of the stream, set up by irregularities in its course, throws the current from side to side of the valley, wearing the valley back along the outer and downstream sides of the curves (Fig. 51), and causing the channel to shift sideways. At the inner and upstream sides of the curves the water is slack, and therefore makes deposits in these places. This combination of cutting and slipping forms alter-

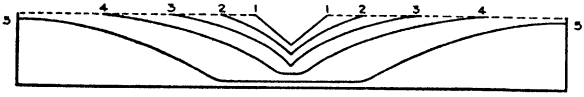


FIG. 50. Cross-profiles of a stream valley, developed successively during the progressive erosion of the valley. *1*, *2*, *3* are V-profiles. *4*, *5* are broadly flaring profiles.

nating steep and gentle valley sides. As downcutting decreases, the gently sloping sides merge into crescent-shaped strips of sloping valley floor on alternate sides of the stream (Fig. 52).

As the curves enlarge and as downcutting decreases further, these strips coalesce, forming a continuous, more or less flat valley floor cut from the bedrock and thinly covered with stream deposits (Fig. 52). This floor is known as a *strath*, a word long used in Scotland in refer-

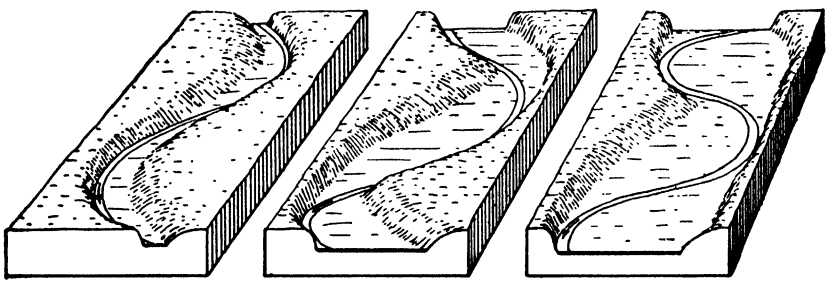


FIG. 51 FIG. 52 FIG. 53

FIGS. 51–53. Evolution of the valley floor, and development of stream curves into meanders.

FIG. 51. Stream is actively cutting at the outer sides, and slipping away from the inner sides of its curves, making crescent-shaped strips of valley floor.

FIG. 52. Later stage. Stream has cut a continuous strath, and is undercutting the spurs that face upstream.

FIG. 53. Later stage. Valley has been widened nearly to the width of the curves (now meanders), which sweep down the valley.

ence to a wide flat valley floor. When the strath has become fully developed, the valley is said to be *mature*. By this time the stream, undercutting the valley sides, has widened the valley floor to a diameter greater than the diameters of the curves of the stream channel. When the curves have reached this condition they are termed *meanders* (Figs. 53, 54). (Not all meanders, however, are formed in this way.)

The steepest bank and deepest water lie on the outer side of a meander, where the current is strongest. As the curvature of a meander becomes more pronounced, a channel is cut through its neck, forming an island. The main current takes the shorter route afforded by the cutoff, and the entrances to the abandoned channel are gradually filled with sediment, leaving a shallow crescent-shaped (*oxbow*) lake (Fig. 54). Such lakes are undercut and destroyed by other meanders migrating gradually down the valley.

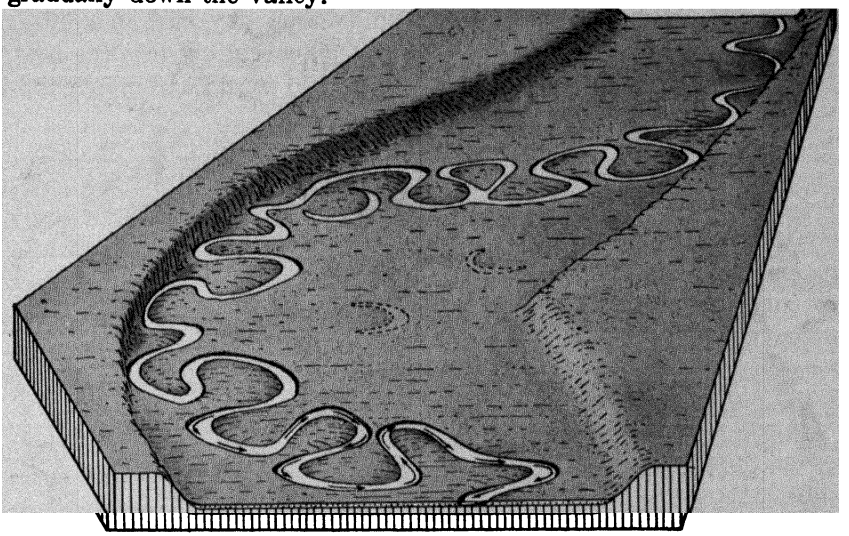


FIG. 54. Valley with wide strath, showing formation of cutoffs and crescent-shaped oxbow lakes. Arrows in near part of stream indicate course of current and position of deepest part of channel. Undercutting on outer banks and deposition on inner banks of the channel give the strath the interlocking gentle slopes visible in the diagram.

Lateral cutting does not cease at this stage. The meandering stream impinges here and there against the valley sides, wearing them back still farther. In this way the strath may be broadened to many times the width of a single meander. Stream cutting takes place more and more slowly, and mass-wasting reduces the valley sides to very gentle slopes. The valley has now become *old.*

The terms young, mature, and old are convenient in describing valleys, because each term implies a group of distinct characters.

How a Land Mass Wastes Away

The change in size and form of a valley as it evolves through its young, mature, and old stages is marked. From visualizing the evolution of a single valley it is only a step to visualizing the evolution of a broad land mass drained by innumerable valleys. Since valleys en-

large at the expense of the areas that separate them, it follows that, given time enough, stream cutting and mass-wasting must eat away even a great land mass and reduce it to baselevel. Such complete destruction is the certain result of these processes if they are not interrupted. The series of changes involved in the upheaval and the complete reduction of a region to baselevel, by these processes, constitutes a *fluvial cycle*. Of course no eye has seen a single land mass undergo all the changes described, because the process is extremely slow. But because we observe many different land masses today, each in a different stage of evolution, and each grading imperceptibly into the next, we can safely infer that, given time enough and freedom from interruption, the entire sequence of changes will occur.

THE FLUVIAL CYCLE IN A MOIST-TEMPERATE CLIMATE

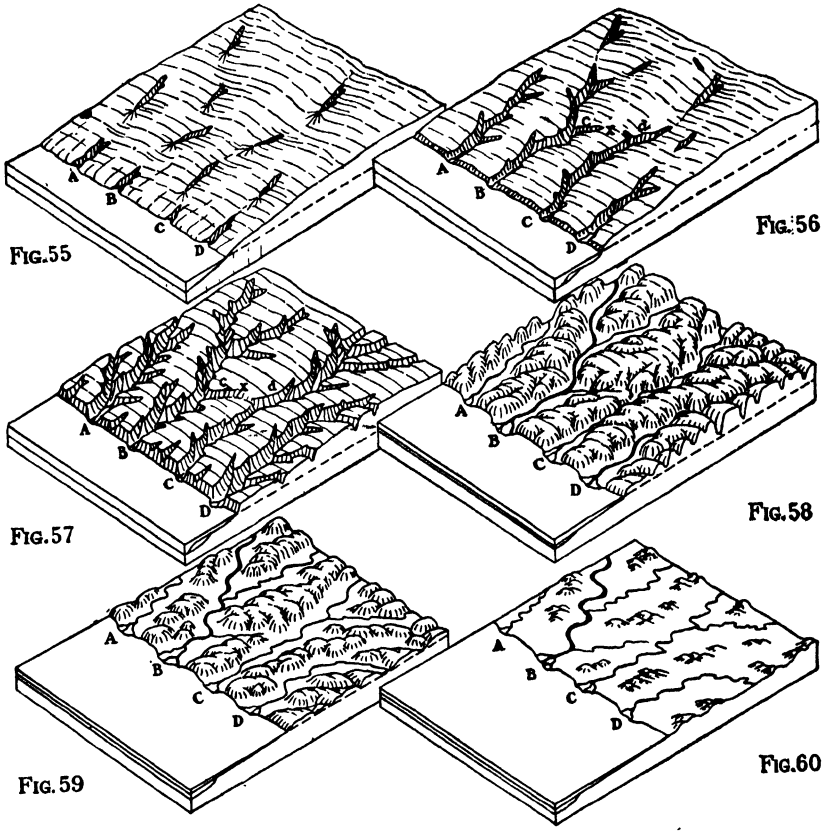
Initial Stage. A land area composed of homogeneous rocks newly emerged from beneath the sea, and lifted up to moderate height in a region of moderate rainfall, will have gullies developed on its surface at once (Fig. 55). Adjacent gullies join downslope and form connected chains, which gradually become valleys. Tributaries develop, lengthening themselves headward from the parent gullies, and the land area passes from the *initial stage* into *youth*.

Youth. The streams in youth have gradients as steep as the height of the land above sealevel permits; they occupy V-valleys with steep sides (Fig. 50) and crooked courses. Tributaries develop rapidly, their valleys growing headward from the main streams like branches growing from the trunks of trees (Figs. 56, 57). As the numerous tributaries, powerfully aided by mass-wasting, dissect the surface, the broad intervening areas contract into narrow irregular ridges (Fig. 58).

Maturity. When the tributaries have lengthened their valleys so far headward that the areas between them have been dissected into short hills and spurs, and when the growing valleys have consumed much of the land mass, the landscape imperceptibly takes on a new aspect and the region is said to be *mature* (Fig. 58). The intricate network of drainage is complete, and most of the area has been carved into slopes with sweeping curves (Fig. 63, *left*). Every hill is cloaked with a blanket of rock waste, imperceptibly creeping toward the valleys. The mass-wasted slopes are graded to the streams at their bases, just as a mature tributary stream is graded to the stream into which it flows. In this way profiles of equilibrium extend not only along the streams but up the hill slopes as well.

Old Age. Because of the ever-decreasing gradients of the main streams, the heights along the steeper tributaries are wasted more

rapidly than the larger valleys can be deepened. The result is a gradual decrease in relief (Fig. 59). Lateral cutting by the sluggish main streams widens the valleys and helps to cut away the adjacent higher land. As the floors of the main valleys slowly approach base-level, and downcutting by the main streams gradually diminishes, erosion is confined more and more to valley widening by the main streams and mass-wasting of the slopes. The hills of maturity merge downward into low elevations in old age, catching less rain and shed-



FIGS. 55–60. Ideal fluvial cycle under a humid-temperate climate and on homogeneous rocks.

FIG. 55. Initial stage, showing gullies developing at points where the runoff is concentrated.

FIG. 56. Early youth, showing headward growth of young valleys.

FIG. 57. Later youth, showing reduction of the initial surface to irregular ridges.

FIG. 58. Early maturity, showing dissection of interstream areas into slopes and development of straths.

FIG. 59. Later maturity, showing decrease in relief, reduction of slopes, and widening of valleys.

FIG. 60. Old age, showing development of peneplane with monadnocks.



Fig. 61. Monadnocks near Moosehead Lake, Maine

MC LAUGHLIN AERIAL SURVEYS.

ding the water feebly. Tributaries diminish in number. Erosion takes place with increasing slowness, so that it might require more time to remove the last few feet of land still above baselevel than was needed for the destruction of all the land that went before.

Peneplanes; Monadnocks. The surface of low relief, very gently undulatory, that is developed in late old age is a *peneplane* ("almost a plane," Fig. 60). Only a few residual remnants of the former high land remain. Here and there isolated hills of resistant rock rise gently above the general surface, like islands above a sea (Fig. 61). Such island-like masses are *monadnocks*, so called after Mount Monadnock in New Hampshire which rises in this manner above the surface of the surrounding country. The creation of a peneplane is the work of stream excavation and mass-wasting combined, each process aiding the other.

The terms youth, maturity, and old age do not refer to periods of years, or to any absolute age. They denote merely stages defined by the amount of work done in proportion to the total amount of work that must be done to complete the cycle. A region of very weak rocks might reach old age while an area of resistant rocks was still in youth as far as the amount of erosion accomplished is concerned. It follows that an extensive valley system may be in different stages in different localities, depending on supply of water and on the nature of the underlying rocks. Other factors equal, main valleys are always more advanced in the cycle than are their tributaries.

Since streams have been carrying rock waste from land to sea for hundreds of millions of years, why has not all the land been reduced to sealevel? The reason is that the Earth's crust is very unstable; while one part is being worn down another part is being lifted up (p. 297). For this reason there are no undamaged peneplanes in the lands of today. Remnants of former peneplanes exist, but none is now near baselevel.

Time Involved in the Cycle. The time required for the great sequence of changes involved in the cycle is enormously long. From measurements of the amounts of sediment carried by the Mississippi River under various conditions, it has been computed that the vast land area tributary to this river is being lowered at the *average* rate of one foot in 7000 to 9000 years. This rate is very rapid in terms of geologic history; it seems rapid even in terms of human history when we realize that since the time when man first appeared on the Earth (about a million years ago) an average thickness of 100 to 150 feet of rock has been removed from every part of the Mississippi basin. Yet we find that even at this rate more than 15 million years would be re-

quired to reduce the region to baselevel, taking no account of the gradual slowing-up of erosion as a result of decreased gradients. The actual time required would be vastly longer.

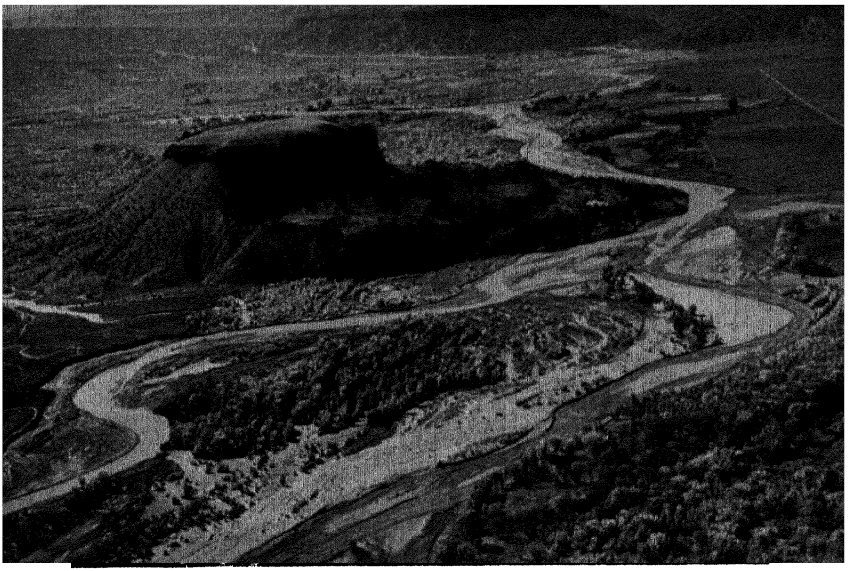
FLUVIAL SCULPTURE IN DRIER REGIONS

Effect of Vegetation on Erosion. In moist regions the surface is commonly covered with an almost continuous blanket of sod, supplemented locally by brush and forest, because under such a climate chemical decomposition (p. 47) provides an extensive covering of fine mantle over the bedrock. Further, because of the relatively large amount of water in the mantle in moist regions, mass-wasting is dominated by creep. The resulting profiles, especially in the mature stage of the cycle, are a series of curves (Fig. 25).

In drier regions trees are rare; the sod mat is present but not generally strong; and the soil is loose, dry, and permeable. Gullying readily occurs where the soil is laid bare. Because flow down all the land slopes is little obstructed, the streams are subject to sudden floods, their waters are turbid, and in times of little rainfall their flow is greatly reduced and some even go dry. Mudflows (p. 60) play a more important part in the general erosional process than they do in moist regions.

Influence of Rock Composition. The steep-sided and commonly flat-floored form of valley that results chiefly from the dominance of lateral stream cutting over creep on the valley sides is accentuated by the dominance of mechanical over chemical processes of weathering. Mechanical weathering takes advantage of original joints which form angular blocks, and, as the blocks loosen and fall, they leave steep rugged cliffs. Hills made of flat-lying layers of rock remain flat topped and steep sided as they grow smaller in area through recession of the cliffs that constitute their sides. Flat-topped erosion remnants of this kind are *mesas;* similar features of smaller extent are the flat-topped *buttes* of western landscapes (Fig. 62). The curving profiles that characterize the humid regions in maturity of the fluvial cycle are less common here.

Mechanical weathering also accentuates instead of minimizing the effect of rock resistance on landscape profiles (Fig. 62). There is no creeping mat of decomposed mantle to obscure the contacts between weak and resistant rock. The Grand Canyon affords an excellent example. It has been excavated by the Colorado River in nearly horizontal rocks arranged in alternating weak and resistant layers. The more resistant layers form broad platforms and steep cliffs whose



SPENCE AIR PHOTOS.

Fig. 62. Butte and mesa along the Rio Grande at San Ildefonso, northwest of Santa Fe, New Mexico. The capping consists of lava flows, resistant to weathering. These protect the weaker rocks beneath and maintain the cliffs near the summits. Probably the lava flows were formerly continuous through this district, the butte having been later isolated from the mesa through erosion by the Rio Grande and its tributaries.

talus*es* (derived from mechanical weathering) only partly cover the weaker beds (Fig. 63).

Weak fine-grained materials such as clay and silt exposed to erosion are rapidly carved into networks of gullies separated by narrow spurs. Such intricate gullying, which grows visibly with every rain, is common along parts of the Missouri, Platte, Cheyenne, and other streams that drain the Great Plains region, most of which is underlain by weak materials. Areas so gullied are termed *badlands* (Fig. 64).

Outline of the Cycle. The idealized cycle represented in Figs. 65–69 embodies the conditions encountered in the more arid parts of southwestern United States, where there are many mountain ranges separated by broad basins whose streams commonly fail to reach the sea. Streams, most of them intermittent, gradually dissect the mountain ranges and deposit the debris in great fans at the bases of the mountains. After infrequent heavy rains the centers of the basin floors are covered with shallow water, which soon evaporates. The central areas of the basins that contain shallow intermittent lakes are called *playas* (p. 119; Fig. 44).

Because the streams do not reach the sea, the levels that limit down-cutting by the streams in the mountains are the basins themselves, and, as the waste from the mountains is deposited in the basins, their floors rise.

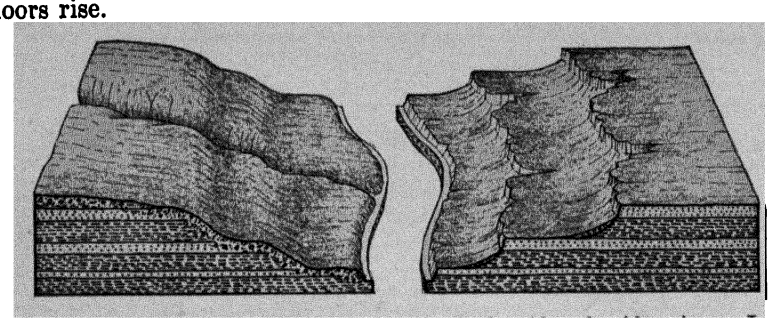
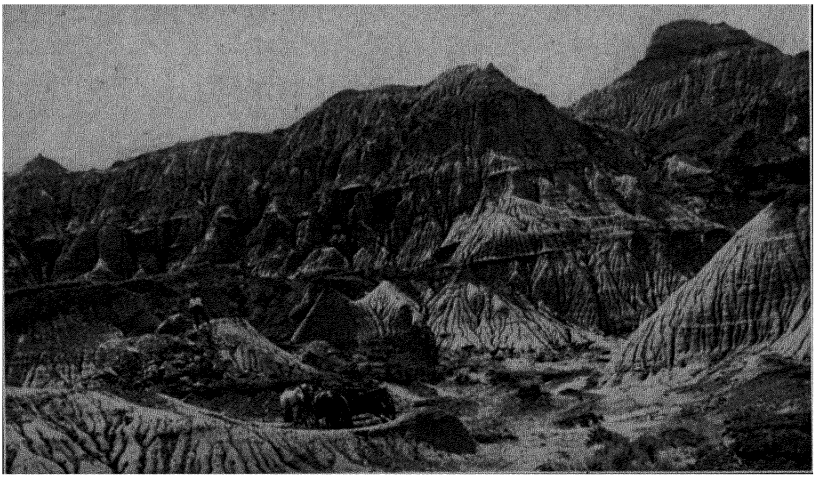


FIG. 63. Contrast between landscape profiles in humid and arid regions. Left — resistant rocks largely masked by mantle of chemically weathered residuum creeping down the slopes. Right — resistant rocks exposed as broad platforms and steep cliffs, with local taluses caused by mechanical weathering.

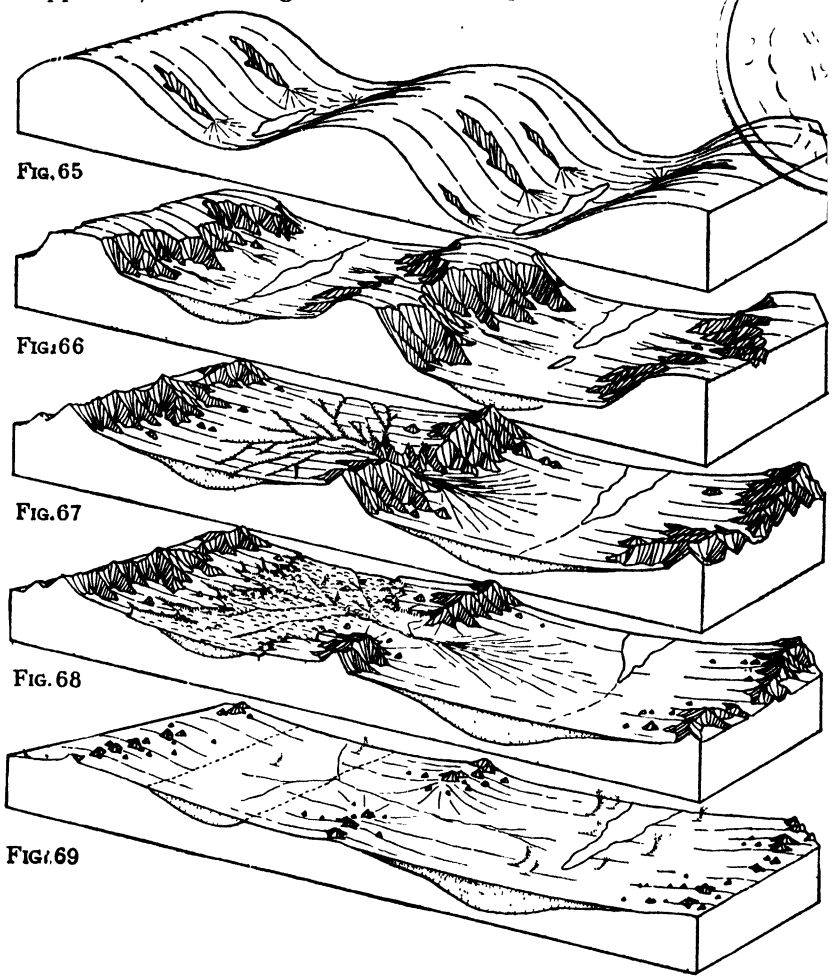
As the mountain streams approach the graded condition, they deposit farther and farther headward up their valleys, until at length a low part of a range may be completely buried beneath stream deposits. A higher basin may then drain downward across the buried range into a lower basin. This " capture " of basins may be repeated until some specially low basin comes to drain many higher ones. This causes conditions in the higher basins to shift from deposition to erosion. As



Geol. Survey of Canada.

FIG. 64. Badlands along Red Deer River south of Happy Jack Ferry, Alberta.

the mountains are worn lower, stream erosion decreases and the wind blows away increasing quantities of loose fine material from the basin floors. Export of fine waste by the wind can go on even after the basins have been brought nearly to a common level, the ranges have disappeared, and the region has become a peneplane.



FIGS. 65–69. Ideal fluvial cycle under a moderately arid climate. (Compare Figs. 55–60.)

FIG. 65. Initial stage, showing ranges, basins, and early development of fans and playas.

FIG. 66. Youth, showing decrease of relief as the basin floors widen and rise by filling.

FIG. 67. Maturity, showing capture of a higher basin by a lower one.

FIG. 68. Later maturity, showing dissection of the higher basin and transfer of its waste to the lower.

FIG. 69. Old age, showing broad filled basins and scattered residual mountains. Export of fine sediment by the wind is indicated by small whirlwinds carrying dust

Sculptured Features on Rocks of Differing Resistance

If all the rocks that constitute the crust were equally resistant to erosion, the features sculptured by streams and mass-wasting would be nearly as simple as those already described. But the crust consists of many different kinds of rocks, and these lie in many different positions. The result is the diversified landscape with which most of us are familiar. One of these diversities is illustrated by the rock benches shown in Fig. 63. Some others are described below.

Subsequent Streams; Hogbacks and Cuestas. Where a stream flows across rocks of unequal resistance, those headward-growing tributaries that chance to be located on the weaker rocks will grow more rapidly than those located on the stronger rocks. If the rocks crop out in belts, such as the inclined sedimentary rocks in Fig. 70,

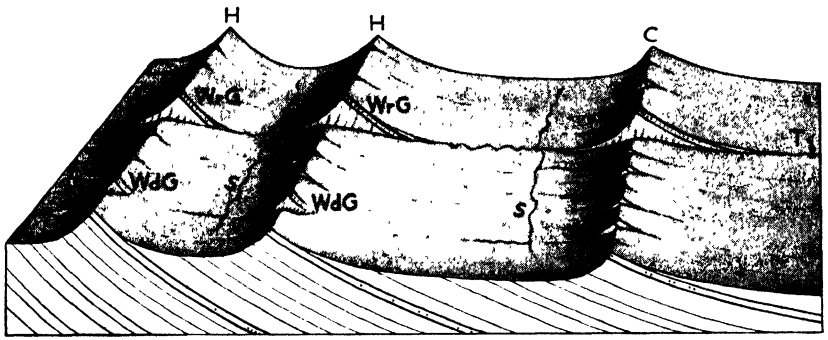


Fig. 70. Block showing ideal subsequent streams (*S,S*), transverse stream (*T*), hogbacks (*H,H*), cuesta (*C*), water gaps (*WrG*), and wind gaps (*WdG*). Length of front of block, about 10 miles.

the direction of growth of the tributaries will be controlled by the weak-rock belts. Streams that grow headward along weak-rock belts are termed *subsequent* streams (Fig. 70), in contrast with streams whose valleys are consequent upon the slopes of the land (p. 85).

The ridge formed by a layer of resistant rock is a *cuesta* if the layer is inclined gently, and a *hogback* if it is inclined steeply (Fig. 70). Niagara Falls spills over a cuesta whose steep face is the Niagara escarpment (Fig. 37, p. 73).

Transverse Streams; Water Gaps. Many large streams and some small ones cut across belts of resistant rock instead of following the intervening weak-rock belts. Most of the major streams of the Appalachian region have this character. The possible reasons for such transverse courses are many and complicated, and therefore can not be explained here. As the belts of resistant rock are usually

marked by long ridges, the transverse streams have cut gaps through them during the slow process of downcutting. These are *water gaps;* the Delaware Water Gap is a well-known example. Water gaps become wind gaps commonly as the result of capture of the gap-cutting streams by subsequent streams which, occupying belts of weak rock, can erode very rapidly. This process is illustrated by Snickers Gap in the Blue Ridge of Virginia 15 miles south of Harpers Ferry. The floor of this wind gap hangs 700 feet above the Shenandoah River at the west base of the ridge. A small stream, Beaverdam Creek, heads at the east base of the ridge and flows east. During an earlier cycle

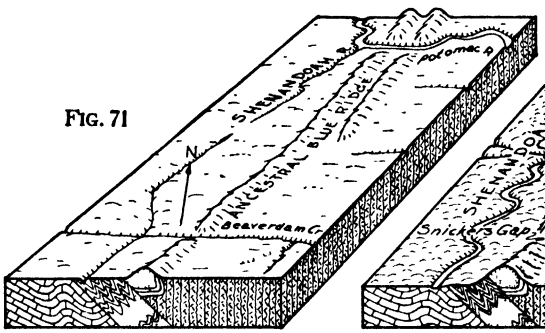


FIG. 71

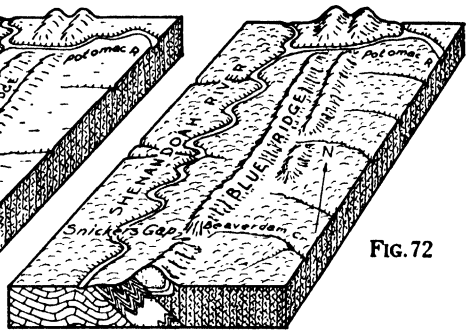


FIG. 72

FIGS. 71–72. Conversion of a water gap into a wind gap by stream capture. Long dimension of block, about 25 miles. Vertical dimension exaggerated.

FIG. 71. Former drainage across the Blue Ridge in northern Virginia.
FIG. 72. Present drainage resulting from beheading of Beaverdam Creek by the subsequent Shenandoah. Note increase in height of the ridge as the weak-rock areas adjacent to it are wasted away by erosion.

the land around the base of the Blue Ridge stood as high as the floor of Snickers Gap, which contained a transverse stream, the ancestral Beaverdam Creek (Fig. 71). But the much larger transverse ancestral Potomac, which crossed the ridge 15 miles farther north, was able to cut its gap downward much more rapidly into the resistant rocks that formed the ridge. The Shenandoah, a subsequent stream tributary to the Potomac, was thereby given a relatively steep gradient, and so lengthened its valley headward toward the south, wore down the divide that separated it from Beaverdam Creek, and captured the latter by diverting its water toward the Potomac (Fig. 72). Thus in consequence the gap was abandoned, and the shortened creek (the present Beaverdam Creek) was confined to the area east of the Blue Ridge. As the Shenandoah and the small streams east of the ridge continued to cut downward, the ridge was left standing in greater relief, with the abandoned gap high and dry.

Stream Adjustment; Rock Structures Beveled by Peneplanes. After each such capture within a drainage system, an increased proportion of the drainage follows weak-rock belts. The result will be a system *adjusted* to the weak rocks — that is, with as much mileage as possible on weak rocks, and as little as possible on resistant rocks. When all the weak-rock areas have been worn down close to baselevel, only the resistant-rock areas remain to be eroded. These continue to be slowly reduced, chiefly by mass-wasting, until ultimately they are worn nearly as low as the weak-rock areas. The result is a peneplane in which both weak and resistant rocks are more or less evenly beveled. Remnants of peneplanes exist in many parts of the world, each one cutting across rocks of various kinds and thereby testifying to the fact that it was formed under the close control of baselevel, the only level at which streams and mass-wasting can cut down both weak and resistant rocks nearly to a common plane. But these remnants are not now near baselevel. Movements of the crust have permitted them to be either uplifted and partly destroyed by erosion, or buried beneath younger sediments.

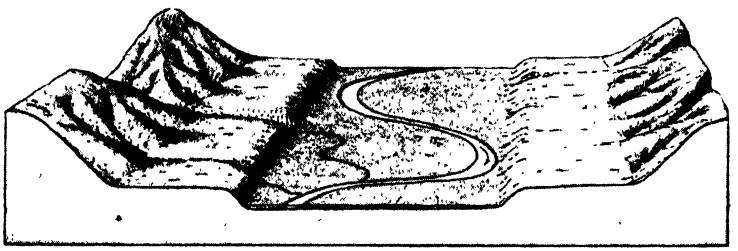


FIG. 73. Terraces caused by rejuvenation, since which the stream has cut a wide strath.

CHANGES OF LEVEL

DROWNED VALLEY SYSTEMS

Both downward and upward movements of the crust (p. 246) and changes in the level of the sea are likely to have marked effects upon stream valleys. Relative downward movement of the land along coasts causes the submergence of valleys beneath the sea. Chesapeake Bay and its Carolina neighbors (Fig. 136, p. 176) represent drowned valley systems, the Hudson River is drowned as far upstream as Troy, 150 miles above its mouth, and most of the bays of the New England coast were cut by streams and later drowned. San Francisco Bay (Fig. 222, p. 276) is a particularly impressive example of a large drowned valley system.



SPENCE AIR PHOTOS.

Fig. 74. Incised meanders, San Juan River west of Mexican Hat, Utah. The stream has been rejuvenated, incising the meanders to a depth of 1200 feet. Note the outcrops of horizontal resistant strata.

Stream Terraces; Incised Meanders. On the other hand, movements that increase the slopes of the land increase the rates of erosion of the streams affected, by increasing their gradients. A stream given a markedly increased gradient by this means or any other is said to be *rejuvenated.* In some valleys rejuvenation results in the excavation of a new valley in the floor of the former valley. Remnants of the earlier valley floor are left as *terraces* (Fig. 73) along the flanks of the new valley. Again, if the gradient of a meandering stream (p. 88) is increased very rapidly, the stream is rejuvenated in its meandering course. The meanders are incised to form a continuous winding gorge whose bends are separated by projecting spurs (Fig. 74).

The common occurrence, throughout every continent, of stream terraces and incised meanders is a striking indication of the instability of the Earth's crust.

Summary

Valleys are made by streams. The most common kind of stream, the consequent stream, cuts its valley under the control of the original slopes of the land. Less commonly, streams develop valleys by growing headward along belts of weak rock (subsequent streams).

Given time enough, a land mass is destroyed by the streams that cut valleys in it, and by mass-wasting of its whole surface. A large land mass, if undisturbed by crustal upheavals or other interruptions, is stream cut and mass-wasted down to the condition of a peneplane, the whole process requiring millions of years. The details of the erosion, and of the intermediate sculptured forms, differ considerably with differing climates.

The destruction of a land mass is often interrupted by changes in the level of the land relative to the sea. Relative downward movements of the land cause the drowning of valleys; relative upward movements are likely to rejuvenate the streams and cause terraces to be cut. Study of all these features permits us to reconstruct part of the history of any land mass.

Chapter 6

SUBSURFACE WATER

One of the reasons why man has been able to establish permanent settlements, not only in well-watered country but also in desert lands, is that there are few districts in which holes, intelligently located and sunk far enough into the ground, do not encounter at least a small supply of water. The depth of an adequate well in a moist country may be only a few feet; in a desert it may have to be hundreds of feet. The Earth's superficial rocks constitute a vast reservoir of *subsurface water,* which not only is of prime human importance, but also plays an important part in the endless process of geologic change. Water in the ground dissolves some of the substances of which the rocks are composed, and thus prepares them for attack by other eroding agents. Conversely, it acts as a transporting and depositing medium for substances that cement loose sediments to form new rocks. The quantity and distribution of water beneath the surface control the flow of rivers, the levels of lakes, and the locations of swamps. And, finally, subsurface water furnishes the water supply of a large proportion of the world's population.

Source and Movement

Source. Most of the water below ground is merely rain and melted snow that has seeped downward from the surface. Once it has penetrated into the ground, it follows various courses. Part of it finds its way back to the surface as springs or through the pores in the mantle or through plants; some of it is held within pore spaces in the rocks, and some of it actually becomes a part of the rocks, by uniting chemically with them.

In most regions with moist climate, wells generally yield water at slight depths. However, most mines and other holes that penetrate to depths of several thousand feet encounter little water; in fact many are dry. Furthermore, at several miles' depth the pressure of the overlying rocks is so great that open spaces capable of containing water probably can not exist. It is likely, therefore, that the Earth's crust contains free water only throughout a restricted zone near the surface.

The chief factor that controls the quantity of water in the ground is climate, which through precipitation and evaporation governs the volume of water contributed to the ground, and the amount of open space in the rocks. The open space consists of tiny openings — pores — between the individual grains of the rock, and of larger openings such as fissures and caverns.

Permeability. Permeability is the capacity of rock or mantle to permit water to pass through it. In porous rocks permeability varies roughly as the square of the diameter of the particles of the material. Thus gravels and sands ordinarily yield the greatest amounts of water, whereas silts and clays yield less. The volumes of some clays include more than 50 per cent pore space; yet when saturated these clays are impermeable, because the pores are so minute that the water is held immovable by the molecular attraction of the clay particles. On the

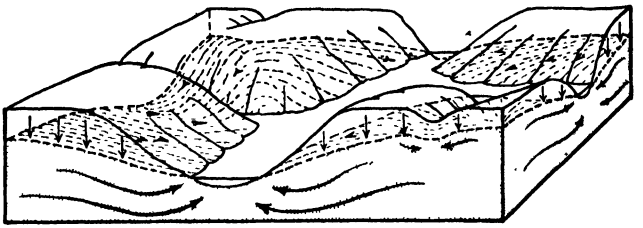


FIG. 75. Ideal diagram showing relation of water table to the land surface, and directions of movement of the subsurface water (indicated by arrows).

For simplicity the area shown is regarded as underlain by homogeneous rock of uniform permeability. The ground above the water table is drawn as if it were transparent, to show more clearly that the water table is a subdued replica of the land surface. Note that the subsurface water below the water table tends to move toward the stream valleys, in which part of it emerges.

other hand, a compact granular rock such as granite, although practically without pore space, is permeable if it contains fractures, because of the ease with which water can flow through the fractures.

Water Table. In most regions the rocks are saturated below a depth that depends largely on the permeability of the rocks, the amount of rain water that sinks into them, and the topography of the land. In permeable rocks this surface below which the rocks are saturated is the *water table*. Far from being a "level," the water table is irregular. Where the rocks are homogeneous, it is a subdued replica of the land surface beneath which it lies (Fig. 75), standing relatively high beneath hills and declining toward valleys. In many low places the water table intersects the surface, forming springs and merging with streams, swamps, and lakes. The water table has gradients,

analogous to the gradients of streams; these gradients ordinarily slope down from points beneath hills to points beneath valleys. The gradient in any place is determined by the permeability of the rock and the quantity of water supplied, usually from the rainfall immediately above. Thus in times of rain the water table rises and becomes more irregular, whereas in times of drought it subsides and flattens out. In general the lowest position of the water table in any region is closely controlled by the vertical position of the largest surface stream, which acts as a kind of baselevel for the water table. As streams gradually lower their valleys by erosion, the water table of the whole region keeps pace by slowly subsiding, until in the peneplane it lies scarcely above the level of the sea.

Movement of Subsurface Water in Homogeneous Rocks. Subsurface water moves chiefly by percolation. From where it enters the ground it moves directly to the water table (Fig. 75). Once below the water table, it moves in the same directions as the surface slopes, but more slowly, because of the friction encountered in its passage through the openings in the rock. Movement is most rapid beneath river channels in sandy and gravelly deposits that cover the bedrock floors of many valleys. In gravel the subsurface flow may be considerable, constituting a vast body of slowly percolating water beneath the bed of the river. Under favorable conditions, the rate of percolation may amount to at least several feet per day.

The continuous contribution to springs, streams, and lakes from this great underground reservoir is the cause of the continuous flow of streams.

In general, the movement of ground water decreases as depth increases, because of loss of gradient and diminishing permeability. At the greatest depths to which ground water can penetrate, movement virtually ceases.

Simple Springs and Wells. In some places subsurface water emerges naturally at the surface as *springs*. There are many kinds of springs, two of which are illustrated here. Figure 76 shows the conditions under which springs occur along the trace of the intersection of the water table with the surface of the ground. Figure 77 shows a type of spring, localized at the contact of permeable rock on impermeable rock.

A well (*A*, Fig. 76) penetrating below the lowest position of the water table is assured of a continuous supply of water, replenishing itself automatically as water is drawn out. The rate at which water is withdrawn, however, has to be adjusted to the permeability of the rock, because wells in very permeable rock replenish themselves much

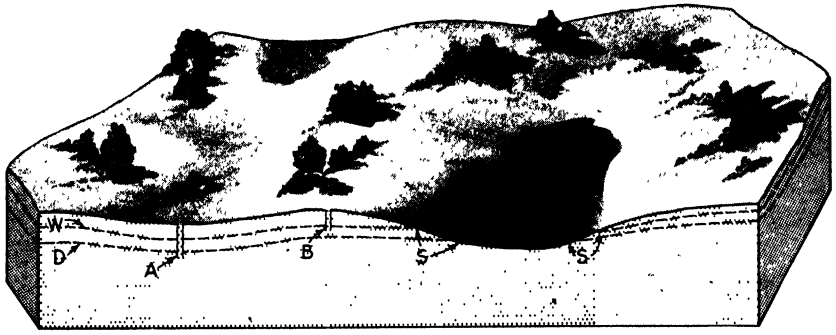


FIG. 76. Conditions controlling locations of springs and wells in homogeneous permeable rocks or mantle. The water table fluctuates between *W* (in the wet season) and *D* (in the dry season). Well *A*, reaching below the dry-season water table, has a continuous supply. Well *B*, reaching the water table only during the wet season, goes dry at times. *S,S*, zone of springs whose migration, with the fluctuating water table, causes the swamp to contract and expand seasonally.

more rapidly than do wells in rock of low permeability. A well (*B*), Fig. 76) that does not reach the water table at all times will intermittently become dry.

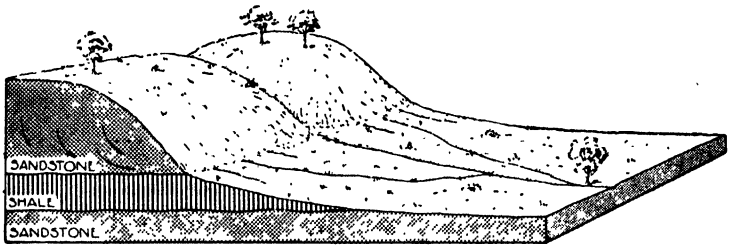


FIG. 77. Springs emerging along a contact between permeable sandstone and underlying impermeable shale. The springs are fed by water that has percolated down through the sandstone, and give rise to small surface streams.

Artesian Wells and Springs. In a series of inclined sedimentary rocks that include a permeable layer such as a sandstone, overlain by an impermeable layer such as a shale, free hydraulic connection between the ground water in the sandstone and the ground water lying above the sandstone is prevented by the impermeable shale, except where the sandstone is cut by the surface of the ground. Here, at the outcrop of the sandstone, water enters this layer. Its percolation is *confined* to the sandstone by the overlying shale, and thus there is developed a hydraulic gradient distinct from the slope of the water table of unconfined ground water. As the shale itself is saturated, the whole system lies below the water table. The significant difference

between the sandstone and the shale is that water moves freely in the sandstone, whereas it is held immobile in the shale. The permeable layer (called the *aquifer*) may be tapped by drilling a hole through the confining impermeable layer. Then the hydrostatic pressure of the column of water extending back up to the intake of the aquifer forces the water up through the hole, to a height equal to the vertical distance between intake and outlet, minus a small amount owing to friction resulting from percolation through the aquifer. If the hydrostatic pressure is sufficient to lift the water in the outlet hole above the local water table, the hole is an *artesian well* (Fig. 78), so called because the

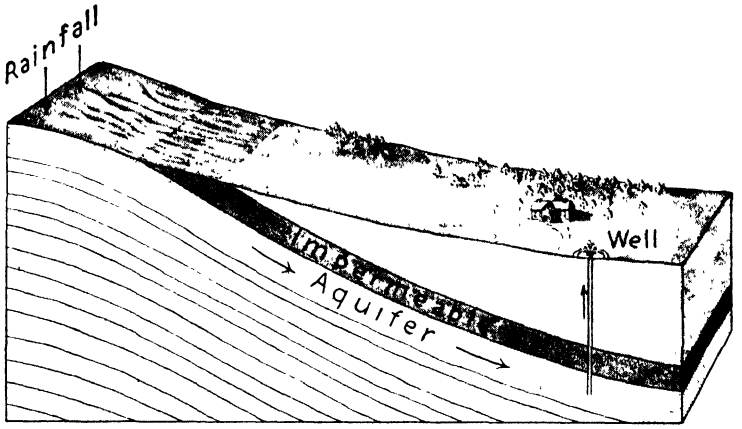


FIG. 78. A simple artesian system.

A permeable sandstone layer (an aquifer) crops out in the hill to the left and absorbs rainfall which descends along the sandstone, sealed in beneath a capping layer of impermeable rock. A hole bored down into the aquifer, farther down its slope, becomes an artesian well. In the vicinity of the well, the water table may lie in any position above the aquifer.

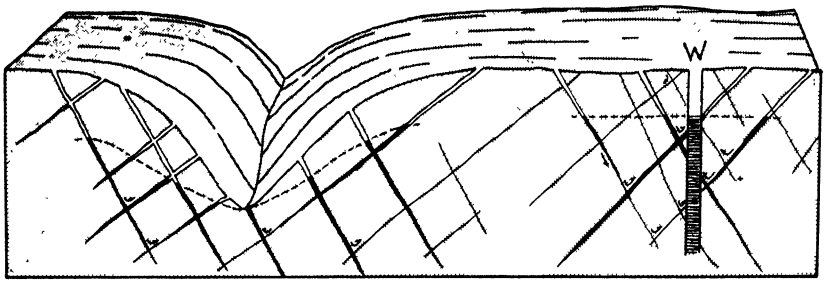
first well of this kind was made in the French province of Artois in the twelfth century. Some artesian wells flow out at the surface, but most of them have to be pumped. Artesian wells can not be made simply by boring deeply unless the requisite conditions stated above are present. Deep wells bored into rock so as to intersect the water table (some of them penetrating far below it) are often called artesian wells, but this is an incorrect use of the term; there is no difference in principle between wells of this kind and ordinary shallow wells.

Artesian systems operate also where the confined water has a natural outlet (usually along a fissure) instead of a well; the resulting outflows are *artesian springs.*

Although the largest artesian systems are dependent on beds of sandstone, smaller but none the less important supplies of confined

water are derived from lenses of sand and gravel in fans, glacial deposits, and other superficial accumulations.

Dakota Artesian System. One of the most important artesian systems in the United States is the Dakota system. The aquifer is the Dakota sandstone, a layer of rock with high permeability. It crops out and absorbs water along the flanks of the Rocky Mountains, Big Horn Mountains, and Black Hills, and underlies large parts of Kansas, Nebraska, the Dakotas, Wyoming, Montana, and Saskatchewan. The first well was drilled into this aquifer in 1882; since that time more than 15,000 wells have been drilled. The resulting withdrawal of water has seriously reduced the hydrostatic pressure, and the yields of all the wells have diminished, and are still declining, indicating that the natural supply of water is being seriously overdrawn. Some of the States concerned have resorted to legislative action to make conservation compulsory. This will hasten the arrival of the time when withdrawal will balance supply.



Modified after U. S. Geol. Survey and C. F. Tolman.

FIG. 79. Subsurface water in rock in which circulation is confined chiefly to fractures. Arrows show directions of circulation. Water table (dashed line) is controlled by depth of master valley. Well (*W*) is fed through fractures. Because fractures pinch out downward, the best water supply is obtained from moderate rather than great depths.

Springs and Wells in Fractured Rocks. In nearly all igneous and metamorphic rocks, circulation of water is restricted largely to fissures. Water enters the openings from above and moves down them to the water table. Below this it is confined, and under hydrostatic pressure it moves down or up the fissures, according to local conditions (Fig. 79). In places it becomes imprisoned in cracks with no outlets; in others it seeps out at the surface.

As holes put down in rocks of this kind derive appreciable flows of water only from fissures, the success of drilling depends largely on chance intersection with fissures. One well may furnish an abundant yield while another, a few score feet away, may yield only a trickle.

In general it is unwise to drill deep if a good yield is not forthcoming from a moderate depth, because of the fact that openings of all kinds decrease with increasing depth.

Although the majority of wells producing from fractures in igneous and metamorphic rocks are of the normal type, some are artesian. Few of the latter, however, produce without pumping.

Thermal springs and geysers (intermittently eruptive hot springs) are abundant in many volcanic regions. Ordinarily they occur in regions of recently extinct volcanoes such as the Yellowstone Park district (Chap. 12).

Pollution and Sanitation. The most common source of contamination of water in springs and wells is sewage, and the infection most commonly communicated by polluted water is typhoid. Drainage

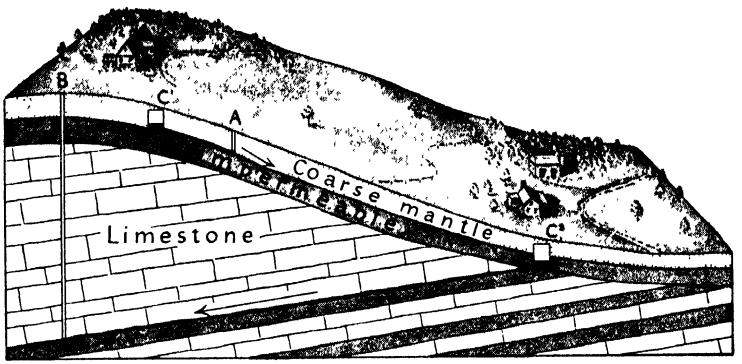


FIG. 80. Contamination of wells.

The shallow dug well *A* was unwisely located downslope from a cesspool C^1, and therefore received contaminated drainage from it. The owner then drilled a deeper well at *B*. This well tapped layers of soluble limestone inclined toward it from the direction of the lower cesspool C^2. The water dissolved openings in the limestone and flowed, unpurified by slow percolation, to where it was drawn out through well *B*. The owner of the two wells will have either to relocate his cesspool or to dig a shallow well somewhere near *B*.

from cesspools, broken sewers, privies, and pigpens percolates readily into the ground and contaminates the subsurface water. Although slow percolation through the ground purifies contaminated water, the purification process requires percolation through 100 or 200 feet at least, and in many cases very much more. Hence shallow wells must be located carefully with regard to possible sources of pollution, and even deep wells must be cased or otherwise sealed near their heads where there is danger of contaminated surface water's leaking into them (Fig. 80).

Geologic Work of Subsurface Water

SOLUTION

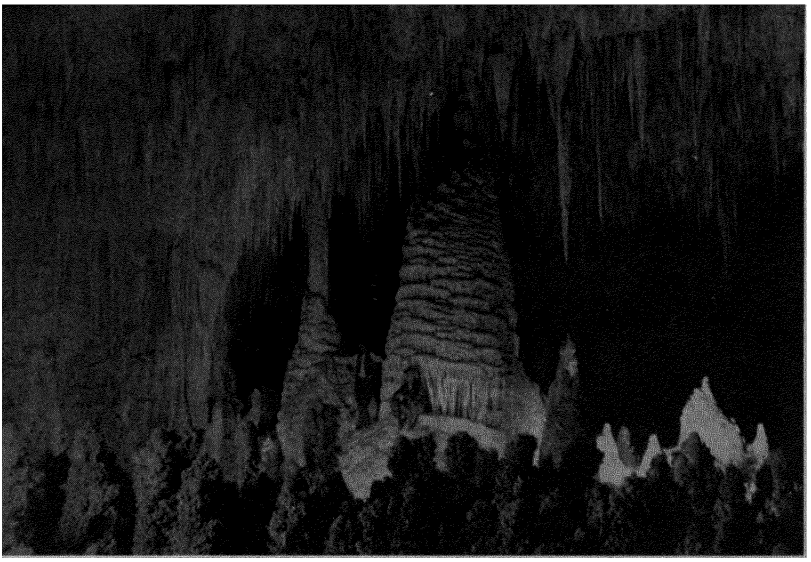
The greatest work of subsurface water lies in solution, transport of dissolved substances, and deposition by precipitation. So widespread are these activities that vast quantities of soluble mineral matter in the rocks of the continents are being slowly eaten away and delivered to the streams by the subsurface water. Containing oxygen, carbon dioxide, and acids acquired during its descent below ground, the water is an efficient solvent. It dissolves the cementing substances between the grains of many sandstones, causing them to break down into loose sand. It decomposes the feldspars and iron-bearing minerals in igneous rocks, destroying the interlocking crystalline texture of the rock and making it crumble away. Thus it is the chief factor in the chemical weathering of rocks (Chap. 3).

Caverns. Solution by subsurface water is most conspicuously evident in limestone, dolomite, and marble, three carbonate rocks that are readily soluble in water charged with carbon dioxide. In moist climates percolating water, both above and below the water table, dissolves these rocks and thus forms caverns, some of which grow to very large size. The Carlsbad Caverns in southeastern New Mexico (Fig. 81) extend down to a depth of more than 1300 feet and include one chamber 4000 feet long, 625 feet wide, and 350 feet high. A single passage in Mammoth Cave, Kentucky, is said to be more than 8 miles in length, and caverns connected with it reach heights of 80 feet and widths of 250 feet.

The only true underground streams occur in cavern systems. Elsewhere the flow of subsurface water is chiefly by slow percolation through the rocks.

Many " caves " are merely rock shelters in cliffs. They are generally made by weathering at the surface, and are not true caverns. In past times, both rock shelters and caverns often served as refuges for primitive man and as the dens of animals now extinct. Because of this the bones of men and animals, stone implements, and other objects have accumulated in them and have been sealed up beneath deposits of calcium carbonate and other substances slowly accumulating on their floors. Relics of this kind, especially in certain parts of Europe, have revealed much concerning the life and culture of prehistoric times.

Sinks; Karst Topography. Not infrequently the roof of a cavern collapses, leaving a depression open to the sky. This depression is one type of *sink* (Fig. 82). Another type of sink is formed by solution at the surface, without the intermediate existence of a cavern. Percolat-



W. T. Lee, U. S. Geol. Survey.

FIG. 81. One of the "rooms" in Carlsbad Cavern, New Mexico, showing dripstone deposits. Stalactites are forming at points where water emerges along cracks in the roof, broad-based stalagmites are growing upward, and some stalactite-stalagmite pairs have grown together to form massive columns.



I. D. Scott.

FIG. 82. Sink in limestone near Sunken Lake, Presque Isle County, Michigan.

ing water simply enlarges a crack or fissure as it trickles downward. The trickling water escapes downward readily from most sinks. In some, however, drainage is impeded and these sinks contain standing water.

The growth of a series of closely spaced sinks connected by a subterranean stream channel (Fig. 83) leaves a series of unreduced areas between the sinks. Enlargement of the sinks narrows the areas between them and reduces them to natural bridges. As the bridges are undermined, an open valley is formed. Although they may bear a

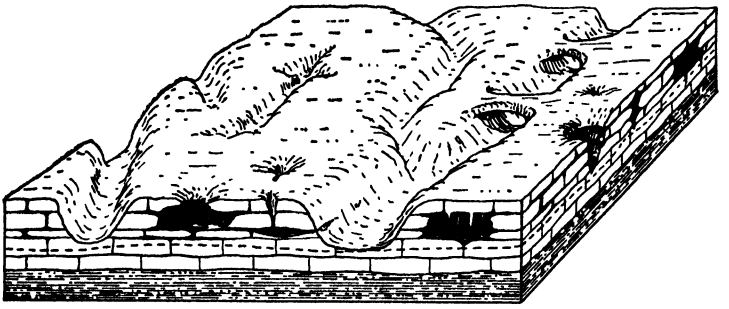


FIG. 83. Karst topography, showing caverns, sinks, solution valleys, and natural bridges. Dashed line represents water table. Area shown is about $\frac{1}{4}$ square mile.

general resemblance to valleys excavated by surface streams, these *solution valleys* are recognized by their highly variable width, by their originating (and in some cases ending) in steep-walled sinks, by natural bridges that may still span them, and by tributary valleys left hanging above them through having lost their water to subsurface drainage.

In some districts, sinks, caverns, and solution valleys are so numerous that they combine to form a peculiar topography with many surface depressions, unsystematic drainage pattern, and disappearing streams. This type of landscape has been termed *karst topography* (Fig. 83) because it is strikingly developed in the Karst region of Italy and Yugoslavia. It is found to a modified degree in such other regions as central Tennessee, Kentucky, and southern Indiana; the Shenandoah Valley in Virginia; northern Florida, Cuba, Yucatan, and the Causses of southern France.

DEPOSITION

Deposits in Caverns. As the subsurface water slowly makes its way through the ground, the physical and chemical conditions change from place to place and cause precipitation of some of the mineral

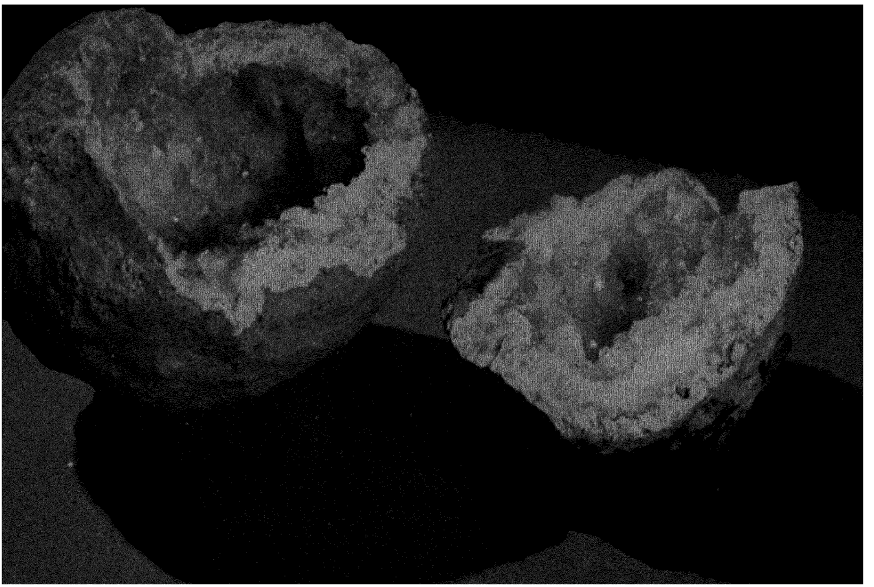
matter it carries in solution. Conspicuous among such deposits is calcite in the form of *dripstone,* with which many caverns are ornamented. Dripstone is formed only in caverns that lie above the water table and that are therefore filled with air. Water charged with calcium carbonate percolates downward from the surface of the ground to the roof of a cavern, where, clinging to the ceiling, it forms droplets. It evaporates a little, loses some carbon dioxide, and therefore deposits some calcium carbonate. Then, as more water is added from above, it falls to the floor below, where more of it evaporates, leaving another minute deposit. As the drops slowly succeed each other, long " icicles " of calcite (*stalactites*) grow downward from the roof, while broader accumulations (*stalagmites*) grow upward from the floor. If the process goes on long enough, each pair coalesces and forms a column. Dripstone likewise develops in irregular sheets on roof and floor, and assumes many fantastic shapes (Fig. 81) curious to the cavern visitor.

In some places fissures, usually below the water table, are filled with mineral matter precipitated from solution, thus forming *veins* (p. 332), many of which are mined for the valuable metals they contain. Most vein fillings have originated, however, not from descending rainwater, but from hot water ascending from intrusive bodies of igneous rock (p. 243).

Deposits in Pores and Cavities. Large open spaces such as caverns are not necessary for the precipitation of mineral matter. Small cavities, usually formed by solution, are commonly filled, under the changed physical-chemical conditions of a later time, with minerals brought in solution by subsurface water. Deposits of amorphous silica are formed in this way, layer after layer. By crystallization, these become *agate.* Where the mineral deposited in the cavity occurs as well-shaped crystals (usually quartz or calcite), with the crystals pointing inward toward the center of the cavity and only partly filling it, the resulting form is a *geode* (Fig. 84).

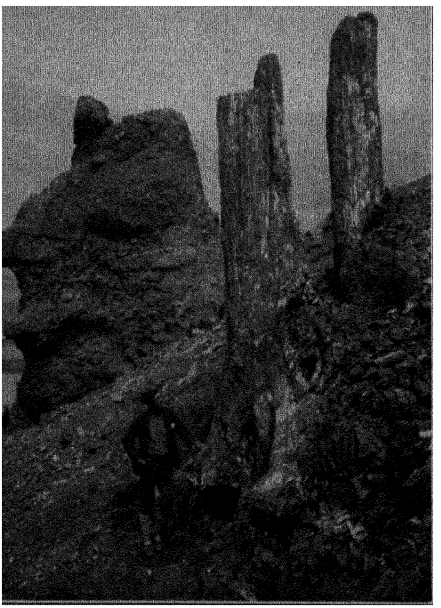
The process of precipitation goes on in even smaller openings than these. The tiny spaces — pores — between the grains of a sediment or rock are similarly filled, and the grains thereby become cemented into a firmer whole.

Replacement; Concretions. In some places subsurface water dissolves matter already present, and concurrently deposits an equal volume of another substance that it has been carrying in solution. In this way, for example, a tree trunk buried below the water table may have its woody matter dissolved and silica simultaneously deposited in its place, and may thus become slowly converted into petrified wood (Fig. 85). The fact that such *replacements* take place volume for



WARD'S NATURAL SCIENCE ESTABLISHMENT.

Fig. 84. Geode, resulting from the partial filling of a cavity with crystals of quartz. Erosion has removed the inclosing rock (a limestone in southwestern Illinois), but the resistant quartz that lined the cavity has remained. This geode (actual diameters 4½ × 3 inches) has been broken open to show its interior.



J. P. IDDINGS, U. S. GEOL. SURVEY.

Fig. 85. Tree trunks petrified by replacement while buried in volcanic ash and lava flows, in the positions in which they grew. The petrified trunks have since been exposed as a result of erosion of the inclosing volcanic material.

volume is shown by the amazingly complete preservation of the fine cellular texture of the original material. Many ore bodies owe their origin to replacement processes (p. 335).

The capacity of subsurface water to dissolve and redeposit is well illustrated by the formation of certain types of concretions — oddly shaped nodules that occur in sedimentary rocks. These forms, gradually built around definite nuclei by precipitation, are described in Chapter 11.

Spring Deposits. Confined water rising from deep sources contains mineral matter in solution, and, emerging as springs (usually thermal), it precipitates some of the substances dissolved in it. Among the factors causing precipitation are loss of temperature, relief of pressure, evaporation, and the action of minute organisms in the water. The substance most commonly in solution in subsurface water and deposited by springs is calcium carbonate, because it is the most soluble of the common rock-making substances. The physical character of the deposit depends chiefly on the rate of deposition. Deposits formed by slow evaporation are hard and compact. The dripstones formed in caverns are of this type. Calcium carbonate formed by rapid deposition from thermal springs, on the other hand, is likely to be porous and spongy. It is precipitated in mounds and terraces, some of which have picturesque forms. The terraces at Mammoth Hot Springs in Yellowstone Park are a well-known example.

Other mineral substances such as limonite, iron carbonate, sulphur, and gypsum are deposited by springs. Even silica is precipitated by some thermal springs, as in Yellowstone Park.

Summary

The three chief aspects of our discussion of subsurface water are (1) its origin, movement, and relation to surface streams, (2) its importance as a source of water supply for human use, and (3) its action in dissolving and depositing mineral matter.

1. Subsurface water is chiefly rainwater. It percolates through the ground at variable rates. Emerging in valleys, it constitutes the chief source of supply of streams, maintaining the stream flow between times of rain.

2. Ordinary wells and springs furnish a huge supply of subsurface water for human use. Where the rocks are such as to confine the flow of subsurface water to definite zones, artesian wells and springs also furnish an important supply.

3. Subsurface water acting on soluble rocks excavates caverns and sinks, and in favorable places produces effects so strong that the whole surface of the land is sculptured into karst topography. The substances dissolved from these and other rocks are in part redeposited as cement between grains of rock, and thus constitute an important factor in the conversion of sediments into firm rock.

stand the significance of such features, we must examine the work being done by existing glaciers.

Glacial Erosion

Quarrying and Abrasion. It has been said that a glacier is at once a plow, a file, and a sled. As a plow it churns up and carries away the soil and other mantle, and breaks off and pulls away blocks of bedrock, especially from surfaces that are unsupported on their lee sides. This process is aided by meltwater that percolates into joints and cracks in the rock, freezes, expands, and thus pries out blocks some of which are of considerable size (Fig. 21, p. 49). As a file its under surface, studded with rock fragments of all sizes, rasps away at the firm rock in its path. As a sled it carries away the plowed-up and filed-off debris, plus whatever additional rock fragments may have slid or fallen from mountain slopes down on to its upper surface.

The effects of such drastic action on the bedrock surface are conspicuous. In Fig. 99, a glacier has broken up the bedrock, and has plowed and quarried out large blocks of it. It has filed and polished the part it could not quarry away, forming small grooves and scratches (*glacial striæ*) on it. From the direction and distribution of the striæ and the quarried rock surfaces in the picture, it is easy to infer that the glacier was moving from left to right.

During the filing process, the stones in the sole of the glacier are themselves worn, usually unevenly, because from time to time they are forced to turn in their icy matrix. An ideal glaciated stone (Fig. 122, *A*) has several facets, some of them bearing striæ, the facets meeting each other along somewhat rounded edges.

Cirques. Valleys that are or have been occupied by valley glaciers have steep blunt heads (Fig. 116). These striking features, known as *cirques*, probably are started by the gradual excavation of niches that are occupied from year to year by snowbanks at the heads of mountain valleys. Meltwater formed on summer days permeates the rock near the edges of the snowbanks. Frost wedging occurs as the temperature at night drops below freezing. The bedrock at the surface is broken up, and the finest particles of the broken rock are carried away by the percolation of meltwater formed during daytime thaws. This process gradually enlarges the depressions beneath the snowbanks. With increasing quarrying and abrasion, the hollows become full-fledged cirques, many of which are so drastically excavated that their floors become basins. Some of the basins contain lakes after climatic change has wasted away the glaciers and snowbanks that caused them. Cirques

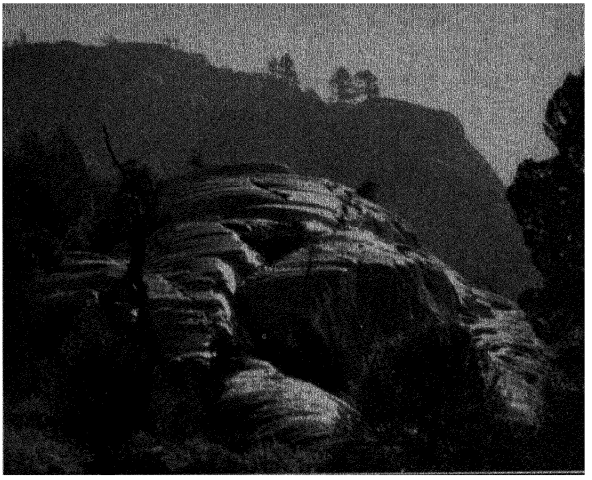
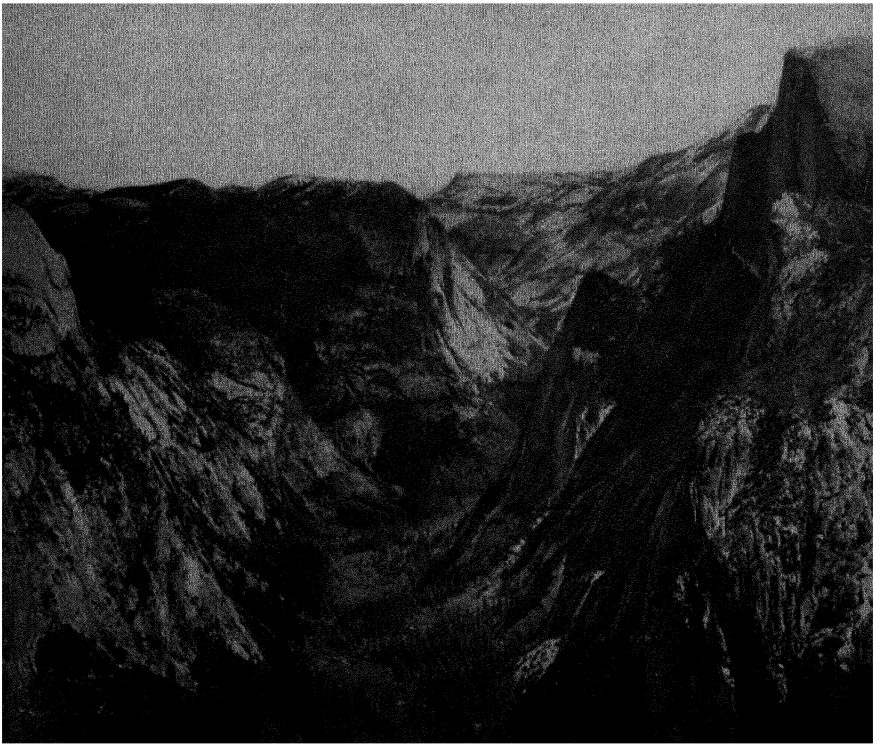
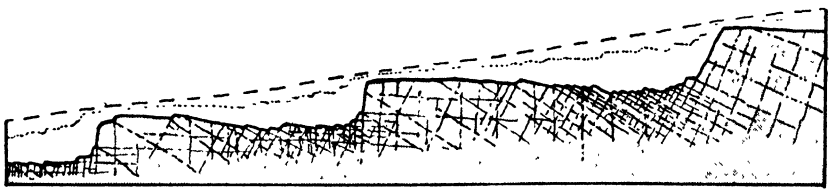


Fig. 99. Smoothed and polished surface of bedrock, Middle Fork of Kings River Valley, California. The ice (a former valley glacier) moved from left to right. Note the difference between the abraded side on the left and the quarried side on the right. [G. S. YOUNG.] *Fig. 100. Valley abandoned by a valley glacier after the glacier had beveled the spurs, smoothed the sides, and given a* U*-profile to the trough. Tenaya Canyon, Yosemite Valley, California.* [F. E. MATTHES, U. S. GEOL. SURVEY.]



are not made by ice sheets, because ice sheets overtop the rock surfaces in the regions where they occur.

Features of Glaciated Valleys. Glaciers do not excavate valleys of their own; they remodel valleys already formed. Both the valley glaciers that creep downward from the snowfields near the crest of a mountain range and the long tongues of ice that are the advance guard of an ice sheet flowing over a mountainous region follow the valleys that had been excavated by streams before glaciation began. Glacier ice, being immensely less mobile than water, does not conform readily to the bends and curves (Fig. 51, p. 88) imparted to the valleys by the former streams. For this reason it grinds persistently against the spurs that project alternately into the valleys, snubbing their ends and gradually



After Matthes.

FIG. 101. Long profile and section of part of a glaciated valley showing smoothed surfaces of glacial abrasion alternating with steep faces caused by glacial quarrying, imparting to the valley a steplike profile. In this valley the steps are shown to be controlled by the unequal distribution of joints and other planes of weakness throughout the bedrock, although other factors may be important in the making of such steps. Dashed line indicates valley profile prior to glaciation; dotted line indicates profile during an early stage of glaciation.

beveling them into facets. The facets grow larger as the spurs grow shorter, until at length the spurs are worn away entirely, leaving wide and nearly straight U-troughs through which glaciers can flow with minimum effort (Figs. 100, 103).

The long profiles of some valleys are greatly altered by glaciation. More or less smooth stream-valley profiles are remodeled by valley glaciers into short treads alternating with steep risers, resembling great flights of stairs (Fig. 101). In some places the outer parts of the treads are cut from rock comparatively free from joints and fissures, whereas the bases of the risers are cut into thoroughly jointed and fissured rock. This seems to indicate that some of the stairs are made by quarrying in the jointed rocks and by abrasion in the places where the joints are scarcer. In the latter places the rock surfaces are commonly polished, grooved, or striated. Some valleys that have been occupied by vigorous glaciers contain, in addition to stairs, basins excavated in the

bedrock. Many of them now contain lakes. Such lakes are common in many glaciated valleys, and are rare in nonglaciated valleys.

Hanging Tributaries. The grinding away of the spurs in a main valley affects the tributary valleys, whose mouths are ground and snubbed back at a rate faster than their own streams, or their thin and relatively weak glaciers, can cut them down. The tributary



Geol. Survey of Canada.

FIG. 102. Valley of Taku River, British Columbia. Widening and deepening by a valley glacier have converted it into an open trough and have left the tributary valley (right) hanging above the floor of the main, forcing the tributary stream to cascade down a cliff.

valleys can no longer enter the main valley at grade, but are left hanging above it, so that, after the glaciers have disappeared, the tributary streams flow out to the edges of cliffs, down which they must cascade in order to join the main. These *hanging tributary valleys* (Fig. 102) are characteristic of regions sculptured by glaciers, although somewhat similar hanging tributaries originate in other ways. Most hanging tributaries result from deepening of their main valleys by valley glaciers. However, some have been made by ice sheets that swamped whole valley systems. The ice sheets deepened the main valleys, over which the ice was relatively thick and free to flow, more than it deep-

ened the tributaries, over which the ice was thinner and more impeded by obstacles. The hanging tributaries of the Finger Lakes valleys in central New York are believed to have resulted from ice-sheet glaciation. If the cut-away parts of the long profiles of hanging tributaries are restored by projecting them into the main valley (Fig. 103) they are commonly found to meet above the floor of the latter. This proves

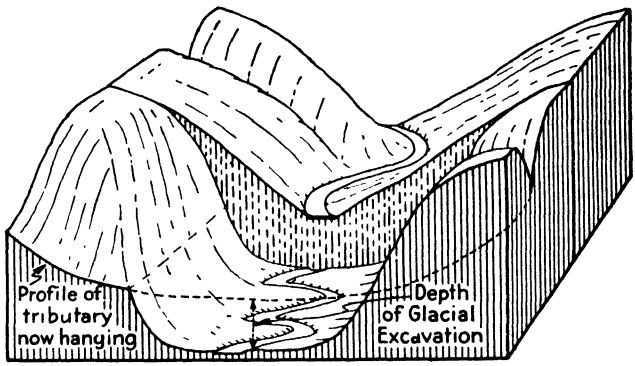


FIG. 103. Block showing alteration of a stream valley by a valley glacier. Rear half of block shows stream valley before glaciation. Front half shows valley deepened and widened by glaciation, with tributaries left hanging above the main valley. (Compare Figs. 102 and 113-116).

that the main valley has been not only widened by the ice but deepened as well. The Yosemite Valley in California, originally cut by a stream, was later deepened as much as 1500 feet by glaciers that occupied it for a considerable time.

Fiords. In middle latitudes the features that show a valley has been glaciated disappear as the valley is traced downward, and the lower limit of glaciation, the place where the glacier terminated, can therefore be approximated. In high latitudes, however, most valleys, even along the coasts, have been glaciated throughout their lengths, and are now in part *fiords.* A fiord is a segment of a glaciated trough that is partly filled by an arm of the sea (Fig. 97). It is a characteristic feature of the coasts of British Columbia and Alaska, Labrador and Greenland, Norway, Chile, and parts of New Zealand. The Franz Joseph Fiord in East Greenland is 100 miles long and 8 miles wide near its mouth, and in places its floor lies more than half a mile below sea-level. Messier Channel in Patagonia, the deepest known fiord, reaches a depth of 4250 feet. Such great depths may be due in part to regional submergence of the coasts in addition to glacial excavation. However, some fiord floors include bedrock basins which, if brought above sea-

level, would still contain lakes hundreds of feet in depth. Such features can not be the result of submergence alone, but must have been excavated by powerful glaciation.

The sculpture of fiords, like the sculpture of other glaciated valleys, is not restricted to valley glaciers. Some fiords have been made by ice sheets as they flowed over mountains or plateaus cut by deep valleys.



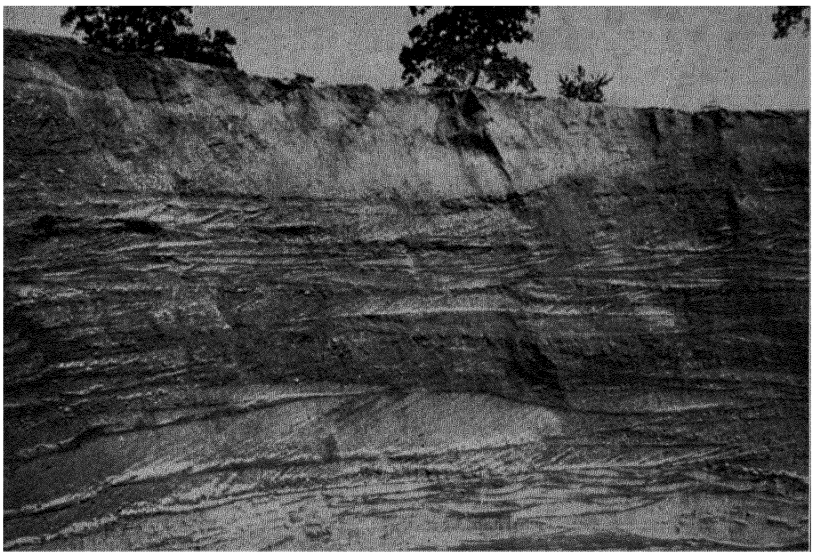
Sanborn Partridge.

FIG. 104. Exposure of till, showing its lack of both size-sorting and stratification, and the glaciated shapes of some of the stones it contains. (Compare Fig. 105.) Fishell's Brook, St. Georges Bay, Newfoundland.

GLACIAL DEPOSITS

All the material in transport by glacier ice, and all the material predominantly of glacial origin deposited directly by glaciers or indirectly in glacial streams, glacial lakes, and the sea, together constitute *glacial drift*. The name *drift* dates from a time more than a hundred years ago, when it was conjectured that such deposits had been "drifted" to their resting places by water. In texture and arrangement, drift varies through many gradations between two extremes. One extreme consists of drift deposited directly by the glacier without having been flushed by meltwater. The other extreme consists of drift so thoroughly worked over by meltwater that it has become well stratified and is actually a deposit made by water.

Till. Drift deposited directly by the ice consists of pieces of rock of many different sizes, usually ranging from large boulders down to silt and clay. The pieces are not sorted according to size and weight; they lie just as they came out of the glacier ice (Fig. 104). This kind of drift is known as *till*, a name given it by Scottish peasants long before its true origin was understood. Till comes out of the ice in a variety of ways. Some of it is merely dumped off the ice terminus.



A. L. Washburn.

FIG. 105. Stratified drift, New Haven, Connecticut. (Compare Fig. 104.) The lens-like beds are the long sections of stream channels, each of which was filled with sediment foreset into them. The currents moved from right to left.

Some of it is heaped up, snowplow-fashion, as the ice terminus creeps forward. Some of it is slowly let down to the ground from positions within or upon the glacier, as the ice beneath it slowly wastes away and disappears. Probably the great bulk of it is plastered on to the ground from the sole of the creeping glacier. Some of the stones in the till — particularly till of the type last mentioned — have glaciated shapes approaching the one shown in Fig. 122, *A*, but the proportion of such stones is commonly very small.

Stratified Drift. Much of the drift is partly or wholly stratified (Fig. 105), indicating that meltwater has partly or thoroughly reworked the rock debris carried by the glacier. In some places stratified drift is deposited in immediate contact with the glacier; also it is dis-

tributed by streams of meltwater far beyond the terminus of the glacier itself.

Stratified drift contains few glaciated stones. Boulders, cobbles, and pebbles are successively deposited as the gradient of the meltwater stream diminishes, and these large pieces are smoothed by the suspended sand and silt washed past them, until their striæ and their glacial facets are worn away.

ACCUMULATIONS OF DRIFT

Terms such as *drift* and *till* refer only to deposits, without regard to their surface form. Some glacial deposits, however, both till and stratified drift, are fashioned into definite forms recognizable as landscape features. Some of the best known of these are ground moraine, end moraine, bodies of outwash, drumlins, eskers, and kame terraces.

Ground Moraine. Drift that is widely distributed, ordinarily relatively thin, consisting chiefly of till, and having a gently irregular initial surface form is referred to as *ground moraine.* The gentle undulations of its surface, in some places including closed depressions, seem to be in part the result of uneven deposition by ice unevenly charged with drift. Ground moraine covers the greater part of the glaciated region from eastern Ohio west to the Rocky Mountains in Montana, and is conspicuous likewise in northern Germany, Poland, and Russia. In these regions the drift is thick enough to have obliterated the hills and valleys on which it rests (Fig. 112).

Drumlins. The ground moraine in some districts in western New York, central Wisconsin, southern New England, and the British Isles is dotted with scores of smooth hills shaped like the inverted bowls of teaspoons. These are *drumlins* (Fig. 106). Most of them are made of clayey till, and many of them have cores of bedrock. Ranging up to more than a mile in length and up to 200 feet in height, their long axes parallel the direction of flow of the former glacier ice, their blunt heads oppose the flow, and their narrower tails point with it. Drumlins are perfect streamlined forms, offering minimum resistance to ice flow. They occur only where clay is an abundant constituent of the drift, and they probably owe their origin to a combination of erosion and plastering deposition, the latter process gradually shaping their tails, the cohesive property of the clay playing an essential part. The chief geologic value of drumlins is that they record vigorous ice flow, and indicate the direction of movement of former glaciers.

End (Terminal) Moraines. A generally ridge-like accumulation of drift, resulting chiefly from deposition by a glacier along its terminal margin, and having an initial surface form of its own, is an *end* (*ter-*

minal) moraine. Such an accumulation may be made by three processes or by combinations of them: (1) the snowplow process in front of an expanding glacier, (2) the plastering process beneath the terminal margin of an active glacier, (3) the dump process at the margin of a glacier whose terminus is stationary owing to temporary equilibrium between flow and wastage.

The end moraines of valley glaciers (Figs. 107, 108) range from a few feet to scores and exceptionally hundreds of feet in height. Ordi-

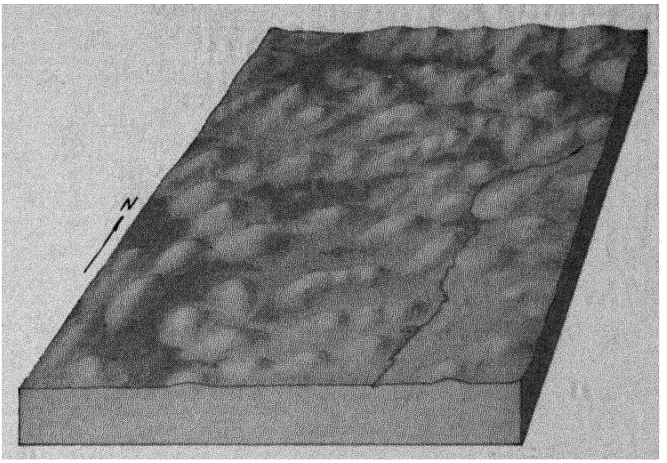


FIG. 106. Relief model of a group of drumlins near Fond du Lac, Wisconsin. The area shown is $4\frac{1}{2} \times 4$ miles. (Vertical scale exaggerated.)

narily their breadths are slight. The length of a fully formed and undissected end moraine is controlled by the width of the containing valley. In plan the end moraine is usually convex down valley, recording more rapid movement of the center than of the sides of the ice.

The end moraines of most valley glaciers contain but a small proportion of the waste removed from cirque and upper valley, some of it having been strewn along the valley floor as ground moraine, and some of it having been carried beyond the end moraines by streams of meltwater. In many steep valleys, indeed, end moraines do not form at all, because the drift is sluiced away by water as rapidly as it forms. The fact that an end moraine of a vanished valley glacier is incomplete, however, does not indicate that it was not once fully formed, as a vigorous stream readily breaches it and eventually destroys it.

End moraines rarely form along the entire margin of an ice sheet because the important factors of topography, atmospheric moisture, and movement of the ice vary greatly from one sector to another. Some of the ridges left at the margin of the ice sheet that recently

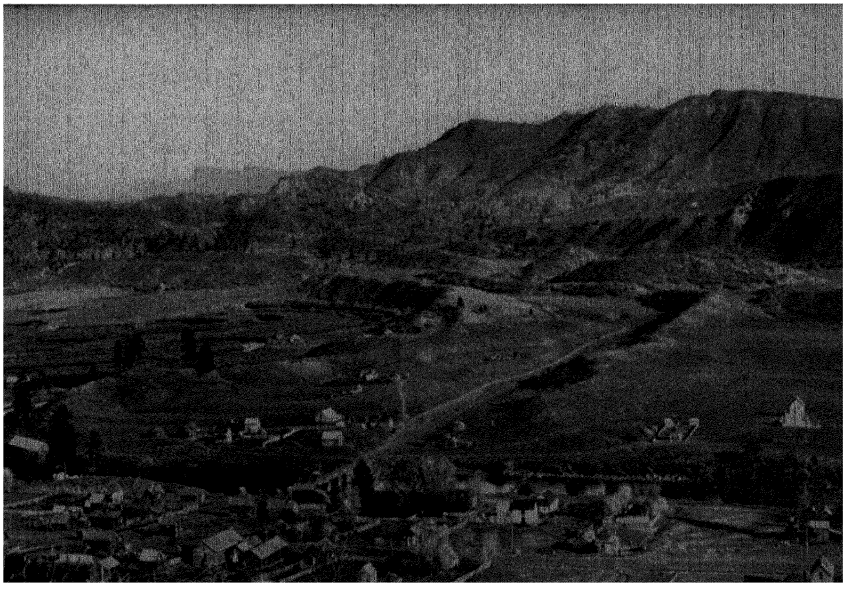


BRADFORD WASHBURN.

Fig. 107 (opposite). Features of a shrinking valley glacier. End moraines (dark-colored arcs) marking successive positions of the margin of a shrinking valley glacier near Mount Iliamna, Alaska. Braided streams of meltwater have breached the end moraines and are building a great outwash plain of stratified drift. One meltwater stream flows along the lateral margin of the glacier. On the glacier surface are crevasses indicating fracture, and sinuous bands of drift (including lateral moraine at left) indicating flow. The ice has steepened the sides of its valley. In the left background ice-abraded rock surfaces, a rock-basin lake, a hanging tributary valley, and a cirque are visible. (Contrast the stagnant terminal zone of a different glacier, Fig. 109.)

WHITMAN CROSS, U. S. GEOL. SURVEY.

Fig. 108. End moraines (low ridges in center) and outwash (smooth plain on right) in the Animas Valley near Animas City, Colorado. The ice margin shrank back from right to left, and both moraines and outwash have since been trenched by the river.



covered part of North America are scores of miles long, 100 to 200 feet high, and 1 to 5 miles wide. Their slopes are gentle, and except for their broadly ridged character they have almost the same undulatory surfaces that characterize the ground moraine back of them. Their continuity is broken by gaps through which meltwater formerly flowed. End moraines of this kind cross the broad region south of Lake Erie and Lake Michigan in great festoon-like belts trending generally east-west. Each of these belts marks an interruption, perhaps climatic, of the wastage that caused the ice sheet to disappear. The great Baltic End Moraine in northern Germany is through many miles not a ridge but a trench, because, being rich in boulders, it has been thoroughly excavated as a source of paving blocks and building stone for Berlin and other cities in a region where rock is very scarce.

BRADFORD WASHBURN.

Fig. 109. Kettles forming in the drift covering over the stagnant terminal zone of Chitina Glacier, Alaska. The small cliffs that inclose the ponds expose glacier ice.



Superglacial Moraines. Many existing valley glaciers carry long ridges of drift on their lateral margins. Built in part by avalanching from valley sides, these are termed *lateral moraines* (Fig. 107). The merging of two lateral moraines beyond the point at which two valley glaciers coalesce to form a larger glacier produces a *medial moraine* (Fig. 97). Lateral moraines often survive the glaciers on which they were built, but medial moraines rarely do so, because their contents are spread out during the shrinkage and disappearance of the ice, and are lost among the debris accumulating on the surface as wastage thins the glacier (Fig. 109).

Forms Built of Stratified Drift: *Outwash.* A great accumulation of stream-deposited drift in the region beyond the ice terminus is *outwash* (Figs. 107, 108). Choked with drift, the meltwater streams aggrade their beds and shift their braided channels, building up deposits of sediment that reach thicknesses as great as hundreds of feet, their channeled upper surfaces sloping away from the ice with steep stream profiles. The traveler along an active outwash plain has a difficult time of it. Because of the braided channel pattern he is nearly always on an island, from which he has no choice but to ford a swift cold stream. Once across the stream he is only on another island.

Some outwash plains, traced headward, lead through gaps in a related end moraine, and merge with the ground moraine on the other side. Other outwash masses end headward in steep slopes facing the positions vacated by the former glaciers. The heads of such outwash masses were built against and upon the terminal margins of glaciers that were there feebly flowing or entirely stagnant. When the ice wasted away, the stream deposits slumped down, locally reversing their surface slopes. Slopes representing the former contact of drift with ice are *ice-contact faces* (Fig. 110). The delicate details of many of these slopes are spared from destruction by gullies because of the very permeable character of the sand and gravel that commonly underlie them. The rainfall sinks into the ground without running off over the slopes.

Kettles. The ice-contact heads of outwash plains as well as other masses of drift accumulated adjacent to a glacier are commonly pitted with closed depressions ranging from a few yards up to a mile or more in diameter. The smaller depressions are usually nearly circular; the large ones are more likely to be elongate. Many contain lakes or swamps. Such features are termed *kettles* (Figs. 109, 111), and their origin is well understood because they are forming today near the margins of some glaciers. Masses of glacier ice of various sizes, either

surrounded or completely buried by drift, slowly waste away and cause slumping and caving-in of the drift.

Kame Terraces. Some glaciated valleys contain terraces made of gravel and sand built up by streams flowing between the side of a glacier and the inclosing valley wall. These are *kame terraces* (Fig. 110); some of them have ice-contact faces. Kame terraces thus differ

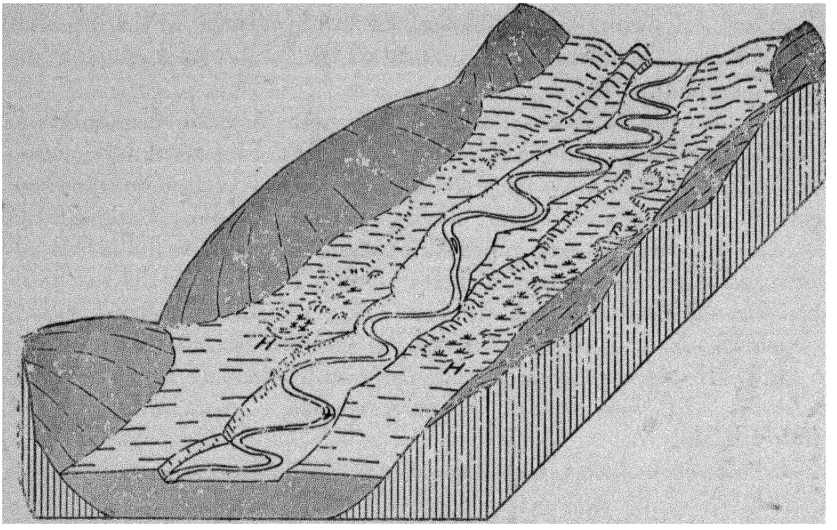


FIG. 110. Outwash plain with ice-contact head (*H,H*), merging up the valley (away from the observer) into an esker and a pair of kame terraces.



H. T. Nation, British Columbia Bureau of Mines.

FIG. 111. Kettles in kame terrace, Chilko River valley, Lillooet District, British Columbia.



W. S. COOPER.

Fig. 112. Esker resting on ground moraine, Morrison County, Minnesota. View from the air. The former ice sheet flowed toward the observer.

both in form and in origin from terraces that have been carved by streams from deposits that formerly filled the valley from side to side.

Eskers. In New England, southern Michigan, and Minnesota, and less conspicuously elsewhere in North America, there are winding ridges of stream-laid gravel and sand, which reach lengths of many miles and heights up to 60 feet or more. The ideal form has steep sides and a narrow top. In North America, such features are called *eskers* (Fig. 112), although the word is used somewhat differently in other countries. This term is probably derived from an Irish word as old as the Christian era, signifying a ridge or path. Eskers are the most conspicuous features of the landscape in parts of central Ireland, where they were used as footpaths by early inhabitants because they stood above the adjacent boggy lowlands.

Probably these curious forms originated in several ways. Some of them were formed in subglacial tunnels; others were built in crevasses without roofs; still others were built successively at the

mouths of subglacial streams, where they emerged at the ice terminus into glacial lakes or the sea, and were added to yearly as the terminus migrated backward. Most eskers appear to indicate that the inclosing ice had become stagnant or nearly so before they were built.

Pitted Outwash Plains. Considerable areas in Minnesota, Wisconsin, Michigan, New England, and northern Europe, and smaller areas in other regions, consist of outwash plains pitted with kettles. The kettles range in diameter from a score of feet up to 10 miles or more, and are so closely spaced in some districts that the plain is merely a network of narrow ridges. Such features are convincing evidence of glacier ice that became stagnant. The ice was seamed with a network of crevasses and superglacial stream channels through which ran meltwater, blanketing the ice with stratified drift which, when the ice disappeared, sagged and slumped into its present position.

Records of Active and Stagnant Ice. The glacial forms described above fall into three general groups: (1) drumlins and end moraines, which record actively flowing ice during their building; (2) pitted outwash plains, some kame terraces, large kettles, and eskers, which record stagnant or nearly stagnant ice during their building; (3) nonpitted outwash plains, which, having been built beyond the ice terminus, do not fall into either group, although they may be associated with either.

As a rule, (1) and (2) do not occur in the same district. From this we may infer that the physical conditions of former glaciers varied from time to time and from place to place. It is likely that the passage of the terminal part of a glacier from an active to a stagnant condition was brought about by thinning of the ice as a result of decreased precipitation or increased wastage.

The Ice Age

In 1834, Louis Agassiz, a Swiss naturalist, observed that the boulders (Fig. 118) and other deposits lying in the ice-free valleys of the Alps were identical in shape and arrangement with the deposits he had seen made by living glaciers in the ice-filled valleys. He realized that the glaciers of the Alps, high and comparatively small then as now, had at some former time spread outward and downward, filling most of the valleys of Switzerland with ice. In publishing this revolutionary idea he paved the way for the now universal belief that the climates of the recent geologic past were so cold that valley glaciers sculptured many mountain ranges, and ice sheets overran vast areas in North America, northern Eurasia, and southern South America. It is probable that the

glaciers covered in all more than one-quarter of the land area of the globe. The time during which these events occurred we call the *Ice Age.*

Since Agassiz made his pioneer observations, the work of the vanished glaciers has been widely studied, and the landscapes fashioned by valley glaciers in high mountains like the Alps have been clearly distinguished from those fashioned by ice sheets, which existed generally but not entirely in less mountainous country.

Forms Fashioned by Valley Glaciers. Figure 113 represents a mountain region sculptured by streams. In Fig. 114 the climate has become colder, snowfields have accumulated in high protected places, and small glaciers have begun to flow out of the snowfields and down the stream valleys. In Fig. 115 the glaciers have expanded to the maximum size permitted by the colder climate. They have widened and deepened the valleys, and have left the tributaries hanging above the main valleys. At the same time they have beveled off the ends of lateral spurs, thereby straightening the main valleys. The enlargement of cirques on opposite sides of a ridge has reduced the ridge to a knife edge, which is kept sharp by frost wedging. Two opposing cirques, back to back, slice through the ridge to form a broad gap, and, where several cirques surround the base of a high peak, the peak takes on the shape of a pyramid, such as the Matterhorn in the Alps or the Grand Teton in Wyoming.

In Fig. 116 the climate has grown warmer, and the glaciers and snowfields have wasted away, leaving straight U-valleys, hanging tributaries, cirques, and jagged sharp-crested ridges that contrast sharply with the smoother mountains of Fig. 113. Most of the very high mountains of the world exhibit these features.

The Former Great Ice Sheets. The New England-Adirondack region, the highlands of Scotland and Ireland, and the interior of British Columbia are mountainous, and, except for some of the highest peaks, have been recently more than once glaciated; yet their landscapes differ strikingly from that described in the foregoing account. The crests of the ranges (Fig. 117) are not sharp; there are no knife-edge ridges and pyramid-like peaks. Cirques are very rare, and the few that are visible are poorly developed. On the contrary, even the ridges are smoothed and rounded, and striated bedrock surfaces are present on them as well as in the valleys. In any one district the striæ on all the ridges point in a single general direction. Evidently glaciation here did not involve frost wedging and the excavation of cirques, but consisted chiefly of abrasion. It is evident that these regions were affected not by mere tongues of ice in their valleys, but by huge ice sheets

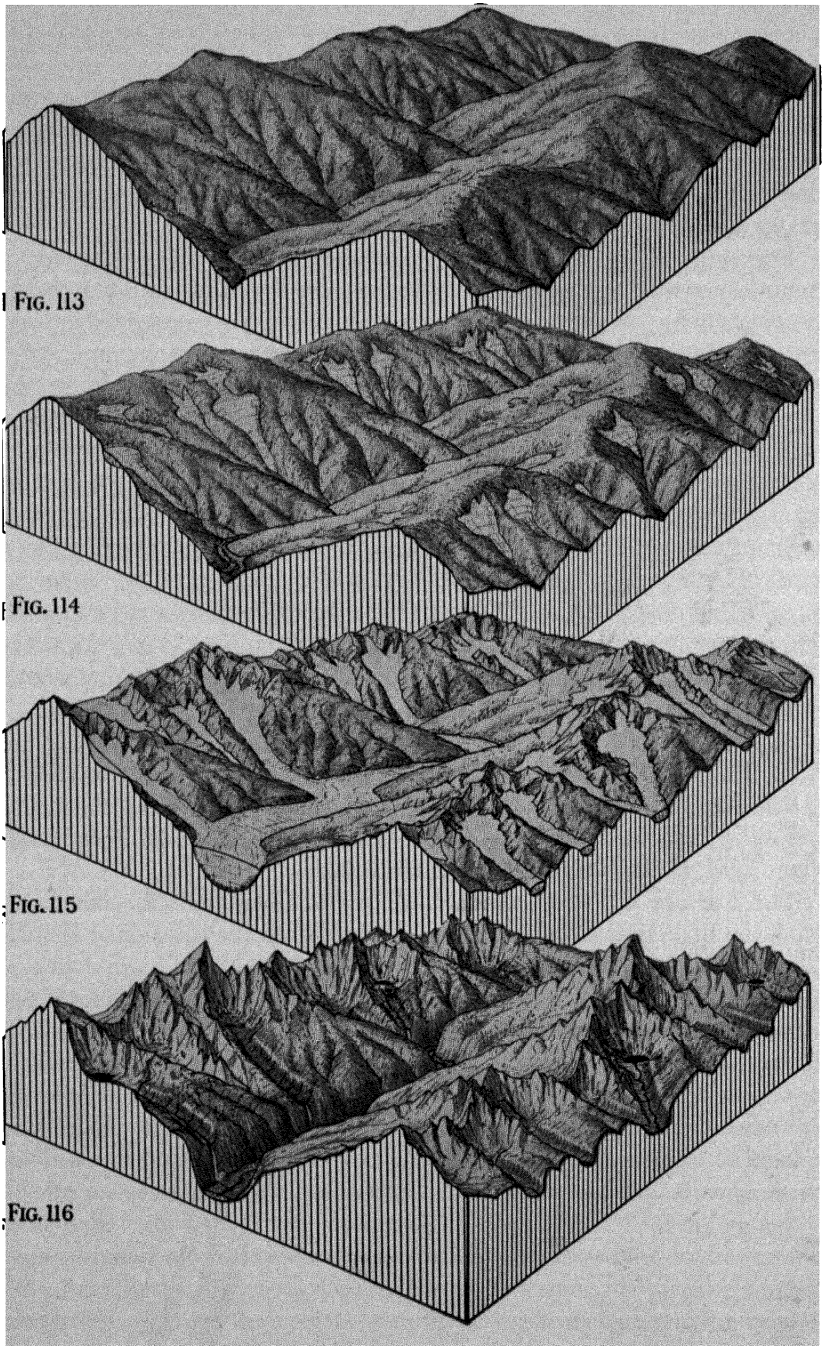


FIG. 113

FIG. 114

FIG. 115

FIG. 116

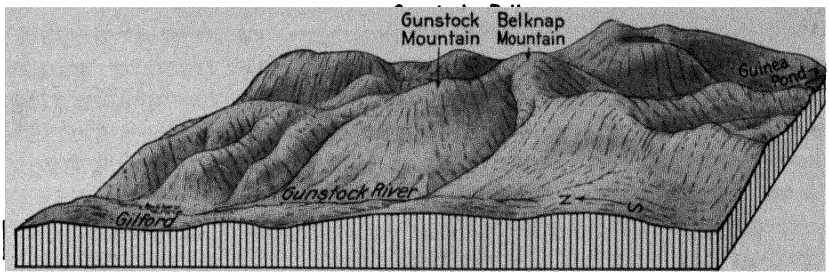
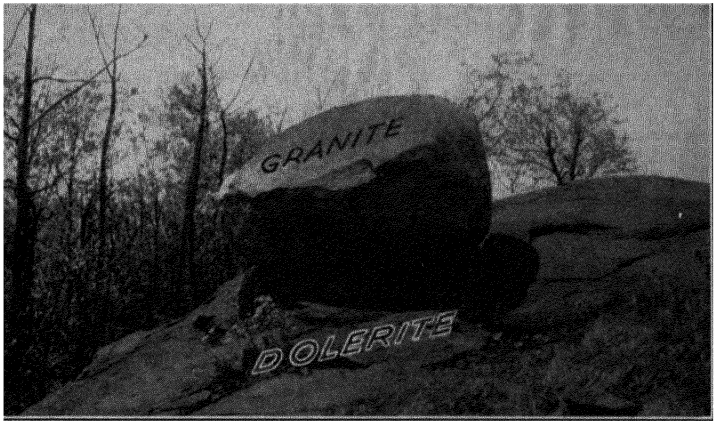


FIG. 117. Belknap Mountains near Lake Winnepesaukee, New Hampshire, showing profiles smoothed by ice sheets. Area of block, 5 × 4 miles. Maximum relief, 1800 feet. Vertical exaggeration, 2 times.



C. R. Longwell.

FIG. 118. Angular ice-transported erratic boulder of granite perched on the top of a high ridge of dolerite, Mount Tom, near Northampton, Massachusetts. The nearest outcrops of granite lie many miles away.

thousands of feet thick that overtopped valley and range alike, as do the ice sheets of Greenland and Antarctica today.

The area covered by the former ice sheets has been determined by tracing the limits of the glaciated regions. The latest centers from

---

FIGS. 113–116. Erosion of mountains by valley glaciers.

FIG. 113. A mountainous region being eroded by streams. The main valley is flanked by interlocking spurs.

FIG. 114. Evolution of cirques as the climate grows colder and snowfields become perennial. The snowfields in the cirques generate small valley glaciers.

FIG. 115. Coalescence of the small glaciers to form a large ice tongue in the main valley, enlargement of the cirques, and frost sculpture of the uplands.

FIG. 116. Appearance of the mass after further glaciation, followed by complete disappearance of the glaciers. The valleys have been deepened and widened, the interlocking spurs reduced, the tributaries have been left hanging above the main streams, and rows of empty cirques, some containing lakes, scallop the uplands, which in turn have been converted into knife-edged ridges punctuated by pyramidal peaks.

which they flowed radially outward have been located by determining the directions of grooves and striæ, the long axes of drumlins, and the paths followed by stray stones and boulders (*glacial erratics*, Fig. 118) derived from known sources in the bedrock. In some places even the general trends of eskers have been used. The results, for North America, are shown in Fig. 119.

The centers of two ice sheets lay on the Labrador Peninsula and in the district northwest of Hudson Bay. From them the ice flowed north and east into the Arctic regions, and south and west as far as New



FIG. 119. Extent of glaciation of North America at the maximum of the Ice Age. Somewhat generalized, especially in Arctic Canada, on which information is very scanty. The boundaries between glacier ice, sea ice, and open sea are conjectural, but are based on modern analogies. Arrows show generalized directions of glacier flow. Note relation of Ohio and Missouri rivers to former ice margins.

Jersey, Pennsylvania, the Ohio River, the Missouri River, and the east base of the Rocky Mountains. The ice of the two coalescent centers was probably more than 2000 miles in north-south diameter and 2500 miles in east-west diameter. The Rockies themselves, and adjacent high ranges in Canada, nourished a multitude of valley glaciers which coalesced as they flowed west and merged with similar valley glaciers flowing east from the high ranges near the Pacific Coast. The resulting great mass of ice, fed from high mountains on both sides, formed a huge piedmont glacier that flowed south into Washington and Idaho, and north to the Yukon, between the ranges that confined it. At its maximum extent this confluent mass of ice was 1200 miles long and 250 to 400 miles wide.

In Europe, the principal ice sheet centered in Scandinavia, and spread south and east as far as Scotland, the Netherlands, Germany, Poland, and Russia. Many mountain ranges in both Europe and North America supported large valley glaciers, some of which still exist, although greatly diminished in size.

Work of Former Ice Sheets. The work done by the vanished ice sheets is considerable. Throughout a huge area in Canada north of the Great Lakes, the weathered mantle was stripped away, and the ice bit into the fresh bedrock beneath, so that today it is naked or thinly covered with drift. Many of the thousands of lakes in that vast region lie in shallow basins scooped out of the rock by the ice.

Nearer the terminal zone the drift is more abundant. Although most of the material of the drift has not been moved more than a few miles, some of it has traveled many hundreds of miles. This is known by the finding of rocks far distant from their places of origin. Slabs of native copper from the great copper lodes of the Keweenaw Peninsula in Michigan have been found as far south as Missouri, and boulders of an unusual conglomerate containing reddish pebbles of jasper, found throughout Ohio, have been traced to outcrops of bedrock on the north shore of Georgian Bay in Canada. In eastern Finland, boulders of ice-transported copper ore were traced backward along the line of former ice flow. This resulted in the discovery in 1910 of Finland's most important copper mine. Several isolated diamonds of good quality have been found in glacial deposits in Wisconsin, Michigan, Ohio, and Indiana. Their position in the deposits indicated clearly that they had been transported and deposited by the ice, but their source is as yet unknown. It is inferred to be somewhere in central Canada.

The surfaces of New England, eastern New York, and the Scottish Highlands are strewn with glacial boulders (Fig. 118). In these regions of resistant rocks the former ice sheets found it difficult to grind

into sand and silt the fragments of bedrock they acquired. From Ohio to the Rocky Mountains and throughout northern Germany, however, the much softer bedrock was more easily ground up by the ice, and therefore in these regions large boulders are rare, those found being erratics from regions of harder rocks far to the north.

Influence of Former Ice Sheets on Drainage. Many of the streams flowing away from the glaciated region were choked with glacial sediments and built great deposits of outwash in their valleys. Parts of these deposits still remain; those made by meltwater that came from the latest of the ice sheets and flowed down the Mississippi valley have been traced down to the region of the river's mouth. Many valleys draining toward the expanding glaciers were filled with meltwater as the ice blocked their mouths, and in consequence numerous lakes were formed. Most of these lakes were drained when the glaciers shrank away, but some of the largest of them, including the present Great Lakes, still remain, partly because the flowing ice had scooped out the preglacial valley floors and thus formed rock basins, and partly because of blockades of drift not yet cleared away. As the ice shrank, it uncovered successively lower points in the basin rims and thereby caused the lake levels to fall. Even though the ice has disappeared, the lake water is still spilling over basin rims in several places, the most notable of which is Niagara Falls (pp. 72–74). The former, higher lake levels are still recorded in old shorelines, beaches, lake deposits, and outlet channels.

The Ohio River throughout the greater part of its length is chiefly a product of glaciation. Prior to the advance of ice sheets into these latitudes, streams in West Virginia and Kentucky drained northwest and north across Ohio and Indiana. The ice sheet flowing from the Labrador Peninsula blocked the valleys and ponded the streams. The rising lakes overflowed westward across the series of divides that lay nearest to the glacier margin, and the overflows were held in these positions long enough so that they were enabled to cut, along the ice margin, a single valley which was followed by the regional drainage even after the ice sheet had disappeared (Fig. 119). This valley is the valley of the Ohio River.

The Missouri River in the Dakotas had a similar history. Prior to the Ice Age the lower Missouri in Missouri and the upper Missouri in Montana were independent streams. An ice sheet flowing southwest from the region west of Hudson Bay blocked the normal easterly drainage of the intervening area, and forced it to flow south along the glacier margin, thus integrating the two rivers into the single stream of today (Fig. 119).

The successive layers of sand added to a dune are deposited parallel with its surface and so are more steeply inclined on the lee than on the windward side. Thus the form of a dune is reflected in its internal structure. When shifting winds partly destroy the original form the layers are cut across and their edges are covered by new layers deposited at a different angle. Therefore sand-dune deposits are characterized by extremely irregular *cross-bedding* (p. 199).



R. F. Flint.

FIG. 127. Sand stopped by protective fences built on the windward side of the Northern Pacific Railway at Vista siding, Washington.

Migration of Dunes. So long as the sand on its surface is free to move, a dune is not stationary. The windward slope is not a fixed incline up which the wind moves only newly acquired sand; the slope itself is eroded by the wind, and the sand grains removed from it are dumped over the crest. By this subtraction of material from one side and addition to the other the dune moves forward slowly, provided the wind direction is fairly constant. In this way dunes migrate steadily across low country (Fig. 126), and the movement halts only when grass or other vegetation gains sufficient foothold in the sand to hold it in place. In France and some other European countries belts of dunes moving from the coast have destroyed farm lands, forests, and villages. Along some parts of the Bay of Biscay and of the Baltic

region the menace of dune migration has been ended by skilful planting of trees and shrubs. In the United States also considerable damage has been done by drifting sand, particularly near some of the Great Lakes and along many parts of the coasts, both East and West. In some dune areas protective fences have to be built in order to prevent railways and highways from being buried in sand (Fig. 127).

Economic Value of Sand Dunes. Although dunes generally are destructive and barren, in some arid countries they are the only natural reservoirs of fresh water. The sands absorb the scanty rainfall,

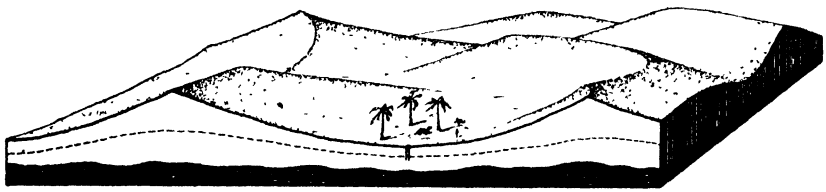


FIG. 128. A well in dune sand, northern Egypt. The dark portion of the block represents bedrock beneath the sand; the broken line shows the position of the water table

the water table rises in a curve roughly parallel with the surface (Fig. 128), and at favorable localities shallow wells furnish enough water to form oases of considerable size; in northern Egypt large groves of palm trees are supported in this way.

LOESS

What has become of the great quantities of material finer grained than sand that have been removed from land surfaces by deflation? Part of the answer is found in a peculiar yellowish, fine-grained sediment that covers vast areas in Asia, Europe, and North and South America. Typically it has no horizontal stratification, like that in ordinary sedimentary formations, but occurs in a single massive layer, 20, 50, or even more than 100 feet thick. On the other hand, it is full of slender perpendicular tubes which cause a rough vertical cleavage; for this reason it forms high bluffs along valley sides in spite of the soft, earthy character of the material (Fig. 129). This sediment, so similar in widely separated continents, is known by the German name *loess* (pronounced *lûs*, not *lo-ess*).

Although loess is exceedingly fine grained, examination with a powerful microscope reveals that a large proportion of the material is not decomposed but consists of fresh, sharp-cornered particles of feldspar, quartz, calcite, mica, and numerous other minerals mingled with clay. It is evident, therefore, that much of the material was ground up

mechanically, and that the particles thus formed were not affected by chemical weathering before their deposition. Because of these characteristics loess is interpreted as an accumulation of wind-blown dust. In support of this conclusion are the numerous shells of land snails and bones of land animals found in the deposits. Moreover, loess is distributed at various heights on very irregular topography; the wind is the only agent that could deposit in this way sediments that are uniformly fine grained. Lack of stratification is to be expected in wind-



U. S. Geol. Survey.

FIG. 129. Typical bluff of loess with vertical columnar structure. Near Beverly, Missouri.

laid dusts, since the deposit made at any one time is thin and after deposition it is worked over with the underlying sediments by rain, frost, worms, and growing plants. The vertical tubes that are so common in loess appear to represent the stems and roots of successive generations of plants that were buried by the accumulating dust.

In central Europe, in the Mississippi Valley, and in eastern Oregon and Washington, the dust forming the loess probably was supplied by the dried floors of temporary lakes and by floodplains of streams that drained from wasting glaciers during the Ice Age (Chap. 8). While these wide sheets of sediments lay unprotected by vegetation, the wind carried the finest-grained material and spread it out on the uplands; the abundance of fresh rock flour ground up by the ice movement explains the large proportion of unweathered, angular particles derived from many kinds of rocks and minerals.

In northern China an area as large as France is covered with loess with a maximum thickness of several hundred feet. This vast deposit of loess represents the age-long accumulation of dust blown across the mountains from the arid interior of Asia, and especially from the Ordos and Gobi deserts. Thus, although dust forming this loess was quite different in its origin from that in Europe and the United States, the material is similar because it also was prepared mechanically; in the deserts of Asia it is the result of disintegration and wind abrasion in an arid climate, and therefore fresh, angular particles make up a good proportion of the deposit. The Chinese loess forms the richest soil of China, and for centuries many of the humbler farmers in the hilly districts have made their homes in artificial caves dug into the steep loess bluffs.

Locally the Chinese loess is well stratified; but this exceptional stratification indicates that running water has moved and redeposited parts of the material after its original deposition by wind.

Loess and related deposits represent only the most conspicuous accumulations of wind-blown dust; unquestionably, dust carried in the upper air, supplied either by deflation or by eruptions of fine volcanic ash, settles slowly on the entire land surface and on the sea floor. Probably almost every layer of sedimentary rock contains at least a small amount of wind-blown dust. Some thick-bedded shales or mudstones are interpreted as loess laid down in various periods of geologic history and preserved by favorable circumstances to become part of the sedimentary record. Most loess deposits, however, because of their elevated positions on the continents and the weak character of the material, are subject to rapid destruction by stream erosion and mass-wasting.

Summary

The wind erodes, transports, and deposits some material in all regions, whatever the nature of the climate. However, it works most effectively in arid and semiarid lands, where the mantle is dry much of the time and poorly protected by vegetation. Wind erosion consists of deflation, the blowing away of fine debris such as dust and sand, and abrasion, the wearing of rock by wind-driven particles. Deflation is responsible for widespread loss of soil in semiarid regions where the sod has been destroyed by plowing or by overgrazing.

Wind deposits sand and other fine material in the form of dunes, which in many situations are migratory and become a menace to settled communities or to highways and railroads. Vast deposits of wind-blown dust, known as loess, form fertile soil in parts of Asia, Europe, and North America.

CHAPTER 10

THE SEA

The gradual crumbling of the land under the pounding of the surf is a fact familiar to all who have lived near the shore, especially along coasts composed of weak rocks. The seaward shores of Cape Cod and the islands near it yield to the sea 1 to 6 feet each year, and at the present rate these lands will disappear entirely at the end of about 4000 years, leaving only submarine banks to mark their former positions. Some stretches of the Yorkshire coast in England have been worn back a mile since the Norman conquest, and 2 miles since the time of the Romans. In the space of 200 years the town of Egmont, on the Dutch coast, was undermined and entirely destroyed by the persistent work of the waves. Cliffs near Dover on the English Channel are receding at the rate of 15 feet each year, and east of them the Goodwin Sands, now a shallow submarine bank, were formerly an island. The island of Helgoland off the mouth of the Elbe, once very large, was being eaten away so rapidly that it would by this time have disappeared entirely had erosion not been checked, near the end of the nineteenth century, by the construction of a strong sea wall.

All these examples concern coasts formed of weak materials, such as chalk, clay, and sand, but the effect of waves on resistant rocks is similar except that erosion takes place more slowly.

A study of shore processes has practical value, for destruction of the land by the sea can be stopped for long periods, measured in human terms, as is demonstrated by the case of Helgoland. Thousands of thickly populated districts where shore property is valuable have been artificially protected in this way. This study also furnishes answers to such broad questions as these: How far can the destruction of land by the sea be carried? Why do not beaches, bars, and other wave-built features stop marine erosion? And above all, since the sea-covered area of the Earth is three times as extensive as the land area, and since the Earth is admittedly very old, why have the continents not already been destroyed by marine erosion?

Functions of the Sea. The sea is a direct and energetic agent of erosion. Bit by bit it tears away the margins of the land, and thereby aids the streams in their work of wearing down the continents. Its

floor is the final resting place of all the rock waste eroded from the lands by waves and currents, and by streams, subsurface water, glaciers, and the wind. This land-derived sediment is shifted for a while along the sea floor, and, coming to rest, is ultimately solidified into the sedimentary rocks that form a conspicuous part of the Earth's crust.

Indirectly, too, the sea exercises a great influence on the development of the Earth's surface. The continuous existence of plants and animals recorded by fossils buried in the sedimentary rocks shows that throughout the hundreds of millions of years of geologic history the general temperature of the Earth has never fallen below the freezing point nor exceeded the boiling point of water. For this stability the nearly uniform rate of radiation of energy by the Sun is chiefly responsible, but the sea also serves as an important stabilizer by storing up excess heat against times of lessened solar radiation. The great currents that carry warm water from the equatorial zone into the higher latitudes and the currents that transfer cold polar water toward the equator likewise exercise an important influence in distributing heat more evenly upon the Earth's surface and in decreasing the contrasts between climatic zones. Moreover, in the last analysis, evaporation from the surface of the sea supplies all the moisture borne by the winds to fall upon the lands as rain and snow. Thus the sculpture of the lands by streams, glaciers, and subsurface water is ultimately dependent on the great reservoir of the sea.

The Attack on the Shore

Waves, Longshore Currents, and Tides

Waves. Waves are generated by the wind blowing along the surface of the sea, which is thereby thrown into undulations. When a wave passes into shallow water, it becomes higher and shorter and its front steeper and more deeply concave until the crest arches forward, loses its support, and collapses in a rush of water, forming a breaker (Fig. 130). The height of the wave determines the depth at which it will break, and therefore small waves break in very shallow water close inshore, whereas great storm waves usually break farther out, where the water is 10 to 20 feet deep.

Undertow. When waves break, they pile water up against the shore, and the piled-up water escapes in the form of *undertow* (Fig. 130), a more or less continuous current which, moving down a shelving bottom, carries rock particles with it. The rush of breaking waves up the beach carries more water to the beach than the corresponding backwash carries from it, because some of the water sinks into the beach.

In addition, the onrush has greater velocity than the backwash. The result is a sorting of the rock fragments being handled: the coarser pieces are moved forward and tend to accumulate on the beach, while the finer ones are gradually moved seaward. The larger fragments are dragged back and forth near the shore, and as they are abraded to smaller and smaller sizes (becoming rounded during the process) they are gradually shifted seaward. As they grow fine, they are moved in suspension rather than on the bottom, and at length each particle drops out in places too deep to be affected by motion of the water.

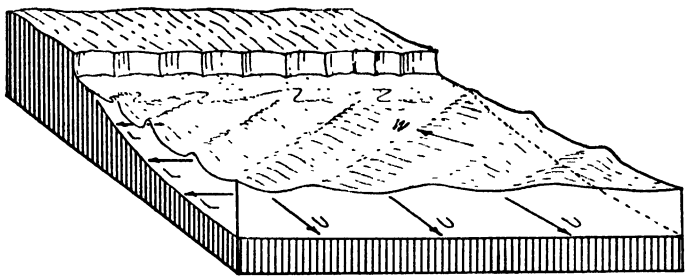


FIG. 130. Relation of undertow (*U*) and longshore currents (*L*) to direction of waves (*W*), when waves strike the shore obliquely. In the background are a wave-cut cliff and beach.

Longshore Currents. Longshore currents are set up by waves that strike the shore obliquely, and thus give the piled-up water a component of motion along the shore (Fig. 130). Because nearly all waves are oblique to the shore, longshore currents are common. They are also fairly steady because they are the result of waves generated by prevailing winds. Sweeping rock waste along, the currents tend to remove it from exposed headlands and to deposit it in protected bays (Fig. 131). They are largely responsible for the formation of beaches, spits, and bars. The fine sand of Daytona Beach, Florida, includes minerals that occur, not in the rocks of the Florida coast, but in the rocks of the Georgia and Carolina uplands. For this reason it is believed to have been swept by the prevailing south-moving longshore currents from farther north, where the rivers of Georgia and the Carolinas bring it down to the sea out of the southern Appalachians.

Tides. The combined gravitative attraction of the Moon and the Sun pulls the surface of the sea into two low but vast bulges, one on each side of the Earth. These bulges cause the tides.

These immense tidal bodies of water, ceaselessly moving in and out of bays and estuaries and along coasts, set up strong currents which

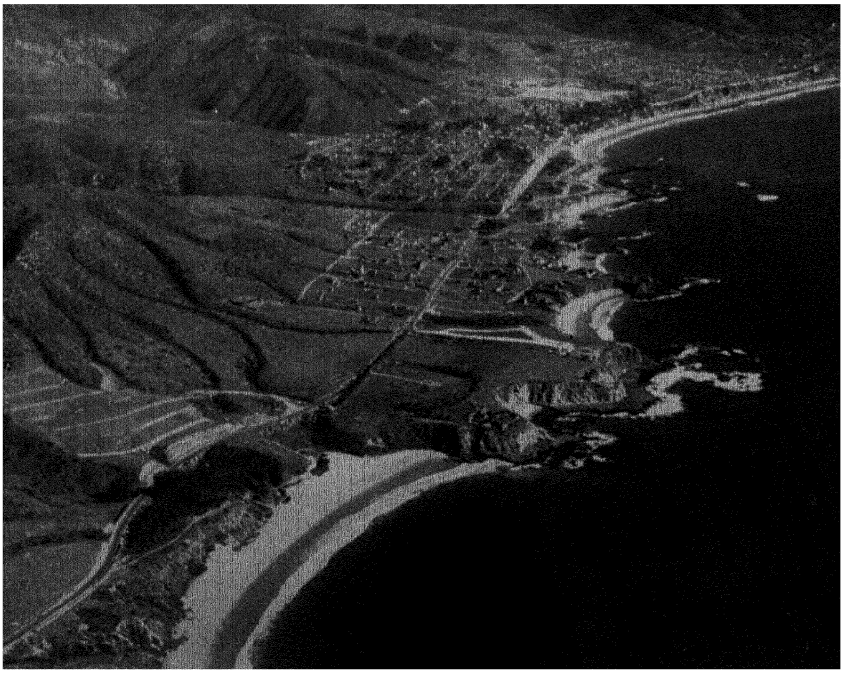
scour the bottom and transport quantities of sediment. The rise and fall of the tides also aid indirectly in the attack of the waves on the land, by increasing their vertical range.

EROSIONAL SHORE FEATURES

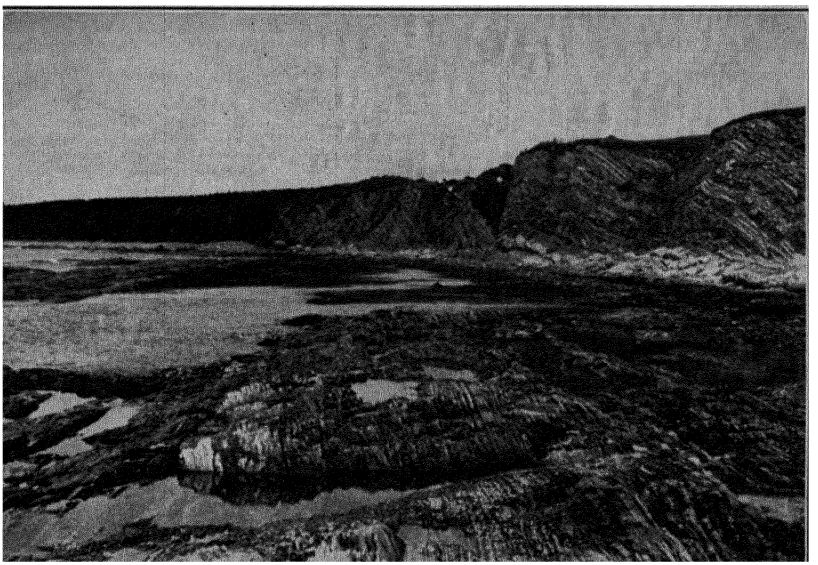
Cliff and Bench. The damage done by storms to piers, breakwaters, and similar structures is a rough yardstick for measuring the force of sea waves. At Wick, Scotland, during a great storm in 1872, a solid mass of stone, iron, and concrete weighing 1350 tons was torn from its place at the end of a breakwater and dropped unbroken inside the pier. The damage was repaired with a much larger block, weighing 2600 tons, but, in a storm five years later, the waves carried away this one too. It is not surprising, therefore, that the faces of cliffs are shattered by the impacts of storm waves. Hydraulically compressed air is an additional factor important in eroding cliffs of fissured and jointed rocks. The air in the fissures, violently compressed by the impacts of the waves, acts as a wedge, springing out large pieces of rock.

SPENCE AIR PHOTOS.

Fig. 131. Coast near Laguna Beach, California, showing wave-cut cliffs and shallow bays fringed with beaches.



These pieces, together with rock fragments contributed by streams, are rubbed together and ground against the shore by every breaking wave. By this process the sea inexorably advances on the land as the opposing cliffs yield ground. The rock fragments dislodged from the cliffs are angular when first seized by the waves, but as they are handled by the sea they become smoothed and rounded (Fig. 122, *B*, p. 160) by abrasion, until they come to resemble stream-worn stones.



R. F. Flint, Geological Society of America.

FIG. 132. Wave-cut cliff and wide wave-cut bench cut across steeply inclined sedimentary rocks north of Bonne Bay, Newfoundland, exposed at low tide. The beach is unusually scanty; it consists of a few rounded stones and boulders.

As the wave-cut cliff retreats under the attack of the sea, it leaves behind it an ever-widening rock platform over which the water is shallow. This is the wave-cut bench (Fig. 132). Its submerged surface is lowered by abrasion as waves and undertow sweep debris back and forth across it.

SHORE PROFILE OF EQUILIBRIUM

The power of waves beating against a coast bordered by deep water immediately offshore is applied entirely to eroding the cliff, because the waves lose no energy by dragging bottom before they reach the shore itself. As the cliff retreats and the wave-cut bench is correspondingly widened, and the cliff debris increases in volume, more and more wave

energy is spent in grinding up rock fragments and in transporting the finer particles to deep water. Thus the work to be done increases, while on the contrary the power of the waves to do work along the shore steadily diminishes. Therefore a time comes when these two elements are balanced; when, in other words, there is a close adjustment between the amount of rock waste on hand, and the amount of wave energy available to deal with it. This delicate adjustment — a mean through which the opposed forces continually fluctuate — is recorded by the steepness of the curving shore profile (Fig. 133), which then becomes a *profile of equilibrium.* The inclination of the profile of equilibrium depends chiefly on the strength of the waves and the kind of rock waste being handled.

Any disturbance of this balance results in adjustment that tends to restore balance. An increase in the supply of debris, for example, makes the profile less steep and slows up erosion of the cliff until the

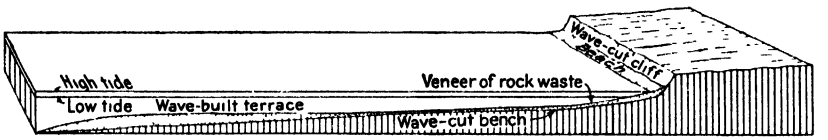


FIG. 133. Wave-cut cliff with beach at its base, wave-cut bench veneered with rock waste, and wave-built terrace made of accumulated debris. The exact form of the wave-built terrace is conjectural.

increase has been got rid of by seaward transport; an increase of wave energy steepens the profile and speeds up the attack on the cliff until the resulting increased supply of rock waste again becomes adjusted to wave energy. The evolution of a new shore profile into a profile of equilibrium is like the evolution of part of the long profile of a very young stream into the graded profile of a mature stream. Like the long profile of a stream, the shore profile of equilibrium gradually flattens out as erosion and deposition continue.

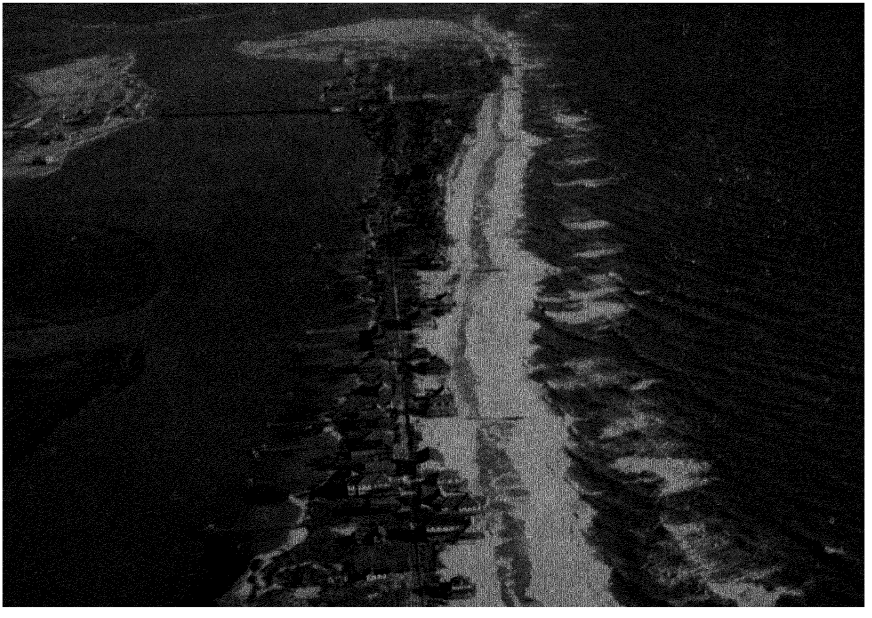
In the profile-of-equilibrium concept, we can now see the answer to the question often asked, and repeated at the beginning of this chapter: why do not beaches and bars stop erosion by the waves? These features are built of sediments *in transit,* and are entirely subsidiary to the long-continued process of erosion by the waves.

DEPOSITIONAL SHORE FEATURES

Usually the wave-cut bench is partly or wholly covered by a beach consisting of wave-handled debris. This debris is in process of being shifted slowly seaward, and it gradually comes to rest in water too deep



Fig. 134. Poponesset "Beach," a spit evolving into a bay bar along an embayed coast. Cotuit, Cape Cod, Massachusetts. The free end of the spit is being turned shoreward by waves and currents moving past it. [FAIRCHILD AERIAL SURVEYS.] *Fig. 135. Bar, probably of the offshore type, near Wilmington, North Carolina. Lagoon and mainland appear to the left; in the background the bar is broken by an inlet. The seaward slope of the bar, a popular bathing beach, is protected by groins, several of which are visible.* [MC LAUGHLIN AERIAL SURVEYS.]



to permit its further transport. Here the beach grades into the wave-built terrace.

In addition to the beach and wave-built terrace other shore features are built by waves and currents. Longshore currents sweep debris from headlands into the deeper water of bays, where, losing velocity, they dump in embankments and build them above sealevel. As long as their far ends are free, these embankments are termed *spits*. Spits not seriously impeded by transverse currents continue to be built across the bays, closing or nearly closing them, and thus form *bay bars* (Fig. 134). Other bars are built in the sheltered water between islands and the mainland, "tying" the islands to the mainland.

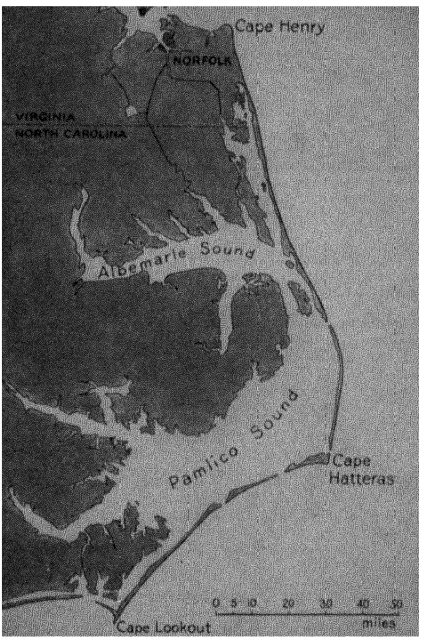


FIG. 136. Large bars inclosing bays and lagoons, in the region of the Carolina capes. The bays are drowned former stream valleys.

As a result of abundant stream deposition from the land, or warping of the crust, or other causes, the offshore slope of the bottom may be less steep than the slope required for a profile of equilibrium. Under these conditions the line of breakers lies well offshore. The waves drag the shallow bottom and pick up sediment which they carry forward to the line of breakers. Here they drop it, building up a narrow ridge or *offshore bar* (often popularly called a "barrier beach") parallel with the general trend of the shoreline (Fig. 135). Wave excavation continues to seaward of the bar, until the profile of equilibrium is attained. The bar itself may be built above sealevel by storm waves, inclosing a shallow lagoon between it and the mainland. The ideal offshore bar is thus a wave-built feature, in contrast with the ideal bay bar, which is built by longshore currents. Probably most bars have been built by interplay of the two processes.

In general, the Atlantic and Gulf coasts of the United States exhibit nearly continuous bars, with bays and lagoons developed on a large scale. At Cape Hatteras (Fig. 136) the bar is about 20 miles from

the mainland, but along the east coast of Florida, as at Palm Beach and Miami Beach, it is near shore, and the lagoon in consequence is very narrow. The city of Galveston is built on a bar, and its disastrous flood of 1900 occurred when high seas, driven by a hurricane, rose 15 feet above their normal height.

SHORE PROTECTION

Buildings and other costly structures standing close to the shoreline frequently require protection from the erosional inroads of the sea. Three general methods are employed to combat erosion of the shore in such places. One is the construction of seawalls along the shore and of breakwaters offshore. The waves are obliged to attack and destroy these structures before they can resume their erosion of the ground back of them. A second method is the construction of groins — low walls extending from the shore out into the water (Fig. 135). Groins are effective in many places where longshore currents are loaded with debris, because they check the currents and cause the deposition of the debris between the groins, thus forming a new beach which protects the land behind it. A third method is the hauling or pumping of sand from elsewhere on to the strip of shore to be protected. Ordinarily this operation has to be repeated annually, and is used commonly in conjunction with the construction of groins. As shore property becomes more and more intensively utilized, protection of the shore will become an increasingly important problem.

THE CYCLE OF EROSION ALONG COASTS

Bold Embayed Coasts. Although the coasts of the continents exhibit endless variety, let us consider two types that occur very commonly. A bold coast marked by long deep bays between pronounced headlands, with comparatively deep water and some islands offshore, is shown in Fig. 137. This general type of coast occurs in northeastern North America and most of western Europe. Its irregular shoreline is the result of depression of the land or actual rise of sealevel, or both, drowning the valleys and thus forming the bays. The headlands, being most exposed to wave attack, are eroded to form cliffs (Fig. 138), and the resulting debris is built by waves and currents into beaches, spits, and bars (Fig. 139). The streams on the land deposit sediment in the bays, and gradually fill them as the headlands are worn away (Fig. 140), until eventually the irregularities disappear and the shoreline becomes comparatively straight. The shoreline can then change no further, but the cliffs continue to retreat, and the wave-cut bench continues to be widened (Fig. 141) indefinitely.

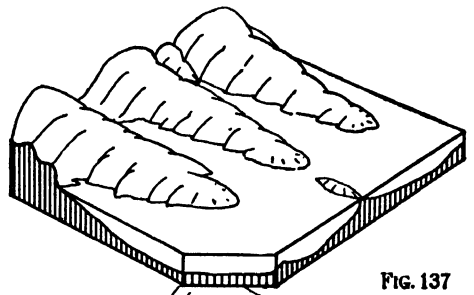


FIG. 137

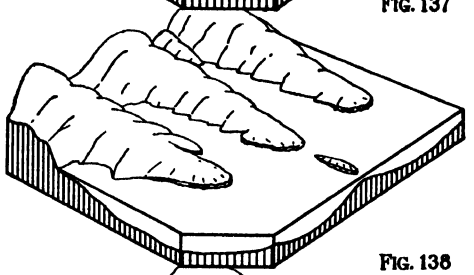


FIG. 138

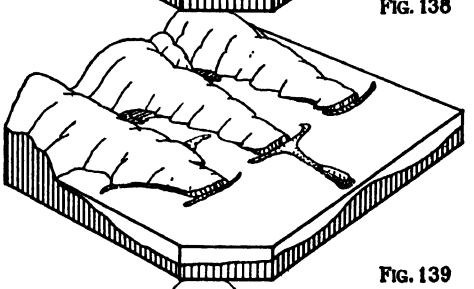


FIG. 139

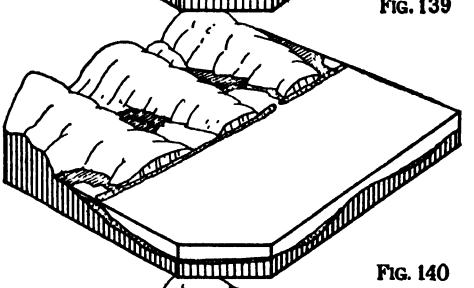


FIG. 140

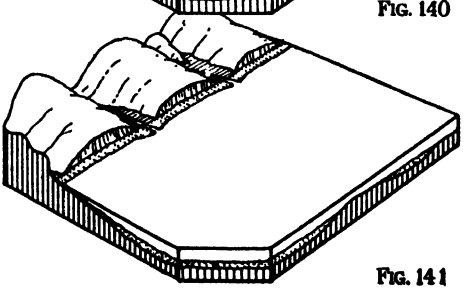


FIG. 141

Low-Plain Coasts. Figure 142 shows a quite different kind of coast — a low plain devoid of bays and peninsulas, and having extremely shallow water offshore. Such a coast results from the spreading of great quantities of alluvium into the sea faster than the waves can attack and remove it; it may result also from emergence that brings a broad area of shallow sea floor out of water. As a result of the shoal water, the waves drag bottom well offshore, and pick up sediment which is dropped at the line of breakers, gradually building an offshore bar (Fig. 143). Built up above sea-level by storm waves, the bar forms islands inclosing a lagoon.

Modified after D. W. Johnson

FIGS. 137–141. Evolution of one type of shoreline on a bold embayed coast.

FIG. 137. Initial condition, marked by deep bays, headlands, and islands.

FIG. 138. Cliffing of headlands.

FIG. 139. Building of beaches and spits. An island has been tied to the mainland by a bar.

FIG. 140. Formation of truncated headlands connected by bars, forming a much-simplified shoreline. The shortened bays are being filled with stream deposits and vegetation.

FIG. 141. Headlands and bays destroyed and shoreline simplified to the greatest possible extent.

The sea floor outside the bar is gradually excavated by the waves, the eroded material is added to the bar, and the profile is converted into a profile of equilibrium. The waves are then able to break with force against the bar itself, eroding its seaward face. Part of the resulting debris is carried out to sea, and during storms part is thrown over the bar into the edge of the lagoon. By this process of erosion of its seaward face and deposition on its lagoonward face, the bar is gradually shifted shoreward (Fig. 144). At the same time longshore currents add to the length of the bar by building out one or both of its free ends.

Meanwhile the lagoon, shallow even at the start, is slowly filled with sediment washed into it from the land,

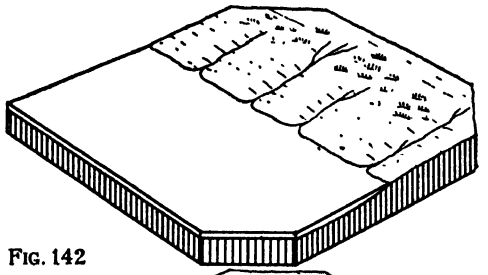


FIG. 142

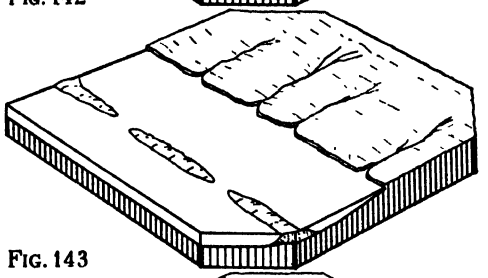


FIG. 143

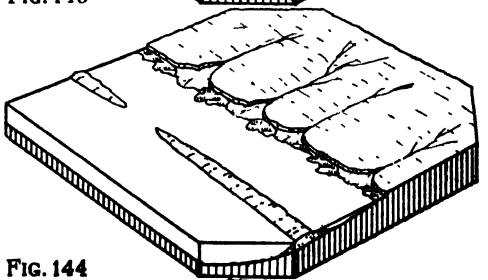


FIG. 144

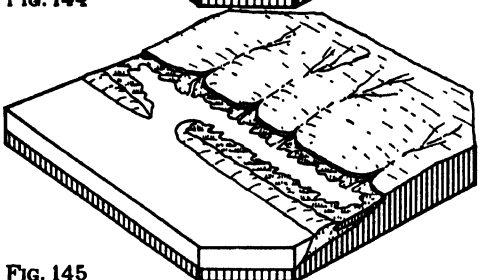


FIG. 145

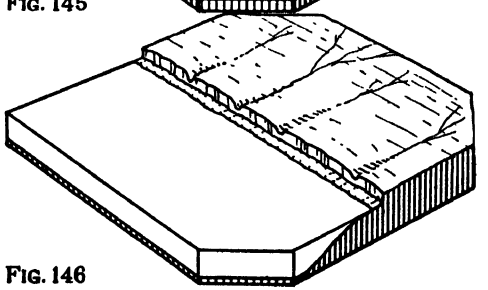


FIG. 146

FIGS. 142–146. Evolution of one type of shoreline on a low-plain coast.

FIG. 142. Initial condition, marked by excessively shallow water offshore.

FIG. 143. Formation of offshore bar and lagoon.

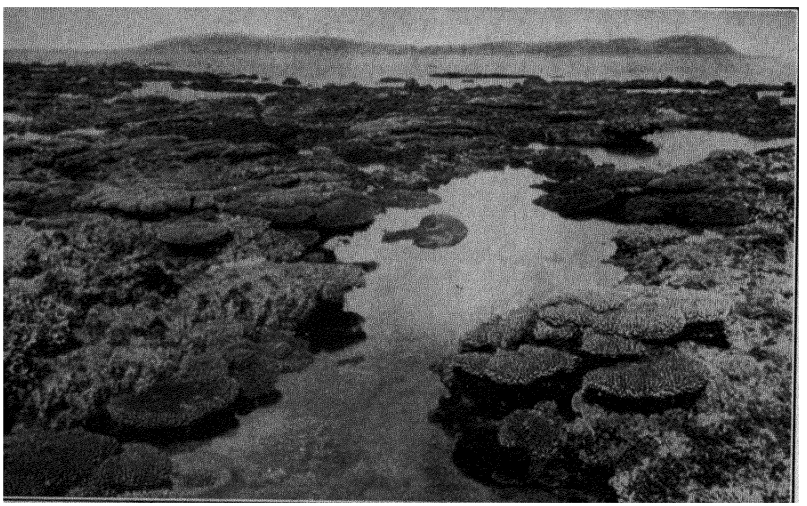
FIG. 144. Shoreward migration of the offshore bar and beginning of filling of the lagoon.

FIG. 145. Continued migration of the offshore bar and conversion of much of the lagoon into tidal marsh.

FIG. 146. Removal of the offshore bar and tidal marsh, permitting the waves to attack the mainland directly.

as well as with the sediment thrown over the bar. Where the water is shallow enough, vegetation thrives and adds its quota to the accumulating sediment, locally forming tidal marshes (Fig. 145; p. 124). As the bar is driven shoreward the lagoon becomes a tidal marsh throughout its extent. Eventually both bar and lagoon filling are completely cut away as the breaking waves continue their attack upon the land. With the disappearance of the offshore bar a wave-cut cliff and beach are rapidly formed (Fig. 146) and the cliff retreats and the bench widens indefinitely.

Much of the Gulf Coast of North America is a low-plain coast of this general kind. In most places it has already progressed to the stage of extensive bar building.



Saville Kent.

FIG. 147. Growing corals, visible at low tide, on the Great Barrier Reef of Australia. View looking across the lagoon toward the mainland 20 miles away.

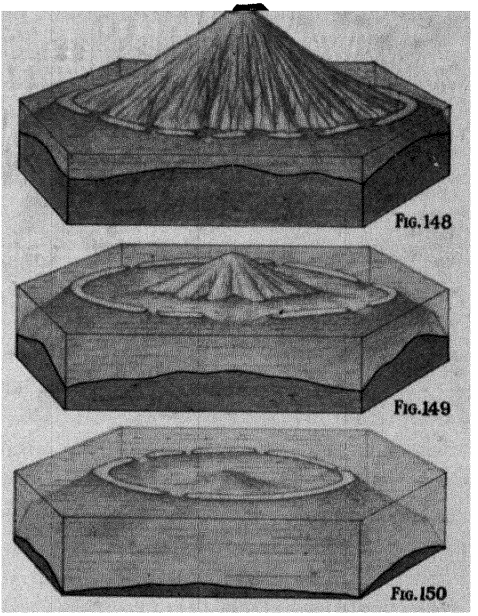
Both the bold embayed coast and the low-plain coast just described are ideally simple. Actually the histories of most coasts are complex, involving both upward and downward movements of the land relative to sealevel, and require very detailed study before they can be fully understood.

ISLANDS

Types of Islands. Here and there the surface of the sea is interrupted by islands and by submerged peaks that are not quite islands.

Many of these are the tops of hills, mountains, and larger land masses that have been submerged (Fig. 137). Most of the islands off New England and the British Isles were so formed. Others, including Bermuda, the Azores, many of the smaller West Indian islands, and the majority of the smaller Pacific islands including the Hawaiian group, are volcanic cones built up on the sea floor. Smaller islands are sometimes formed by the rock residuals left by wave erosion, and by deposits in the form of off-shore bars.

Coral Reefs. In the warm shallow water around many tropical and subtropical islands, especially in the Pacific, coral reefs abound. Corals (polyps), other shell-forming animals, and lime-secreting marine plants build these elaborate structures of calcium carbonate which they secrete as limy skeletons outside their bodies. The corals reproduce by budding in plant-like fashion, so that colonies of many thousands of individuals, each living in its own tiny protecting chamber like a cliff-dweller in a city of stone, combine to build a structure of great size.



FIGS. 148–150. Types of coral reefs.

FIG. 148. *Fringing reef*, growing around the margin of a volcanic island.

FIG. 149. *Barrier reef*, grown upward from a fringing reef during either sinking of the island or rise of sealevel. The reef now incloses a lagoon.

FIG. 150. *Atoll*, grown upward from a barrier reef during further submergence of the island.

As the colonies expand and build upward, the older organisms die, and gradually the dead base is buried by the growth of new generations and by the debris broken by storm waves from the living parts above. The accumulating deposit is eventually cemented into a white spongy limestone upon whose upper surface the living organisms flourish (Fig. 147). The resulting structure is a *coral reef*. Over the reef the waves swirl and break, and at its outer edges, where oxygen, calcium carbonate, and food material are most abundant, the organisms thrive best. Figures 148-150 illustrate three common types of reefs, differing from each other only in their relation to the land.

The Sea Floor and the Sediments on It

Deep-Sea Basins and Continental Shelves. The enormous depressions that contain the greater part of the sea are the largest individual features of the Earth's crust (Fig. 1). Not only is their combined area more than twice that of the continental masses, but they have an average depth of 2½ miles, whereas the average height of the continents (above sealevel) is only about half a mile.

At present the sea more than fills its basins, and, spilling over them, it floods the margins of the continental masses, covering the continental shelves with shallow water (Figs. 1, 151). The shelves are widened partly by continuous erosion of the land by the sea and partly by the

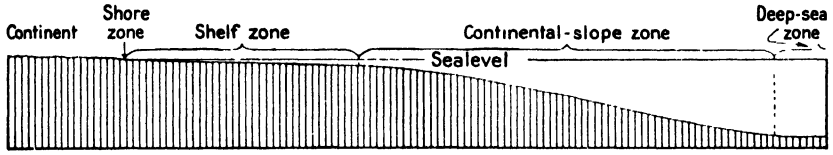


Fig. 151. The four marine depth zones at the margin of a continental mass. Vertical exaggeration 10 times.

deposition of sediment swept into the basins by marine currents. Along stable coasts where these processes have operated with least interruption for a long period, the shelves are broad. Thus the shelf off the Atlantic coast of North America is 60 to 80 miles wide in the latitude of the Carolinas. The shelf off the unsteady Pacific Coast, however, is in many places less than 10 miles wide, because throughout recent geologic time this part of the continental mass and the adjacent deep-sea floor have not stood still long enough to allow a broad shelf to be made.

Depth Zones. There is a marked distinction between the depth of water over the continental shelves (whose greatest depths range from about 350 to more than 600 feet) and the depth of water in the deep-sea basins themselves. The shelves slope off into the basins, forming *continental slopes,* most of which are gentle and are many miles in length from top to base. Accordingly three important depth zones can be recognized: (1) the *shelf zone,* covering the continental shelves, (2) the *continental-slope zone,* covering the continental slopes, and (3) the *deep-sea zone,* covering the deep-sea floor. At present the combined area of the first two is but a fraction of the area of the third, although a slight upwarping of the deep-sea floors with concurrent downwarping of the continental masses would enormously increase the shelf zone by forcing the sea to spread far inland over the lowest lands.

A fourth zone must be included to make the classification complete: a *shore zone*, embracing the area between the levels of high and low tide, and therefore losing its water twice every day. These four zones (Fig. 151) have an important geologic significance, because the processes in operation upon them, the deposits being formed within them, and the forms of life that inhabit them differ strikingly from zone to zone.

Topography of the Sea Floor. The sea floor was formerly conceived to be a monotonous plain with gentle slopes and very little local relief. This belief resulted from the fact that until recently, soundings were made from exploring ships by the process of paying out wires to which weights were attached. This operation was so laborious that soundings were few and too widely spaced to detect much local relief. Within recent years, however, there has been developed a method whereby sound waves are transmitted from a ship to the bottom, from which they are reflected and are picked up again on the ship by an instrument which automatically calculates and records the depth. The position of the ship is determined by surveying methods, and in this way an area of sea floor can be charted both quickly and accurately.

Sound-wave surveying of this kind has revolutionized our picture of the sea floor. Instead of the plains-like surfaces that were once believed to be nearly universal, broad areas of the floor are now known to have an intricacy of detail that rivals that of complex land surfaces. In some places the detail appears to have resulted from local warping and faulting of the crust (p. 244) and submarine volcanic activity, but in others it consists of valley systems somewhat like those that diversify the land (Fig. 152). Geologists are not agreed as to whether these features are valley systems cut by streams and later submerged, or depressions excavated by currents beneath the sea.

Sea-Floor Sediments. Depth of water is a factor supremely important to marine deposition, for it determines the effectiveness of waves and currents in distributing rock waste worn from the lands, and at the same time, by controlling the sunlight and heat that penetrate to the sea floor, it regulates the habitats of rock-forming sea animals and plants.

No two marine regions are exactly alike in the nature and distribution of the sediments that are accumulating upon them, but certain general principles are applicable to all. The rock waste derived from the land is in more or less constant transit seaward, until bit by bit it comes to rest upon parts of the bottom too deep to be reached by waves and currents, and there it remains as long as those parts of the sea become no shallower.

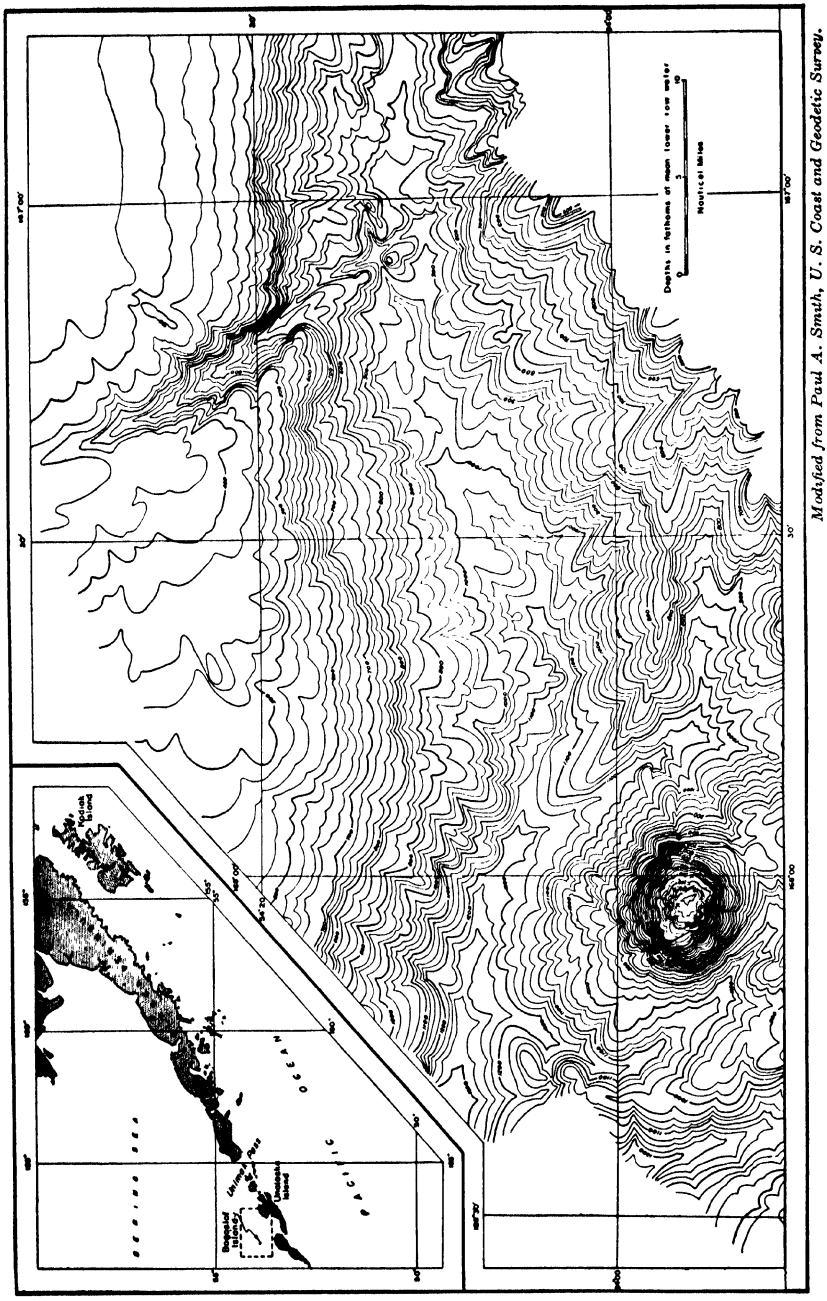


FIG. 152. Submarine topography near Bogoslof Island, Bering Sea. (See explanation at left.)

Note the broad shallow shelf at the north, the system of valleys or valley-like features reaching depths of more than 1250 fathoms (7500 feet), and the volcanic cone of Bogoslof. The tiny irregular area at the summit of the cone is Bogoslof Island, one mile long, the only part of the map area that is above sealevel.

The continental shelves and continental slopes are mantled with fine sediments washed out or blown out from the land. But the deep-sea floor is widely covered with extraordinarily fine, slimy deposits known as *oozes*. Thousands of samples have been caught by ingenious scoops let down on wires many miles in length from specially equipped vessels. In recent years the scoops have been replaced by a heavy gun which, when it reaches the bottom, fires a 10-foot tube like a giant apple corer, into the sea floor. The tube closes, and the core of sediments is hauled to the surface.

When these oozes are examined under the microscope, they prove to be made up of fine wind-blown dust (much of it volcanic), meteoritic dust fallen from outside the Earth, and a great quantity of shells of microscopic floating animals and plants that have drifted down upon the deep-sea floor.

Composition of Sea Water. About 3.5 per cent by weight of sea water consists of dissolved mineral substances, most of which have come from the lands (p. 191). When sea water is evaporated, more than three-quarters of its mineral content is precipitated as common salt (NaCl). Among the many other substances present are calcium carbonate ($CaCO_3$) and silica (SiO_2), both present in small quantities although delivered to the sea by the rivers of the world in large quantities. They are prevented from accumulating in the sea through being removed by chemical precipitation and by marine organisms which use them in forming their shells. The total quantity of the salts dissolved in the sea is astonishing. If precipitated and crystallized into a bed of solid salts, it would form a layer nearly 150 feet thick over the entire surface of the Earth.

Summary

The effect of waves along coasts is to erode the land. The shore retreats, and the eroded rock waste is carried seaward and spread out on the sea floor. During the process, the cliff and bench, the beach, and the bars of various types are fashioned. The detailed changes that occur depend in part on the form of the coast at the outset of erosion.

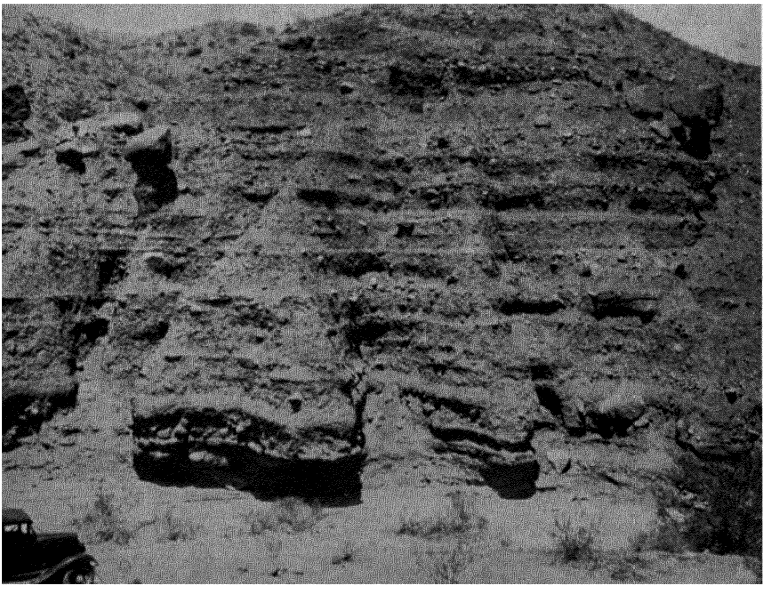
In the opening paragraphs of this chapter we asked: How far can the destruction of land by the sea be carried? Now we have the answer: In theory there is nothing to prevent all the lands from being gradually eaten away by the sea. But actually the possibility is very remote, because the uneasy crust does not stand still long enough to permit the thing to happen. A very slight uplift suffices to bring a great deal of land out of water, and when this happens (it

has happened many times during the Earth's decipherable history) the process of erosion by waves is forced to begin again long before the original job has been completed.

What of the rock waste produced by this erosion? Most of the sediment thus derived from the land settles to the bottom in the comparatively shallow shelf zone; very little of it reaches the deep-sea floor. Most of the sedimentary rocks exposed in the continents were once marine shelf-zone sediments that have been converted into rocks.

strata, the sedimentary rocks are known also as *stratified* rocks (Fig. 153).

Sediments now being formed, or formed so recently that we can be sure what were the conditions under which they were laid down, can be seen at many localities. In an alluvial fan (p. 78), the abandoned stream courses radiating from the apex of the fan expose vertical sections that they have cut into the deposit. In these sections we can see the material of which the fan is made and its arrangement or structure (Fig. 154). Recent stream-laid deposits also can readily be examined. Reservoirs that for some reason have been drained off become gullied, and these gullies furnish excellent cross-sections of the accumulated sediments. The cores of deep-sea sediment brought up from the bottom of the North Atlantic Ocean in recent years (p. 185) give us sections as much as 10 feet long of the material that is now accumulating there. The sediment contains shells of organisms of the kinds living in the surface waters as well as of those living on the muddy sea floor. Thus the environmental conditions in which the sediments are accumulating as well as the sediments themselves are completely known. To all these examples, from fan deposit to deep-sea sediment, we can apply the uniformitarian principle of Lyell that the present is the key to the past (p. 10). The facts obtained by examining sediments now being formed under known conditions help us to interpret how the sediments in the past were formed.



C. R. Longwell.

FIG. 154. Deposits in an old alluvial fan (fanglomerate), now exposed in the steep side of a youthful stream valley. The largest boulders in the deposit are 5 or 6 feet across. Grand Wash, Arizona.

For the problem considered in this chapter is the inverse of that considered in the earlier chapters, which explain the processes now visibly operating on the Earth. The problem now before us is one frequently met in geology. It is this: Given a sedimentary rock, what can we infer in regard to the conditions that prevailed while it was forming? Where was the land mass from which its material was derived, what was the climate of this land mass, and what was the nature of the rocks in it, how was the material carried to the place where it was deposited — was it carried by water, wind, or ice — and what conditions prevailed at the place where the sediment accumulated?

Origin and Kinds of Sediments

The products of the wearing down of the land area of the globe by erosion are of two kinds: one, mechanical — fragments of rocks and minerals (detritus, p. 36), and the other, chemical — substances, such as calcium carbonate, dissolved by the waters of the streams. The fragments are eventually dropped by the transporting agent, be it water, wind, or ice, and they accumulate as a sedimentary deposit. The dissolved matter is carried to the sea, where some of it separates from solution and the remainder accumulates in the sea water. Consequently there are two main classes of sediments: (1) detrital sediments, and (2) sediments separated from solution.

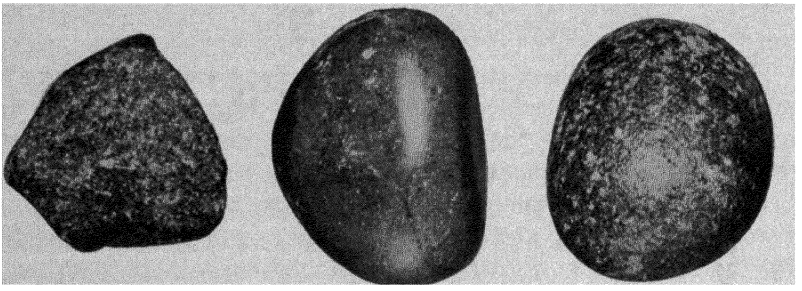
The detrital sediments are classified on the basis of the size of their constituent particles. In descending order of size they comprise *gravel, sand, silt,* and *mud.*

Gravel is a coarse sediment consisting mainly of rounded fragments larger than 2 millimeters in diameter; commonly more or less sand is admixed. When first torn from their parent ledges of bedrock, the stones that comprise the rounded fragments in a gravel were irregular, angular pieces bounded by joints or fracture surfaces. As the result of abrasion and impact in streams or waves they lost their edges and corners and became rounded; as the technical phrase goes, they have become water worn (Fig. 155). Angular and subangular pieces in gravels indicate, therefore, that they have not traveled far from where their parent rocks occur in place.

As they travel downstream, the pebbles of the softer and less coherent rocks are the first to be worn down to the size of sand. Consequently, hard materials, such as quartz and rocks composed of quartz, predominate in gravels that consist of well-rounded pebbles. Toughness, in the sense of resistance to fracture under impact, is even more important than hardness in prolonging the life of pebbles during transport. On the other hand, gravels whose pebbles have not trav-

eled far may include less durable minerals (feldspars) and rocks such as schist and limestone. Limestone pebbles, in fact, are rare in the gravels of humid regions, because they are reduced in size not only by abrasion but also, because of their relative solubility, by being dissolved.

Sand is composed of grains smaller than pebbles but exceeding 0.2 millimeter in diameter. Quartz is the commonest constituent in sand, because of its chemical indestructibility and its hardness; and unless otherwise specified " sand " means quartz sand. However, rock frag-



A. Angular stone. *B.* Subangular pebble. *C.* Well-rounded pebble.

FIG. 155. Degrees of rounding as shown by several stones. The longest diameter of each stone is about 1 inch.

ments and many minerals other than quartz, such as feldspar, occur in some sands. The beaches of coral islands are in places formed of " coral sand " made up of broken bits of coral and other organic remains; and the green sands on Hawaiian beaches consist of grains of olivine.

Silt is so fine grained that, unlike sand, it will cohere when wet. *Mud,* and its principal variety, *clay,* consist of particles still finer than those of silt size — less than 0.002 millimeter in diameter. Along with this decrease in grain-size goes a change in the minerals that make up the clay. Quartz decreases in amount, and the finely flaky minerals increase. During transport the flaky minerals, because of their easy cleavability, become comminuted to the tiniest flakes, and, because of their great tendency to float, these flakelets lag behind the quartz in settling out of the water in which they are suspended.

To its content of flaky minerals and the effect of the films of water on the flakes, which act as a lubricant, clay owes its most important technologic property — its plasticity, by virtue of which it can be molded when wet into any desired shape, and will retain this shape on drying.

Clays, as the products of the deposition of the finest detritus, have a wide range of composition. The most characteristic components, the flaky minerals already mentioned, are white mica, chlorite, and various compounds of aluminum. These minerals are formed chiefly by the chemical weathering of the source rocks. In glacial clays and silts deposited in lakes and seas receiving the meltwater from glaciers, particles of fresh, unweathered rocks and minerals predominate, however, since glaciers by their powerful abrasive action grind immense quantities of "rock flour," *i.e.*, rocks and minerals ground to an impalpable powder.

There remains yet to account for the fate of the matter taken into solution during the chemical erosion of the lands. Every square mile of the 40,000,000 square miles of the Earth's surface draining to the sea contributes yearly 70 tons of dissolved matter, mainly calcium carbonate and silica, but also many other constituents. Some of these minor constituents, such as phosphates and nitrates, are of profound importance in determining the abundance of life in the sea. We may add that one very minor constituent — iodine — is also of importance to life on land, being absolutely essential in human nutrition, and the main source of iodine in the soil is wind-borne spray from the sea.

The dissolved matter is in part withdrawn from the sea by various means; in part it accumulates, increasing the saltness of the sea. At many times in the geologic past, arms of the sea have evaporated sufficiently to cause the dissolved salts to be thrown down as rock-salt beds, but vast as these are, humanly considered, they are mere bagatelles compared to the enormous deposits of calcium carbonate that have been precipitated from the sea.

Limestone represents the dissolved calcium carbonate that was carried by the streams to the sea and was there withdrawn from solution. The solubility of calcium carbonate is extremely sensitive to the amount of carbon dioxide present in the water, and anything that decreases the content of the carbon dioxide in a saturated solution of calcium carbonate causes immediate precipitation of calcium carbonate. Rise of temperature drives off some of the carbon dioxide dissolved in the sea water and thus causes calcium carbonate to precipitate; precipitation of this kind is termed inorganic. Removal of the carbon dioxide by algae, plants of simple organization, which under the influence of sunlight are able to utilize the carbon dioxide in the sea water as a source of carbon in building their tissues, is another cause of precipitation; and certain groups of bacteria, by producing ammonia, which combines with the carbon dioxide, can cause precipi-

tation. Precipitation of this kind is called biochemical. In addition lime-secreting animals and plants abstract enormous quantities of calcium carbonate from the sea water to build their shells, and eventually these shells become incorporated in the sediments; removal of carbonate by organisms in this fashion is termed organic. Sediments formed by these processes acting singly or in combination, are rich in calcium carbonate and are termed *calcareous.*

Calcareous sediment in the form of a fine mud is now being precipitated extensively in parts of the sea. One of the largest areas in which this is taking place is the Bahama Banks, south of the Florida Straits. The area of this great shoal exceeds 7000 square miles, and the depth of the water over it averages less than 20 feet. Much of the floor of the shoal is mantled by fine white calcareous mud. The cause of deposition of this mud is still uncertain. Coral reefs are limited to the margins of the shoal and appear not to contribute much to the deposit at the present time. It is thought that bacteria, chiefly those of the group that produce ammonia, cause the precipitation of the calcium carbonate, but purely inorganic processes, namely evaporation and warming of the sea during the summer months, may have co-operated.

Silica, although carried in dissolved form to the sea in enormous quantity by the rivers of the world, is kept down to a vanishingly small amount because it is being steadily withdrawn by silica-secreting organisms — sponges, radiolaria (microscopic unicellular animals), and diatoms (microscopic unicellular plants), all of which use the silica in building their shells. In former times radiolaria and diatoms have flourished in such inconceivable abundance that their remains gave rise to thick series of strata of wide lateral extent. The organisms are so minute that there may be as many as a million to the cubic inch. Later these remains became transformed into exceedingly hard, waxy-lustered or porcelain-like rocks called *cherts.* Rocks formed in this way are common in the Coast Ranges of California and Oregon.

Tuff and *volcanic breccia* — rocks made of *pyroclastic* material (Chap. 16) in contradistinction to the detrital material produced by the fragmentation of older rocks by erosion — have formed stratified deposits, many of them of great thickness and wide extent. The finer pyroclastic material, the so-called volcanic ash, forms the most widely continuous deposits known. A single mighty explosive eruption, such as that of Tamboro, on Sambawa Island east of Java, in 1815, when between 28 and 50 cubic miles of material were blown out, can spread a continuous layer of tuff over an area of 1,000,000 square miles.

Tuffs and volcanic breccias are regarded by some as igneous rocks, because they are made by igneous activity; on the other hand they consist of fragments that accumulated according to the laws of sedimentation, and from this point of view they can be regarded as sedimentary rocks.

Conversion of Sediments into Rocks

Sediments when first laid down are generally loose, incoherent, and highly porous. They become changed into rocks by compaction as the result of sedimentary loading, by the deposition of cement in the pore spaces, and by physical and chemical changes in the constituents. Not all these processes necessarily affect every sediment. The result of any or all of them is to render the sediment firmer, harder, more coherent — it has been changed into a rock; it has become *lithified.*

Compaction by loading is most effective in the clay sediments. As the sediments grow in thickness, the overlying beds press more and more heavily on those below them. In clays this loading crowds the grains together and squeezes out the water in the pores. The clay becomes a shale. A freshly deposited clay has a porosity of 50 per cent or more; by the time the clay has been buried 1000 feet deep it has become compacted to 80 per cent of its original volume; to 60 per cent at 3000 feet; and to 55 per cent at 5000 feet.

Pressure produced by sedimentary loading is of minor effect in sands, causing little or no compaction, but it may aid them to become consolidated by welding, by bringing the individual grains into such close contact that the molecular attractive forces will cause them to cohere. The result of this process is to change the sand into a sandstone.

Another process that changes sediments into rocks is due to the habit of the colloidal constituents — the mineral jellies (the hydrates of silica, alumina, and iron) — to undergo spontaneous changes soon after coagulation, whereby they lose water and harden. Silica jelly (or "gel") when freshly precipitated is a soft, gelatinous mass; on *aging,* as the chemists say, it hardens into opal, and the opal may later crystallize into chalcedony. Changes of this kind, though affecting only the mineral jellies distributed in small amount through the mass of a sediment, can cause a marked increase in coherence and hardness.

Cementation is the deposition of mineral matter in the spaces between the grains of sediment. The most common cements are calcite, silica in the form of quartz or chalcedony, and iron oxide. These cements may be deposited concurrently with the crystallization

of any colloids disseminated through the sediments, or they may be brought in later, either from the adjacent body of sediment or from afar, by subsurface water moving through the pore spaces. Sands, because of their permeability, are particularly subject to cementation by material deposited in their pore spaces. The more cement brought in, the less pore space in the resulting rock. If the cement is quartz and was so abundantly deposited as to fill the interstices completely, the resulting rock is a quartzite.

Calcareous sediments manifestly are easily lithified, the resulting rock being a limestone; rarely do we find incoherent calcareous sediments, such as chalk. This ready change into limestone is doubtless determined by the relatively easy solubility of calcite.

The change of a sediment into rock by compaction, by the welding together of adjacent grains, and by the hardening caused by the aging of the colloidal constituents may go on practically contemporaneously with accumulation; or it may be postponed, and in some sediments it may never occur. In general, the older sediments have become more thoroughly consolidated than the younger. Sediments of geologically recent origin as a rule are loose and incoherent; the more ancient sediments have generally been converted into firm rocks. That time, however, is not the factor that converts sediments into rocks is shown by the occurrence of very ancient clays, which are still plastic; or of an ancient sandstone at Minneapolis that is so weakly cemented that it was cut with a high-pressure water jet during tunneling operations.

Characteristic Features of Sedimentary Rocks

Stratification. The most conspicuous feature of the sedimentary rocks as seen in exposures in the field is their layered structure (Fig. 153). Each layer is a *bed* or *stratum* (plural, *strata*), the two terms being synonymous. Beds differ greatly in thickness: from those hardly more than a film to those scores of feet thick. Each bed is separated as a rule from the bed below it and the bed above it by distinct parting planes or surfaces, which are the *bedding planes* or *stratification planes*.

Stratification is made most evident to the eye by the bedding planes. It is emphasized by the fact that adjacent beds may differ in color, or in composition, or in texture; commonly a bed differs from those inclosing it in all three of these characters. Other features, such as joint planes and the cleavage of slates, in places deceptively resemble stratification. Bedding is fundamentally significant in interpreting the geologic structure of a region, and therefore the ability to distinguish it surely from all other apparently similar features is of prime importance.

Sedimentary strata are horizontal or nearly so at the time when they are laid down. Consequently, strata that are flat lying, as in Fig. 153, are said to be in undisturbed attitude. In many places, however, they are found to be not horizontal but inclined or even standing vertically. We are then forced to conclude that they have been tilted from their original horizontal position; they have been disturbed, and if steeply inclined or vertical they have been greatly disturbed.

Most sedimentary rocks have the layered structure called bedding or stratification. Absence of this structure in a sedimentary rock suggests, in fact, that the rock was formed in one of the less common ways of sedimentary deposition. Such lack of stratification is a feature by which we recognize a tillite — a lithified till (p. 139). Loess, formed by wind deposition (p. 166), and talus accumulations also are unstratified.

Stratification is commonly caused by changes in the velocity of the transporting agent. An obvious example is afforded by the fine silt and clay that are deposited upon coarse gravels during times of diminished flow of water on an alluvial fan. Changes in velocity may occur daily, as on the outwash plain fronting a glacier, where the transporting competence of the streams varies enormously with the time of day. Such variation is vividly impressed on anyone who has had to ford the braided network of streams flowing from a glacier: low water in the cool of the morning when melting of the ice is at a minimum, flood water in the heat of the afternoon, when the continuous bumping of boulders moving downstream can be heard.

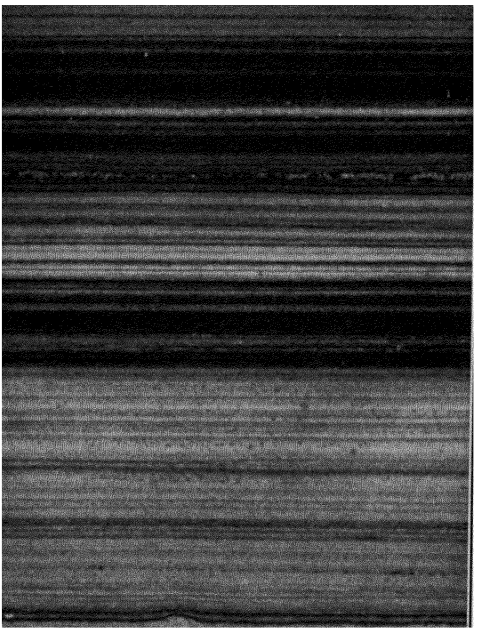
More commonly the changes in the velocity of streams are seasonal, owing to flood stages during the rainy season and low water during the dry season.

In the sea the normal arrangement of sediments is this: coarse material lies near the shore and grades seaward into fine material — muds. In times of storm, however, when a strong undertow develops, the coarse sediment is moved out into deeper water and is laid down on the muds that had accumulated earlier during periods of calm. An alternation or interstratification of coarse and fine sediments is thus produced.

Change in the kind of material deposited causes the resulting sediments to be stratified. Limestone beds alternating with shale beds exemplify how greatly the composition of the sediment differed from time to time. Shifting of marine currents is one cause of such abrupt changes.

A layering caused by the annual march of the seasons appears to be well developed in certain sedimentary deposits. Such an annual

deposit is called a *varve*, regardless of whether it was formed in the sea, a lake, or elsewhere. Most varves consist of two thin layers of differing composition, one of which was laid down during the summer and the other during the winter. Such laminated sediments occur in glacial clays where their annual origin appears to be well established, so that they can confidently be called varves. Annual deposits occur in some lake deposits now forming; and they are thought to have been recognized in certain marine shales, in playa clays, in dune sands, and in marine salt deposits in Stassfurt, Germany, and in Texas. The regular alternation of layers of unlike composition is easy to recognize, but to establish its annual origin is difficult, and so far conclusive evidence is not at hand for all laminated sediments suspected of being varves. It is a matter of great interest, however, for varves give us a means of establishing eventually a chronology based on years.



W. H. Bradley, U. S. Geol. Survey.

FIG. 156. Laminated sediment from an ancient lake in Colorado. Shows probable annual layering, the light-colored laminæ having been deposited during the summers and the dark laminæ during the winters. (Enlarged three diameters.)

A laminated sedimentary rock that is regarded as of varved origin is shown in Fig. 156; it is from an ancient lake deposit in Colorado. Each varve consists of a pair of laminæ, one composed largely of calcium carbonate and the other much higher in organic matter, and hence much darker. During the summer the lake warmed up, diminishing the solubility of carbon dioxide in it, and consequently abundant calcium carbonate was precipitated, and the production of floating microscopic organisms reached its annual maximum. The carbonate, being the heavier, sank promptly, but the organic matter subsided more slowly and so most of it came to rest above the carbonate layer. By counting and measuring the supposed varves, it is estimated that about 6.5 million years were required to form the total deposit. Furthermore, the thickness of the couplets

shows a cyclic fluctuation averaging 11.5 years, which corresponds to the sun-spot cycle. This correspondence adds strength to the conclusion that the couplets, like tree-rings, are of annual origin — are truly varves.

Fossils. Fossils are the remains or imprints of animals or plants that were buried with the accumulating sediments (Fig. 157). Few organisms are preserved entire in the rocks; only the hard parts, such as shells and bones, as a rule endure. These parts may be preserved

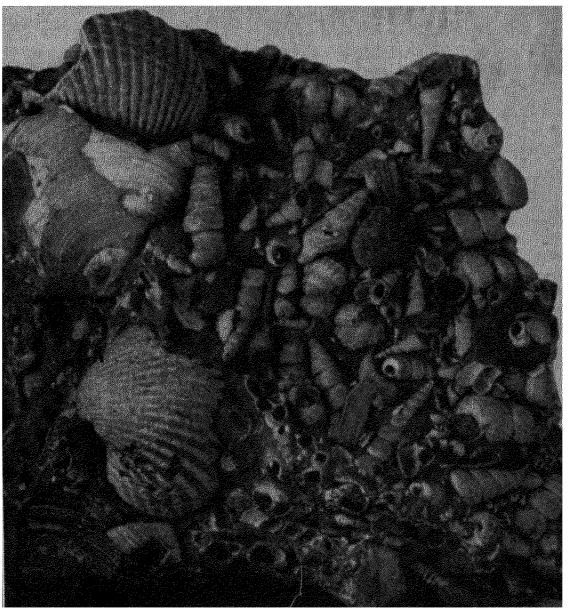


FIG. 157. Fossil marine shells, which prove that the rock in which they are imbedded was originally a deposit on a sea floor.

unchanged, but the original material with which the organism built its hard parts is generally dissolved by circulating solutions and new material is put in the place of the removed substance so perfectly that the original form and details of structure are exactly preserved. Petrified wood is a well-known example, in which the woody tissue was removed and silica was concurrently put in its place. The shells or other hard parts may even be wholly removed, and only an imprint or hollow mold be left in the rock. A *natural mold* of this sort may later become filled by mineral matter, and this filling forms a copy or *natural cast* of the organic object.

As most fossils represent the animals and plants that were living when the sediments were forming, they throw much light on the conditions that prevailed during the deposition of the rocks in which they occur. They show, for example, whether the beds were laid down on the land or beneath the sea, since sediments laid down on the continents contain the remains of land plants, bones of land animals, or shells of river clams, whereas sediments laid down in the sea contain marine shells.

The climate of the region at the time of deposition may be indicated also; for example, fossils of tropical plants, such as palms, and ani-



C. K. Longwell.

FIG. 158. Mud cracks formed in the playa of Pintwater Valley, Nevada.

mals, such as alligators, occur together in certain formations in the Badlands of South Dakota. All these inferences based on fossils, however, must be checked against the inorganic evidence given by the rocks, for the living organisms were subject to evolution, whereas the rocks were formed in accordance with changeless laws.

Mud Cracks. Soft muddy sediments exposed to the air and sunshine shrink and crack into characteristic polygonal blocks like those shown in Fig. 158. The desiccation cracks thus formed are known as *mud cracks.* Further exposure bakes and hardens the blocks of mud. Later, during the dry season, wind-blown sand or silt may cover the blocks and fill the cracks with sediment that is coarser than the material of the mud-cracked layers. The form of the polygonal blocks will thus become preserved even if the mud flat is again inundated.

After the deposits thus formed have been changed into beds of shale and sandstone, they may later be exposed by erosion, and the " fossil " mud cracks will be revealed on the bedding planes.

Clearly, the conditions that favor the formation and preservation of mud cracks are ideal also for preserving the footprints of animals that may have crossed the soft mud soon after its deposition; therefore mud cracks and footprints commonly occur together in sedimentary rocks. These conditions favor also the preservation of raindrop imprints, which record a brief shower that fell while the mud flat was exposed to the atmosphere.

The most favorable places for mud cracks to form are the floodplains of large rivers, the landward portions of large deltas, and the wide, flat shores of shallow lakes that shrink or disappear during the dry season. Marine tidal flats, in spite of their alternate wetting and drying, are unfavorable for the forming of mud cracks, because the mud has not sufficient time to dry thoroughly before the tide returns. Mud cracks form to a minor extent, however, at the upper margins of estuaries where the spring tides reach for only a few days in each month. As mud cracks can form only when the sediment is exposed to the air and allowed to dry and shrink, they are generally lacking in marine deposits.

Ripple Marks. Where currents sweep sediments along the bottom, the surface of the resulting deposit develops parallel ridges that resemble the ripples on the surface of a pool of water. These are *ripple marks* (p. 163). They are formed also by wind action on sand dunes (p. 162). Ripple marks made by currents migrate slowly with the current but retain their form, because the sand grains are rolled up the currentward side and fall down the leeward slope. Current-formed ripple marks, therefore, are asymmetric, the currentward side having a gentle slope and the lee side a steeper slope. The direction of flow of the current is thus autographed in the form of the ripple marks (Fig. 159).

Where oscillatory waves touch bottom, they too develop ripple marks by moving the bottom particles to-and-fro. Such oscillation ripple marks, in contrast to current-formed ripple marks, are symmetric (Fig. 160).

Cross-Bedding. In many sedimentary rocks, especially in conglomerate and sandstone, the layers of certain beds are inclined at considerable angles to the general planes of stratification (Fig. 161). This arrangement produces a diagonal structure which is known as *cross-bedding*.[1] It develops wherever sediment is being shifted by

[1] Termed also false-bedding and cross-lamination. The " real " bedding is perpendicular to the direction of upgrowth of the deposit.

currents in such a way as to be spilled over the front edge of the growing deposit: as the foreset edge of a delta, the front of a gravel bar, the front of a sand dune, or the front of a current ripple. The indi-



E. M. Kindle, Geol. Survey of Canada.

FIG. 159. Current-formed ripple marks exposed at low tide near Windsor, Nova Scotia. The current flowed from left to right.

vidual layers thus formed are diagonally inclined to the floor on which the deposit as a whole is growing upward (Fig. 105, p. 139).

The scale of the cross-bedding ranges from minute to very large. In sand dunes the cross-bedding may extend across a stratum that

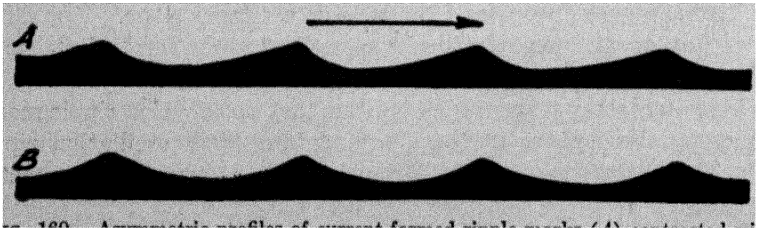


FIG. 160. Asymmetric profiles of current-formed ripple marks (*A*) contrasted with the symmetric profiles of oscillation ripple marks (*B*).

is tens of feet thick, but in silts shifted by small ripples the cross-bedded strata are fractions of an inch thick. Since the diagonal layers invariably slope downstream, the direction of the currents that formed the cross-bedded deposits can be inferred.

layering, and the thickness at once impress the observer. The lowest formation shown in the figure consists of strata of sandy shale and shaly sandstone more than 1000 feet thick; above it is the Redwall limestone, whose massiveness causes it to crop out in 500-foot cliffs and to form some of the most striking scenery of the Canyon; the third is a thick series of shales and sandstones; the fourth consists entirely of shale; the fifth is the Coconino sandstone, a prominent white sandstone formed in an ancient desert; and the uppermost is the Kaibab limestone, so called because it forms the floor of the Kaibab Plateau in which the Canyon is incised. All these formations were laid down either in the sea or at sealevel.

The formations revealed by the deep incision into the crust at the Grand Canyon total 4000 feet in thickness. They are still horizontal, although they have been lifted far above sealevel, and they are in undisturbed sequence. From the fossils in them we find that the lowermost formation was laid down near the beginning of Paleozoic time and the uppermost near the end of Paleozoic time; translated into years, this means a span of 300 million years. From the fossils we learn further that the time during which the formations were deposited was only a fraction of this vast span of time. Therefore there are significant time breaks between some of the formations; that is, there were long intervals when no sediments were deposited at the Grand Canyon. These intervals of time, although not represented by strata at the Grand Canyon, are represented elsewhere by great thicknesses of strata.

Areal Extent of Sedimentary Formations. No geologic formation is worldwide in extent. Many sedimentary formations, however, are remarkably constant in composition and thickness over areas exceeding several thousand square miles. A notable example is the Dakota sandstone, which, cropping out along the Black Hills and the eastern front of the Rocky Mountains, extends far eastward under the Great Plains; and because of this continuity it transmits artesian water hundreds of miles east of the mountains.

The most persistent strata consist of volcanic ash, for as we shall see (p. 222) the fall of ash from a single great explosive eruption, like that of Tamboro in 1815, may form a continuous stratum that extends over an area as large as 1,000,000 square miles.

Summary of the Sedimentary Rocks. The sedimentary rocks, except the tuffs and volcanic breccias, are made of materials that were derived from the erosional destruction of older rocks. Because the history of the Earth is long, the materials of some of the sedimentary rocks have gone through several cycles of weathering, transport, sedi-

mentation, and consolidation to rock. That is, some sedimentary rocks have been formed as results of the destruction of still older sedimentary rocks; but the ultimate sources of all the sediments were the igneous rocks. Only durable minerals survive this rigorous treatment, and therefore such minerals, represented pre-eminently by quartz, predominate in typical sedimentary rocks, such as sandstone.

From sedimentary rocks much can be learned as to what rocks were exposed to weathering when the sediments were accumulating, the climate that prevailed, the means by which the sediments were transported, whether water, wind, or ice, and the conditions that existed at the site where the sediments were being deposited. They are thus of the utmost service in determining the geologic history of a region. Some, of course, like conglomerates give up their secrets more readily than others. Finally, the sedimentary rocks are the repositories of our most valuable mineral resources — coal, oil, gas — to mention only the most important commercially — and this fact has been a powerful stimulus in recent years to the intensive study of these rocks in their scientific aspects.

Chapter 12

VOLCANISM AND DEEP-SEATED IGNEOUS ACTION

Volcanoes

Vesuvius, overlooking the Bay of Naples, is the world's best-known volcano. In times of quiet activity it discharges vast volumes of dense white clouds of steam, which issue from it with a rude rhythm: first come a succession of gigantic puffs, followed by a roaring expulsion, and so on, in continuous repetition. All this energy is drawn from beneath a densely populated area! At times of heightened activity the crater becomes a lake of brilliantly incandescent lava, pieces of slag are hurled to a distance of many miles, earthquake shocks become violent, and flows of lava pour out and overwhelm unfortunate villages on the slopes of the mountain. During a major eruption all activity is intensified beyond all imagination.

The concept of what a volcano is — a steep conical mountain having at its top a crater, from which at intervals are ejected gases, rock fragments, bombs, and lava flows — takes its general outlines from Vesuvius. There are hundreds of active volcanoes the world over, however, and many of them diverge widely from this picture. The really essential feature of a volcano is an eruptive apparatus, generally a conduit that connects the exterior of the Earth with the interior.

Volcanoes range in size from small cones that are hardly larger than a beehive to majestic peaks that are amongst the loftiest mountains on the globe. Many of the highest peaks of the Andes are volcanoes; some of these are still active, as Cotopaxi in Ecuador, famed as the world's highest active volcano, 19,600 feet in altitude; but others have become extinct in the recent geologic past. The Andean volcanoes stand on a dissected platform of much older rocks, above which they tower 10,000 to 12,000 feet. Certain volcanoes in mid-ocean are much larger, however. The volcanoes of the Hawaiian Islands rise from the floor of the Pacific Ocean at depths of 14,000 to 18,000 feet; and, as the highest project 14,000 feet above sealevel, they attain a total height of 30,000 feet.

Phases of Volcanic Activity. Materials of three kinds are ejected from volcanic vents: gases, liquid lava, and solid material in the form of fragments. The character of a volcanic eruption depends largely on

the proportions in which these three materials are being ejected. According to the predominant material that it is erupting, a volcano is said to be in a particular phase of activity. For some volcanoes, notably Vesuvius, definite cycles of activity are recognized. Each cycle begins with a phase of increasing emission of gases; this is followed by the second phase, the discharge of lava, ending with copious outflow of lava from the slopes; and the final phase consists of the ejection of fragmental material.

A phase of activity may vary enormously in intensity during the course of an eruption or in successive eruptions, as measured by the violence of explosions or by the quantity of material ejected.

Lava-emitting Phase of Activity. Volcanoes in this phase of activity discharge flows of liquid lava, unaccompanied by the explosive escape of gases and the ejection of fragmental material. The lava thus discharged is very hot, and hence highly liquid. More or less gas constantly escapes from it but without explosive violence. Activity of this kind is particularly well exemplified in Hawaii.

The island of Hawaii is an immense mass of basaltic lavas crowned by five great volcanoes, of which Mauna Loa (13,700 feet high) and Kilauea (4000 feet high) are active. Mauna Loa is the vastest of existing volcanoes. It also surpasses all others in the magnitude of its eruptions. Marvelously spectacular are the great columns of white-hot molten lava that at times play as mighty fire-fountains hundreds of feet high. As the fountains are often nearly continuous along the eruptive fissure, they form a veritable curtain of fire. The molten lavas of Mauna Loa generally issue from fissures in its flanks rather than through the crater rim, and sometimes they issue below sealevel.

On the eastern slope of Mauna Loa, 22 miles from its top and 10,000 feet lower, is Kilauea. In its summit is an oval depression, 9 miles in circumference, shut in except on the south by vertical cliffs which reach a height of 450 feet. This depressed area is often called Kilauea's "crater" but is in reality a caldera (p. 222). In the floor of the depression is Halemaumau, the "Everlasting House of Fire," a pit which before 1924 was 1300 feet across and contained a seething lake of liquid basalt. The temperature of the lava ranged from 1000° to 1200° C.,[1] the higher temperatures prevailing at times of increased activity. In 1924 the lava column in the pit of Halemaumau suddenly dropped 700 feet, and this subsidence was followed by great explosions, the first explosive eruption since 1790. Avalanching from the sides of Halemaumau began and enlarged the pit, so that it became 3000 by 3400 feet

[1] About the temperature of molten gold (1062° C.).

across and 1340 feet deep. After the eruption the pit began to fill again with molten lava, but up to the year 1940 the top of the lava column was still 800 feet below the level of the floor of the " crater " of Kilauea.

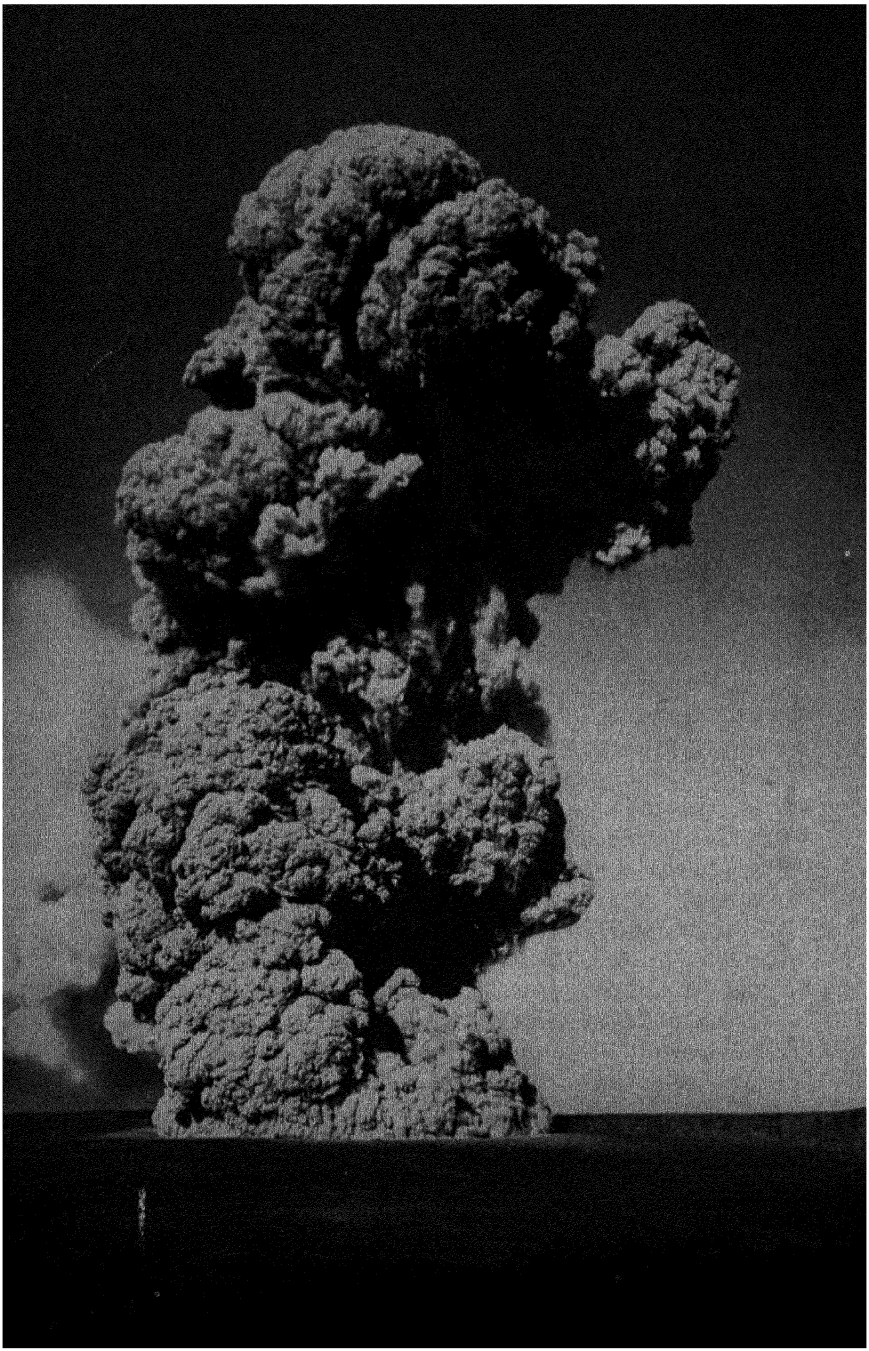
The explosive outburst of 1924, after an uninterrupted period of 134 years of quiet extrusion, shows that even basaltic volcanoes, which normally emit the most fluent of lavas, may on occasions become violently explosive. The sudden influx of ground water into the volcanic pipe, as undoubtedly occurred in 1924 as the result of the lava column in the pipe dropping abruptly to great depth, generated immense quantities of steam and caused the spectacular features of an explosive eruption (Fig. 164).

Peléan Phase. The phase of volcanic activity termed *peléan* is probably the most remarkable of all.

The volcano of Mont Pelée on the island of Martinique in the West Indies, after small premonitory symptoms, began in May, 1902, to erupt in a series of violent explosions; it had been in repose since 1851, and had then been only feebly eruptive. No lava was now poured out but on the morning of May 8 an enormous dense black cloud of superheated steam heavily charged with fragments of hot lava blew out horizontally from the flank of the mountain and sped down its slope to the sea, at a rate of more than a mile a minute. The cloud swept through the town of St. Pierre, 5 miles from its point of origin, and instantaneously destroyed the town and its inhabitants and those who in the previous days had fled to it for safety. Some 28,000 people were killed within a few seconds; only two persons are known to have escaped alive. For many months Mont Pelée continued at irregular intervals to eject similar clouds, one of which is shown in Fig. 165 as it arrived at the sea. Not till well beyond 1905 was the eruption finally over.

On September 16, 1929, strong explosions suddenly broke out on the summit of Mont Pelée. Next day, after this preliminary eruption, not 30 people remained in St. Pierre. In mid-November peléan clouds began to be ejected. Hundreds were emitted, differing enormously in intensity, but none attained the terrific destructiveness of those of the earlier eruption. This relative mildness is ascribable to the fact that the interval had been too short to build up the tremendous gas pressure that obtained in 1902.

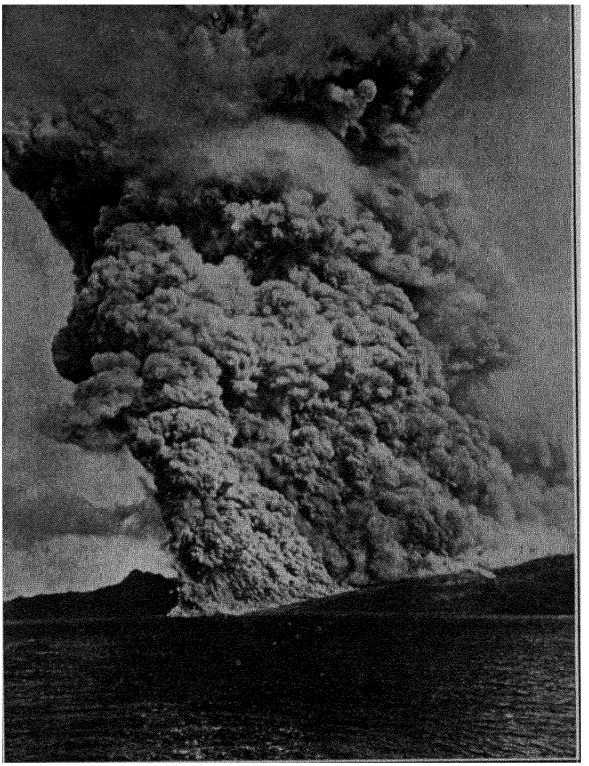
The great eruption of Pelée in 1902 directed attention to a phenomenon previously unrecognized. The remarkable clouds ejected are now called *peléan clouds*. The extraordinary features of a peléan cloud are: it is emitted as a horizontal blast from beneath a lava plug in the



K. MAEHARO, HILO, HAWAII.

Fig. 164. Explosive eruption of Kilauea in 1924. The "cauliflower cloud" was considerably more than a mile high at the moment the photograph was taken.

summit of a volcano; it is extremely hot; it travels at great speed — about a mile a minute; it carries with it an enormous amount of rock fragments, including blocks many yards in diameter; and all this material is deposited chaotically together, instead of raining down according to size, as from other volcanic clouds. In reality the cloud is



A. Lacroix.

FIG. 165. Peléan cloud from Mont Pelée, Dec. 16, 1902, arriving at the sea. Height of the cloud is 13,000 feet.

an enormous smoke screen, which hides the essential feature of the ejection — the immense quantity of hot lava fragments moving close to the ground at incredible speed.

Factors Determining Explosivity. The explosivity of a magma depends on viscosity and gas content. If the magma contains no gas, it has no explosive power. Viscosity is determined by the chemical composition of the magma and is diminished by increased temperature and to some extent by increased gas content. As the temperature and

gas content of a magma may change, the explosive power of the magma can change; and therefore the same volcano may at different times have enormously different explosive power.

Vesuvius. Vesuvius illustrates remarkably well the fact that one and the same volcano may vary greatly not only in the intensity but also in the nature of its activity.

Vesuvius stands on the site of an older volcano, Somma, which to the Romans seemed to be extinct, for, although they recognized its volcanic nature, they had no traditions that it had ever been active. In the year A.D. 79 the volcano became violently active in eruptions that destroyed the towns of Herculaneum and Pompeii on its seaward

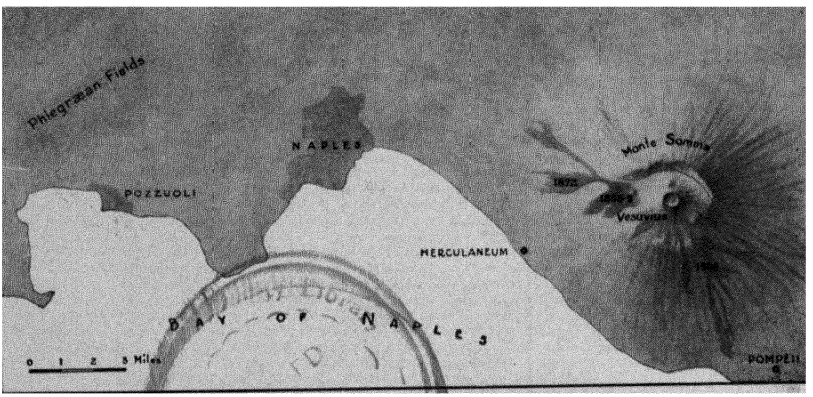
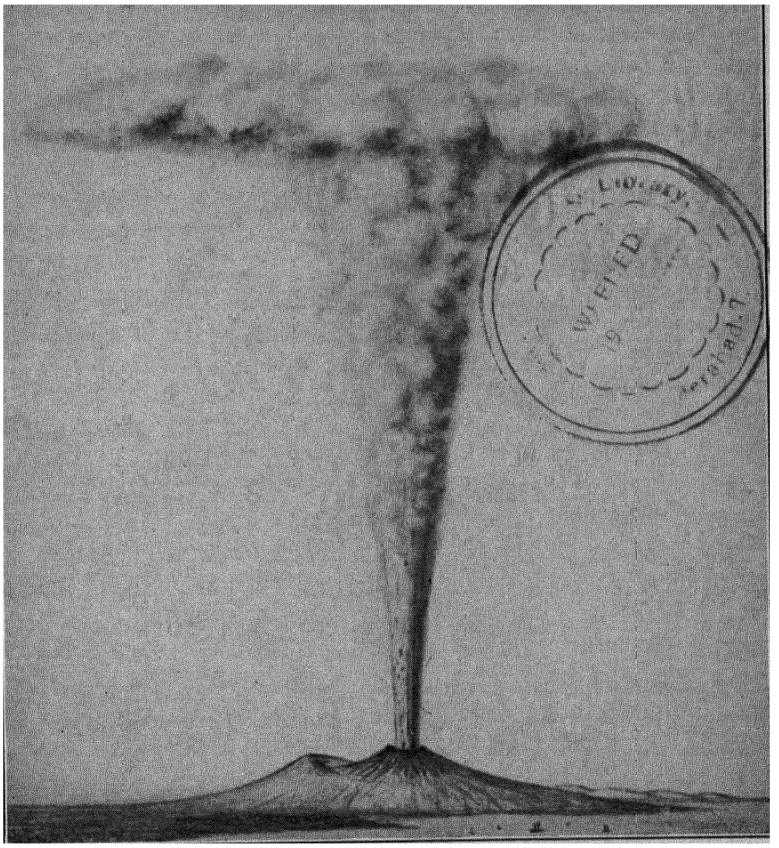


FIG. 166. Map of Vesuvius and vicinity, showing some of the larger streams of lava erupted in recent years.

flanks. The top and much of the older cone on the side toward the sea were blown away or engulfed, and, within the cone thus truncated, the modern Vesuvius began to be built. This building up has continued until Vesuvius is now 4000 feet high. Partly inclosing it is the crescentic ridge called Monte Somma, the remains of the truncated older volcano (Fig. 166).

Vesuvius is in a state of almost constant mild activity, with irregular periods of violent eruption. It has had three major outbreaks, in 79, 1631, and 1906. Three stages of activity in the great outbreak of 1906 were recognized. During the first stage, lasting four days, fiery floods of lava were discharged, from fissures that opened successively lower and lower on the flanks of the cone; earthquake shocks increased in violence; and great explosions hurled out immense quantities of

incandescent lava thousands of feet into the air. During the second stage there was a stupendous emission of gas; it blew out under enormous pressure and rose as a continuous blast with tremendous speed to a height of 8 miles, where it spread laterally as cauliflower clouds (Fig. 167); and it lasted all of the daylight of April 8 as a *continuous blow-*



Modified from F. A. Perret.

FIG. 167. The climax of the great gas blow-off, during the eruption of Vesuvius in 1909.

off. The discharge of this colossal jet of gas enlarged the crater. This stage was succeeded by the ejection of dark (nonluminous) ash expelled by powerful isolated explosions. The whole eruption lasted 18 days, and at the end of the eruption the crater was 2200 feet wide at the top and 2000 feet deep.

Ejecta of Volcanoes

Gases. Steam is discharged by active volcanoes in immense amount, as is indicated by the height and the enormous volume of the clouds that accompany many eruptions. These clouds consist of the dust and ash borne aloft by the uprushing column of steam and other gases. The great quantity of steam thus discharged into the atmosphere condenses and causes heavy downpours of rain near the volcano; but part of the torrential rains is probably caused by condensation from moisture-laden air that was sucked up to high altitudes by the up-draft created by the discharge of the volcanic gases. Owing perhaps to the friction of the ash particles and to atmospheric disturbance, the eruptions and rains are accompanied by electrical manifestations, which culminate during paroxysmal outbursts in spectacular lightning discharges.

Although the composition of the gases during an actual volcanic eruption is not directly known, and probably varies at different volcanoes and at different stages of an eruption, it is inferred with good reason from indirect evidence to consist chiefly of superheated steam.

Besides steam, many other gases and volatile products are exhaled by volcanoes. They are given off not only from the vent itself, but also from the flows of lava, which as they cool and harden continue to emit gases for weeks and months after extrusion. Carbon dioxide, hydrochloric acid, hydrofluoric acid, and hydrogen are given off. Sublimed sulphur and various compounds of sulphur, such as hydrogen sulphide (H_2S) and sulphur dioxide (SO_2), are emitted by some, but not all, volcanoes.

Chlorides are exhaled abundantly at many volcanoes during eruptions. In fact, abundant chlorides discharged by the Italian volcanoes suggested the idea that eruptions are caused by sea water leaking into magma at depth; but even were this inference true for the Italian volcanoes, it can not hold universally, because no chlorides are given off by Kilauea, which is on Hawaii, an island in the Pacific Ocean.

Fragmental Products. Fragmental materials of many kinds are blown into the air by the explosive liberation of the gases. They are derived from the crust of hardened lava left in the upper part of the conduit after a previous eruption; from rock material torn from the walls of the conduit; or from lava ejected from the top of the liquid column by gases violently escaping from the magma.

The pieces of rock and the clots of molten lava blown out range greatly in size: from dust so fine that it floats in the atmosphere for several years to large masses weighing many tons. They are classified

according to size for the sake of precision, somewhat arbitrarily, as follows: pieces larger than 32 millimeters (1¼ inches) in diameter are called *blocks*, if ejected as solid fragments and hence angular, and *bombs*, if ejected as particles of still-fluid magma and hence roundish or ellipsoidal; those between 32 millimeters and 4 millimeters are termed *lapilli* (Latin for *little stones*) or *cinders;* those between 4 millimeters and ¼ millimeter, *ash*, and the still finer is called *fine ash* or *dust*. Although the terms " ash " and " cinders " are commonly used in referring to the products of eruptions and aptly describe their appearance, the " ash" and " cinders " are *not* the residues of something that has burned. A volcanic bomb is illustrated in Fig. 168; its spirally twisted ends prove that it was liquid while in flight.



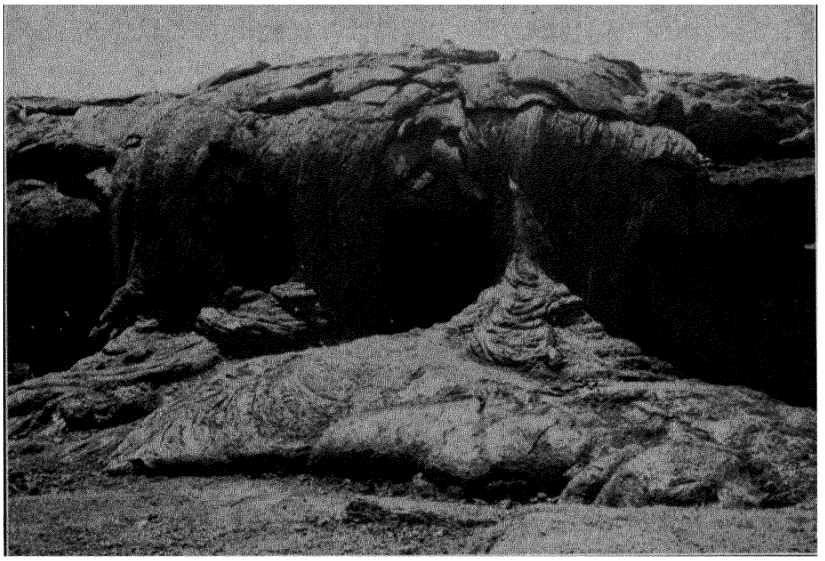
FIG. 168. Volcanic bomb, Hawaii. Shows spirally twisted ends. One-third natural size.

The coarser pieces and most of the ash fall near the vent and help to build up a cone around it. The dust is carried by the prevailing winds long distances, hundreds of miles or more, and is thus spread over an immense area.

Liquid Material: Lavas. A volcanic cone has no strength, and so is easily fissured by the explosions and by the pressure of the lava column in the conduit. Hence the magma does not as a rule flow out over the lip of the crater, but issues through fissures in the sides of the cone. It may even happen, especially if the cone is built of cinders, that, unable to withstand the hydrostatic pressure of the lava column in the conduit, one side of the cone gives way and allows the lava to rush out through the breach thus made.

The appearance and character of a lava stream and the rock formed from the lava as it solidifies depend on several things. The chemical composition of the magma determines the nature of the resulting rock,

whether it will be a light-colored lava (rhyolite) or a black basalt, or of intermediate character (andesite), as previously explained. The viscosity determines the rate at which the lava flows, the distance it flows, and in large measure the aspect of its surface. When the lava first issues from a volcano, it is red- or white-hot. It soon cools on the surface, darkens, and crusts over. The lower part of the flow may still be moving, however, while its upper part crusts over and breaks up into rough, angular, jagged blocks, which are borne as a tumbling, jostling mass on the slowly moving lava flow. When the flow finally



W. C. Mendenhall, U. S. Geol. Survey.

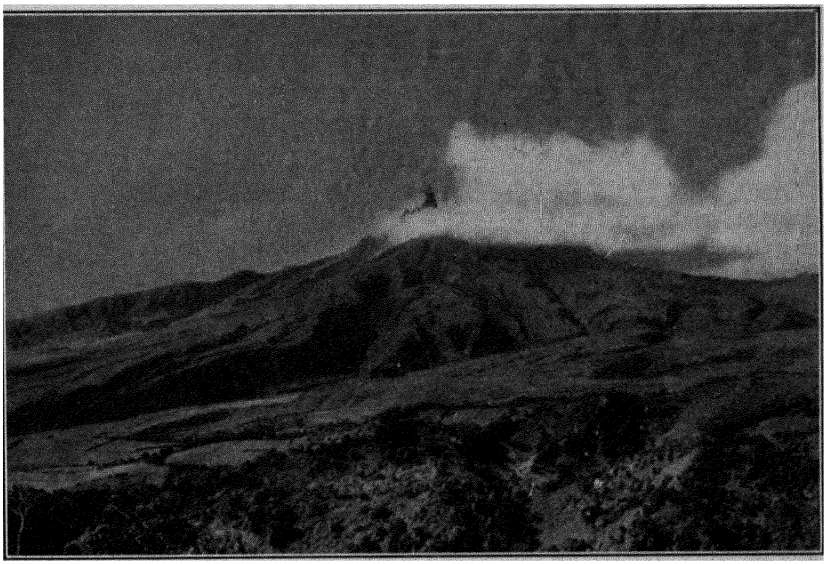
FIG. 169. Basalt lava cascade, Hawaii. The basalt has solidified as corded lava.

comes to rest, the resulting lava sheet is extremely rough and difficult to traverse. Such a lava sheet is termed *block lava.*

In marked contrast to the block lavas, other lavas harden with smooth surfaces, which have curious ropy, curved, and billowy forms, as seen in Fig. 169; they are known as *corded* lavas.

Very fluid lavas move rapidly, especially on steep slopes (Fig. 3); some, like the great flow from Mauna Loa in 1850, average 10 miles an hour. Speeds of more than 5 miles an hour, however, are exceptional. As a lava flow cools, it becomes more and more viscous and its motion becomes almost indefinitely slow, the stream creeping onward, possibly for several years.

Some magmas when ejected are too viscous to flow; they then pile up over the vents in great domes. Such doming is confined chiefly, though not wholly, to the silicic lavas. The condition essential to forming a dome is that the magma be in a highly viscous, pasty state, because of low temperature or low gas content, or both. Thirteen such domes occur within an area of 50 square miles in Lassen Volcanic National Park, the largest being Lassen Peak itself. After the violent eruption of Pelée in 1902, the column of silicic lava that filled the vent hardened into rock at the surface but remained highly viscous in the interior; and



E. O. Hovey.

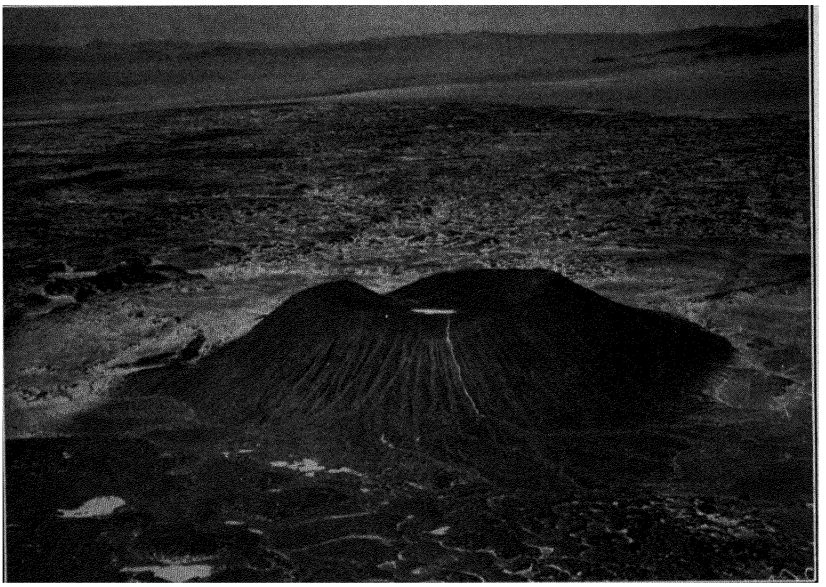
FIG. 170. Spine of Mont Pelée, March 25, 1903.

the whole mass was pushed up so that it rose like a vast tower above the volcano, until it attained a maximum height of 1200 feet above the crater rim, a year after the destruction of St. Pierre. As viewed from the northeast, the tower resembled a gigantic spine and therefore was often called the spine of Mont Pelée (Fig. 170). Gradually it crumbled into a mass of blocks as a result of continuous explosions of gases.

Effect of Escaping Gases: Vesiculation of the Lava. That lava, even after it flows out from the volcanic vent, still contains dissolved gases is amply shown not only by the clouds of steam that issue for weeks and months from it but also by the structures it assumes as it solidifies into rock. The upper part of a flow, especially of the viscous, silicic lavas, may become so crowded with countless bubbles of gas

expanding and escaping on relief of pressure that it is transformed into a veritable froth. Rock froth, which is generally white or light colored, is known as *pumice.*

In more fluid lavas, especially the basalts, the gas cavities or vesicles attain larger sizes, and if the cavities are highly irregular in shape and size and are so abundant that there is at least as much empty space as solid matter the resulting rock is *scoriaceous,* and loose pieces of such material are called *scoriae.* They are commonly dark to black, or reddish.



Spence Air Photos.

FIG. 171. Cinder cone, 200 feet high. Amboy, California.

VARIETIES OF VOLCANOES AND CRATERS

Pyroclastic Cones. The nature of the edifice built up around a volcanic vent depends on the material of which it is formed. If the edifice is made wholly of fragmental ejecta, a cone is built that is high and steep relative to the area it covers. Slopes of 30°, rarely 40°, are attained before the accumulating mass begins to slide. Volcanic edifices of this kind are *pyroclastic cones;* they are characteristic results of explosive eruptions. If consisting wholly of cinders, they are called *cinder cones.* Cinder cones are relatively small; none of them exceeds a height of 1000 feet (Fig. 171).

Shield Volcanoes. In contrast with the pyroclastic cones are the volcanoes that have been built chiefly or entirely by the piling up of lava flows around a central vent. They are low in proportion to the large area they cover, and on top are gently convex plateaus; hence they are called *shield volcanoes* (Fig. 172). The flows of which they are built were highly fluid lavas, which spread widely as thin, nearly horizontal sheets. Shield volcanoes are well represented in the Hawaiian Islands. Mauna Loa, 13,675 feet high, is a grand example: it is a vast, gently sloping dome; its slope near its base is 2°, increasing summitward to 10°, but flattening above an altitude of 10,000 feet.

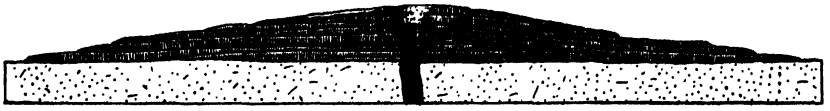


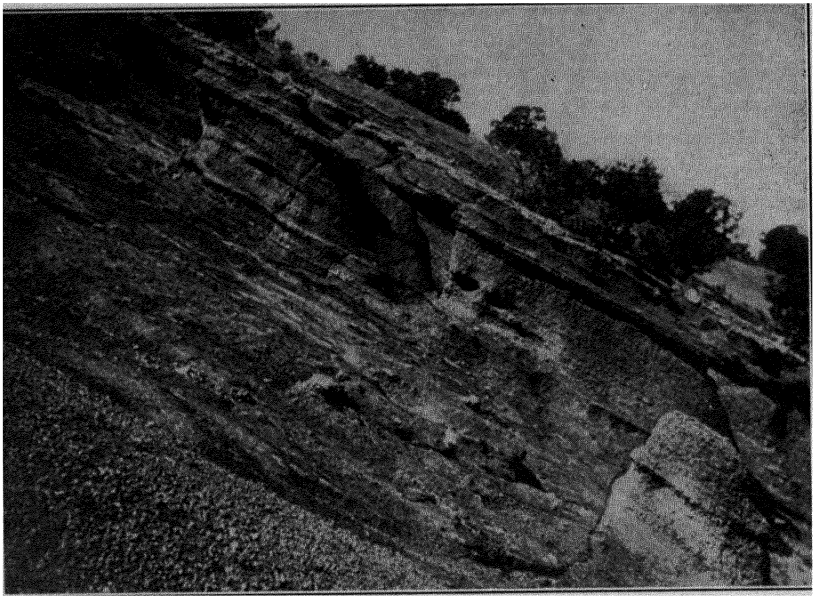
FIG. 172. Section through a shield volcano. Sills, dikes, and the rock filling the central conduit are shown in solid black.

Stratovolcanoes. Most volcanoes, including many of the world's largest, have cones that are intermediate in form between those just described. A cone of this kind is built up by the fall of fragmental ejecta around the vent when the volcano is explosively active and by the discharge of lava flows when it erupts quietly.

The deposits of successive explosive eruptions form layers, some of coarser, some of finer material. Thus a rude layering or stratification is produced, the beds sloping down and out from the conduit of the volcano (Fig. 173). The materials composing the beds gradually become compacted by their weight and by the infiltration and deposition of cementing substances. They are transformed into rocks called, if made of the coarser materials, *volcanic breccia*, and if of dust and ash, *tuff*.

At times liquid lava flows down the outer slopes of the growing cone, and when these streams solidify they protect the less coherent layers of pyroclastic material from erosion and give strength to the edifice. Because of the well-marked layering produced by the alternation of beds of tuff and breccia with sheets of lava, a cone built up in this way is called a *stratovolcano* (Fig. 174).

Lava rarely flows over the lip of a crater, but, especially in high volcanoes, is discharged from fissures on the sides of the volcano. The molten lava filling these eruptive fissures later hardens into rock after the discharge has ceased, forming *dikes*. The dikes radiate outward from the vent as a center, and they serve as ribs to strengthen the volcanic cone.



W. T. Lee, U. S. Geol. Survey.

FIG. 173. Part of volcanic cone near Trinchera, Colorado, showing inclined beds of tuff and breccia.

As a result of its composite construction, a volcanic cone of this kind has a characteristic profile of great beauty: concave upward, with gentle slopes near its base that steepen upward to the summit crater. Mayon, the most active volcano in the Philippine Islands, is regarded

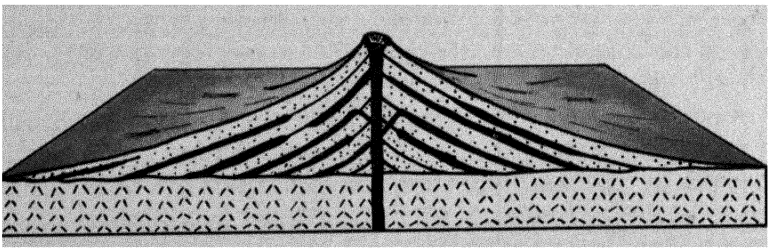


FIG. 174. Stratovolcano, showing the internal layered structure dipping away from the central vent, as the result of the alternation of lava sheets with pyroclastic layers. The profile is that of Mayon (Fig. 175).

as the finest example of a stratovolcano (Fig. 175). Within our own country are the majestic cones of the Cascade Mountains: Rainier, Adams, Hood, Shasta, to name only some of them; all of them stratovolcanoes, which give those mountains their distinctive scenic grandeur.

adjacent outer slopes. The former volcano, which has been named Mount Mazama, had the size and general character of Mount Shasta and was deeply covered with snow and glaciers during the Ice Age. Late in the life of the volcano there were eruptions of pumice, which culminated in the ejection of peléan clouds of extraordinary size and intensity. The upper part of the volcano then collapsed into the partly emptied reservoir, thus forming the caldera. This catastrophe happened several thousand years ago. The caldera has since filled with water, and this body of water is Crater Lake.

Explosion Pits. In some places volcanic activity has been unable to do more than to drill a vent through the country rock. The material

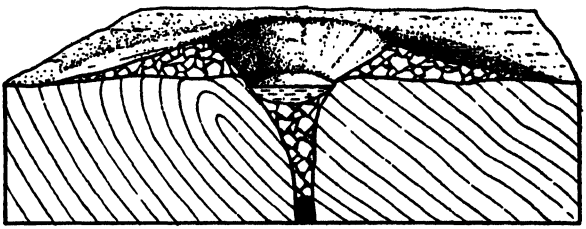


FIG. 177. Explosion pit, occupied by a lake. The fragments blown out consist chiefly of the foundation rocks perforated by the volcanic vent. Such pits are also termed embryonic volcanoes.

blown out, therefore, consists chiefly of pieces of the country rock mixed with only a minor amount of fragments of volcanic rock. It makes a low ridge around the pit, but no real cone was built (Fig. 177). Such explosion pits (embryonic volcanoes) range in width from a few hundred feet to possibly two miles. Most of those in humid regions are filled with water and form lakes. Some of the best examples are west of the Rhine in Germany, in the region known as the volcanic Eifel.

A pit strongly resembling an embryonic volcano occurs near Flagstaff, Arizona (Fig. 178). It is 4000 feet across and 500 feet deep. The presence of meteoritic iron in and around it and other more cogent evidence prove that it is not of volcanic origin, and have led to the view that it was caused by the impact of a huge meteorite and the explosion produced by the heat generated by the collision. Hence it has been named Meteor Crater. In recent years many meteorite pits have been found in widely separated parts of the world.

EROSION OF VOLCANIC CONES

Destruction of Volcanoes by Erosion. During all its life a volcano is subject to weathering and downcutting. Its height and general appearance are determined by the balance between these destructive



SPENCE AIR PHOTOS.

Fig. 178. Meteor Crater, Arizona, as seen from the southeast.

forces and the constructive forces of volcanism. Even active and growing volcanoes are trenched by ravines and gulches.

As soon as a volcano becomes extinct, the ravages of erosion are no longer repaired, and demolition begins. The tuffs and breccias are carried away rapidly; the more resistant flows and dikes and the parts protected by them are removed more slowly. Eventually, as erosion progresses, the *volcanic neck* (p. 240), consisting of the material filling the central conduit, becomes exposed to view. When the cone is completely demolished, the volcanic neck because of its greater resistance is left and generally forms a conspicuous prominence; and, when all external evidence of the cone has been finally swept away and has revealed the foundation rocks on which the volcano stood, the volcanic neck remains projecting, a monument to the vanished volcano. Eventually, it also vanishes, the " roots " of the volcano become more and more deeply exposed, and finally all evidence that a volcano was once present is obliterated.

Extinct volcanoes occur in every quarter of the globe, many of them where volcanic activity has long ceased. All stages of demolition are represented among them: from cones only slightly attacked by erosion to those so greatly eroded that the original shape has disappeared, but

whose central rock shaft (the volcanic neck), outlying concentric masses of lavas, tuffs, and breccias, and radial dikes still plainly show that they were once volcanoes.

Life and Distribution of Volcanoes

New Volcanoes. A few volcanoes have been born within the span of recorded human knowledge, and most of them are still active. Vesuvius, born A.D. 79, is generally regarded as an example, but it stands on the site of the older volcano, Somma. Jorullo in Mexico came into being September 28, 1759, in the midst of a cultivated plain. The initial explosions blew out fragmental materials, peléan clouds were ejected, and lavas were discharged. Four cones were formed, of which the highest, Jorullo, grew to a height of 1300 feet above its surroundings. Izalco in Salvador, which began in 1770, has been almost continuously active and has built a cone rising 2600 feet above its base. In its short life it has already discharged more lava than any other Central American volcano, and it ranks among the most active volcanoes in the world. The infant among volcanoes is Chinyera, on Teneriffe, one of the Canary Islands in the Atlantic Ocean; it was born in 1909 and is the only volcano whose birth is known to have had eyewitnesses. All these new volcanoes broke out in volcanic areas; none was born in a previously nonvolcanic area.

Geographic Distribution of Volcanoes. The present active volcanoes exceed 500; but those that are dormant or but recently extinct, as shown by their slightly eroded condition, amount to several thousand.

Volcanoes tend to occur in long belts on the Earth's surface. The most marked of these belts encircles the Pacific Ocean. It extends northward along the Andes, through Central America into Mexico, through the United States and Canada to Alaska, then along the Aleutian chain to Asia, and, turning southward through Kamchatka, Japan, and the Philippines, it crosses the East Indies, and by various island chains again passes into the Pacific. Portions of this belt, like the Andes and the Aleutian chain, are remarkably linear and well developed (Fig. 179).

Volcanoes occur both on the continents and in the oceans. They are notably abundant in the Pacific; though many of these are extinct or dormant, many are still active; in fact, three-fifths of all active volcanoes are in the Pacific alone. Here also many of the volcanoes are along lines and stand on submarine ridges that rise from the deep-sea floor. A superlative example is the Hawaiian ridge, which extends for 1800 miles and is crowned with mighty volcanoes, active and extinct.

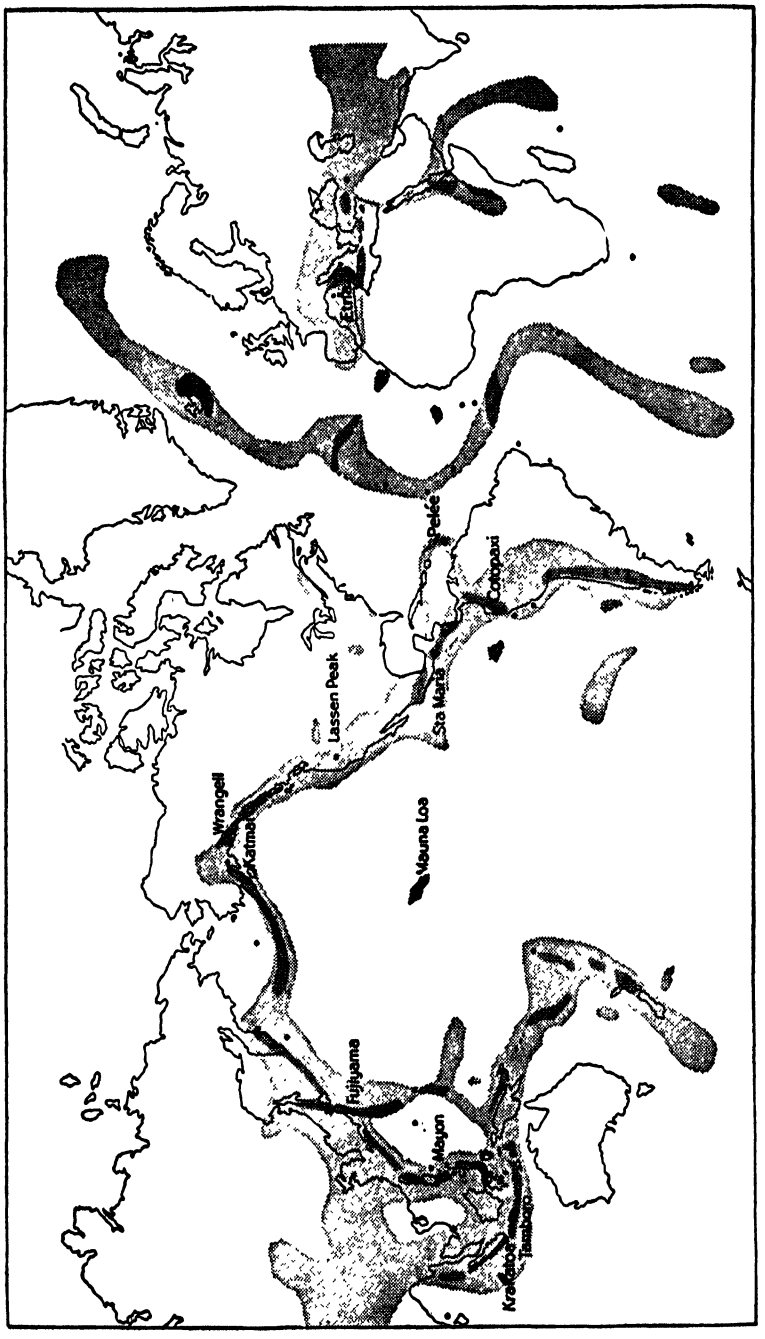


FIG. 179. Distribution of volcanoes and earthquake belts throughout the world. Active and recently extinct volcanoes are shown by small circles. Shaded areas are subject to frequent earthquakes; the darker shading indicates zones of especially violent earthquake activity.

The linear arrangement of volcanoes suggests that they are as a rule situated on, or near, lines of weakness marked by fracturing (*faults*) or by folding in the Earth's crust (p. 246). On the other hand, a volcano, or a group of volcanoes, may originate without being connected with fracture lines or axes of folding. A good example of this is in the Highwood Mountains, a group of extinct and deeply eroded volcanoes situated on the great plain of central Montana. Although the tuffs, breccias, lava flows, and dikes that still remain, together with their arrangement and attitudes, clearly indicate that volcanic cones once stood here, the cones have been eroded so deeply that their shapes have been destroyed, the central conduits filled with massive rock are now exposed, and the relation to the stratified rocks through which the conduits extended upward is laid bare. The foundation on which the volcanoes stood shows no fissures that might have determined the positions of the vents, and the conduits of the several volcanoes are not linearly arranged. In short, the volcanic forces appear to have been sufficiently powerful to make their own outlets without needing the aid of a fracture in the outer crust.

Mass Eruptions. Lava has been poured out on a gigantic scale at intervals since the beginning of geologic time and has deluged enormous tracts of country. These floods of lava were discharged from deep-going fissures in the Earth's crust, *i.e.*, from fissures not connected with volcanoes, and were erupted with little accompanying explosive activity. By these outpourings immense broad plains or plateaus have been formed, consisting of superposed horizontal sheets of lava with a few intercalated beds of tuff.

A basalt plateau formed in this way is the immense lava field of the Columbia Plateau in Washington and adjacent portions of Idaho and Oregon, which is 200,000 square miles in extent. In places, as shown by the deep canyons of the Columbia River, Snake River, and other tributaries, the lava pile is 4000 feet thick (Fig. 180). The Deccan trap (basalt) of western India now extends over a compact area of 200,000 square miles, but erosion has been at work ever since it was erupted 40 or 50 million years ago, and has detached many areas as outliers. Originally the extent of the Deccan trap as a continuous basalt plateau was nearly 500,000 square miles. In places the thickness of the piled-up lava sheets, which are individually thin, averaging about 15 feet, attains 10,000 feet.

The horizontal layering of the lava sheets that make up these plateaus testifies to the extreme fluidity of the issuing magma, which permitted the lava to flow on a nearly level surface for many miles before congealing. Another result of the easily fluent nature of the lavas is

that the average flow is thin — 15 feet for the Deccan trap and 20 to 40 feet for the Columbia River basalt. It is the vast outpourings of mass eruptions as plateau basalts, which have occurred in other regions as well as in those mentioned, that display the most extensive results of volcanism.

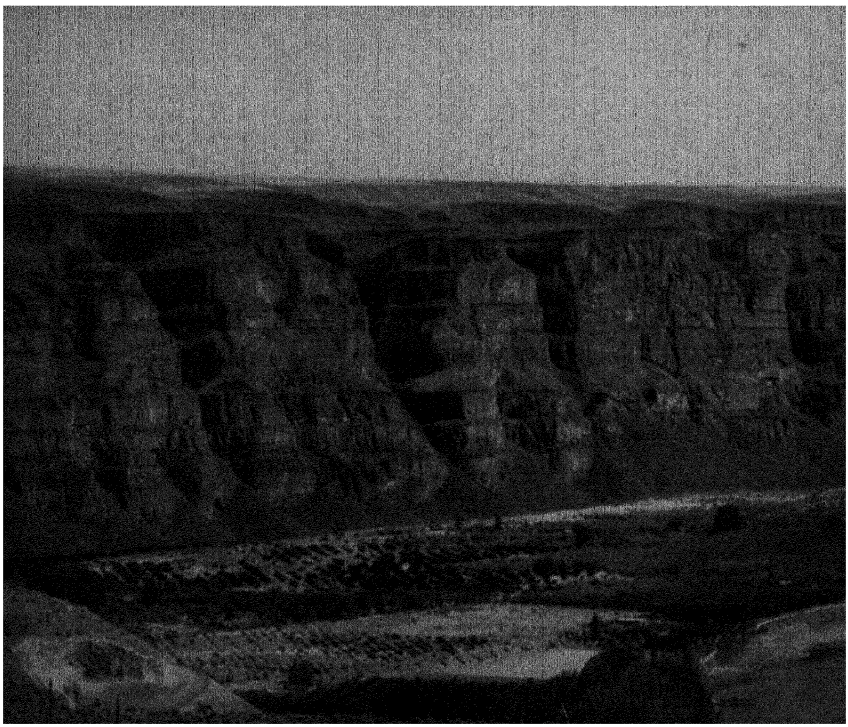
Although basalt is the chief lava poured out from fissures by mass eruption, rhyolites have been discharged in some regions on a large scale. The rhyolite plateau of the Yellowstone National Park appears to have been formed by lavas that issued from fissures during mass eruptions.

Origin of Volcanism

Origin of the Magma. This is a complex problem. Different volcanoes erupt lavas of different kinds. Vesuvius erupts one kind, Etna another. More remarkable still, neighboring volcanoes may erupt very unlike lavas. Stromboli and Vulcano are in the Lipari Islands north of Sicily, but Stromboli ejects basalt whereas Vulcano ejects

SIMMER STUDIO, WENATCHEE, WASHINGTON.

Fig. 180. Basaltic lavas, showing the horizontal piling of flow on flow. The cliff is 2000 feet high. Columbia River near Trinidad, Washington.



rhyolite — lavas about as far apart in composition as it is possible to be.

Furthermore, a volcano may in the course of time erupt lavas of several kinds. Did the supply pipe of such a volcano tap different reservoirs containing these different magmas? It is thought that originally there was a homogeneous magma beneath the volcano and that by a series of internal changes this magma yielded the other differing magmas. This process by which a magma of initially homogeneous composition splits up into unlike fractions is called *magmatic differentiation.* To this process appeal is made to account not only for the diversity of lavas erupted, but also for the variety of igneous rocks that make up the intrusive masses — the laccoliths, stocks, and batholiths. The methods by which magmas differentiate are many but need not be explained here.

Magmatic differentiation, although helping to account for the variety of magmas erupted at a particular volcano, does not explain the origin of the initially homogeneous magma, the parent magma from which the diverse magmas were derived. It is thought that the parent magma the world over is basaltic in composition. One of the cogent reasons for this belief is that the great mass eruptions that have discharged such enormous volumes of lava at intervals throughout the whole span of geologic time are basalts; and the ample source of basaltic magma thus proved to exist at depth indicates that a layer of basalt in a stiffly liquid (glassy) or potentially liquid condition underlies everywhere the visible crust.

Origin of the Gases. The chief magmatic gas is superheated steam (referred to also as water vapor, or simply as water), as a rule making at least 80 per cent of the total and generally 95 per cent or more. This water may have been part of the original substance of the Earth, entrapped at the time the Earth was formed, or shortly after; or it may have been formed by the union of primitive hydrogen with oxygen of atmospheric or other origin; or it may have been atmospheric water absorbed by the magma from the surrounding rocks; or it may have been acquired by the magma in melting up rocks containing water-bearing minerals. A quantitative evaluation of these possibilities is beyond the present powers of science. A magma that has dissolved much limestone would become highly charged with carbon dioxide, which is one of the important volcanic gases. Such absorption of limestone would generate enormous pressures, and such local development of pressure, it has been ingeniously suggested, may have determined the sites of certain volcanic vents.

The combustible gases — hydrogen, sulphur, carbon monoxide — appear to be original constituents of the magma. Their combustion,

especially that of the hydrogen, produces the only true flames seen at an eruption, and the heat liberated makes the magma somewhat hotter than it is at greater depth in the vent.

Cause of the Rise of Magma to the Earth's Surface. The fact that the long volcanic chains are situated in those belts of the Earth's crust in which movement and disturbance have taken place is significant. The great volcanic belts previously outlined coincide with the world's principal seismic belts. These belts are zones of weakness in the crust, and have manifestly afforded favorable places for the magma to rise and to flow out on the surface.

Two analogies have long been used to illustrate the rise of magma to the Earth's surface. The escape of lavas, said Dutton in 1880, " is analogous to what takes place when a bottle of warm champagne is suddenly uncorked." The energy of the imprisoned gases is thus considered to be the prime motive power. For the volcanoes that are fed from shallow-seated reservoirs, meaning thereby reservoirs at depths of two to three miles in the crust, this still appears to be the best explanation. The other analogy is that of the cracked ice-pond, where the water floods out over the ice. According to this idea, the weight of the outer crust forces the magma upward. The explanation thus suggested appears to fit eruptions of the type exemplified by the Hawaiian volcanoes, which are fed not from reservoirs within the crust but from the basaltic layer below the crust, and it appears to account particularly well for mass eruptions.

Fumaroles and Hot Springs

Between eruptions, during periods of dormancy, many volcanoes give off steam and other gases. Furthermore, long after volcanoes have ceased to be active these emanations continue to issue from their craters, or from their flanks, or even from places in the surrounding country. Large bodies of magma that rose high in the crust without reaching the surface or forming volcanoes have, while solidifying, given off their dissolved gases, which escape through fissures to the Earth's surface. The emanations issue at the surface either as gases or as liquids.

Fumaroles. *Fumarole* (from the Latin *fumare,* to smoke) is applied to a fissure or hole in the rocks from which steam and other gases escape with more or less force (Fig. 181). Steam predominates, generally forming 99 per cent of the total, but other gases, such as carbon dioxide, hydrochloric acid, hydrogen sulphide, hydrogen, methane, and others also occur.

Hot Springs

Hot springs as well as fumaroles abound in many volcanic regions. An intimate relation exists between hot springs and fumaroles: some of the hot springs as the dry season comes on become fumaroles, and when the wet season returns the fumaroles revert to hot springs. This evident seasonal variation leads to the theory that hot springs are fed chiefly by subsurface water that has become heated by magmatic steam: hot springs are " drowned " fumaroles.



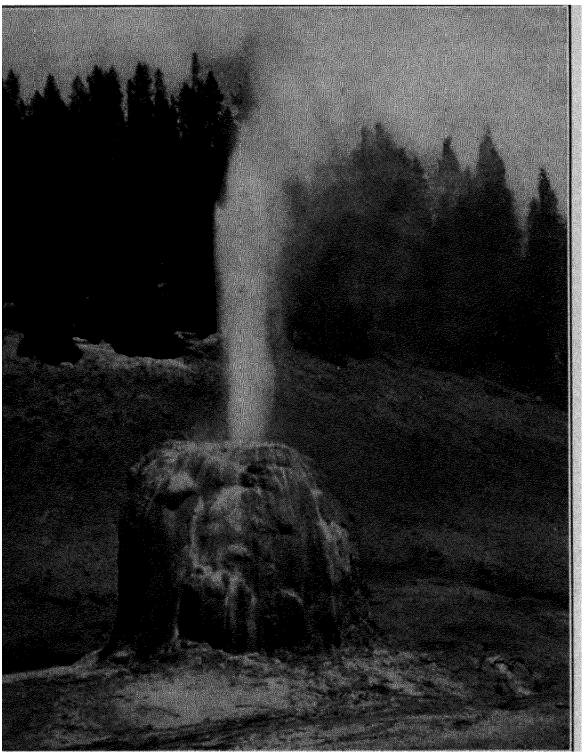
C. N. Fenner.

Fig. 181. Fumaroles in the crater of Katmai Volcano, Alaska.

Although there are many kinds of hot springs, according to temperature or substances in solution, the most interesting are boiling springs and geysers.

Boiling Springs. Boiling springs are a feature of many volcanic regions. They are abundant in Lassen Volcanic National Park and in Yellowstone National Park, especially in its various geyser basins. They grade from pools that are hot but rarely boil, or else simmer quietly, into springs that boil strongly and steadily, and even some that boil somewhat explosively, interrupted by short periods of repose. The violently boiling springs form transitions to geysers. So long as a spring has a sufficient supply of water to maintain an overflow, it remains limpid and is usually deep blue or green; but if evaporation by boiling equals the inflow, the water becomes turbid from particles of disintegrated rock and eventually becomes a mass of boiling mud.

Geysers. *Geysers* are hot springs that at intervals erupt a column of hot water and steam. They display an endless, fascinating variety. Some geysers spout a column of water only a few feet high, others spout columns several hundred feet high; some geysers have eruptions that last but a few seconds; others play for minutes or hours; and the water blown out ranges from a small quantity to hundreds of thousands of



C. D. Walcott.

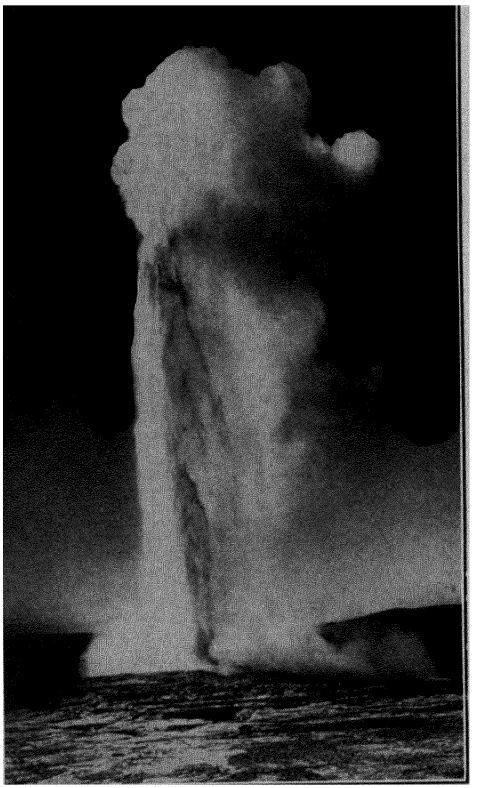
FIG. 182. Siliceous sinter cone of Lone Star Geyser, Yellowstone National Park, 1915.

gallons. Some geysers erupt at regular intervals, but most of them erupt irregularly at intervals ranging from minutes to hours, days, weeks, or even longer; some geysers, in fact, erupt at intervals of years. As geysers are boiling springs of a special kind, they are not common; in fact, almost all of them occur in three regions: Yellowstone National Park, Iceland, and New Zealand.

Some geysers erupt into pools, which are several feet or yards across and may be rather deep. Most of these pools are beautifully orna-

mented around their sides by deposits of silica, called *siliceous sinter.* From the bottom of each basin a tube or fissure extends downward, as shown in the diagram (Fig. 184). Other geysers have built cones of siliceous sinter around their orifices, from a foot to several yards high, which form upward extensions of the tubes (Fig. 182).

The most celebrated geyser in Yellowstone National Park is Old Faithful (Fig. 183), which at intervals of about 66 minutes erupts to a height of 110 to 160 feet. About 10,000 to 12,000 gallons are blown out during each eruption.



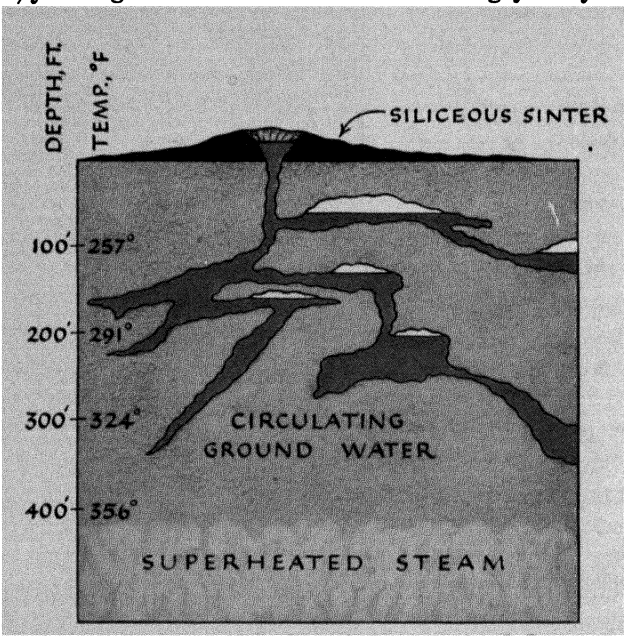
Haynes Studio.

FIG. 183. Old Faithful in eruption. Yellowstone National Park.

Cause of Geyser Action. The intermittent spouting of a geyser depends on the delicate adjustment of several factors: the amount and rate of inflow of subsurface water, the supply of heat, and the nature of the geyser tube and its underground connections of pipes and fissures ("the plumbing"). Because of so many variables, it is easy to understand why each geyser has its own idiosyncracies.

The explanation of geyser eruption depends ultimately on the relation between pressure and the boiling point of water. The boiling point of water under ordinary atmospheric pressure at sealevel is 212° F.; an increase of pressure raises it, a decrease lowers it. Consequently, the boiling point at the bottom of a column of water is raised by the weight of the water above it. As shown in Fig. 184, the boiling temperature increases in the tube of the geyser from the surface downward. If the tube is regular in form and large in diameter, the water rises as it becomes hotter; convection currents are thus established, mixing the water, so that it becomes nearly of the same temperature in all parts of the tube, and a boiling spring re-

sults. But if the tube is narrow or crooked, equalization of temperature by convection is prevented and the water reaches its boiling point in the deeper levels at the increased temperatures corresponding to the greater pressures. Suppose that at various points (Fig. 184) heat is being supplied by steam that enters the pipes of the geyser. At first the steam condenses, yielding much heat to the water in the geyser system. Con-



Modified from E. T. Allen and A. L. Day.

FIG. 184. Vertical section to show the conditions necessary for geyser action. White areas represent accumulations of steam in large cavities.

sequently the water becomes hotter until it is at the boiling point corresponding to the depth and pressure, and the steam no longer condenses. Finally, when the steam thus accumulating attains sufficient volume, it has expansive power enough to lift the column of water in the geyser tube to cause some overflow at the orifice, or as in Old Faithful to blow out jets 10 to 25 feet high, which herald the coming eruption. These preliminary actions reduce the length of the overlying column and lower the pressure on the water in depth; and this water, being now above the boiling point for the diminished pressure, flashes into steam, and a column of mingled steam and hot water is driven roaring out of the pipe into the air.

To account for the great quantity of water ejected by some of the geysers, much larger than the capacity of their tubes, it is necessary to assume that the tubes are connected laterally with one or more chambers, in which water and steam can accumulate.

That the geysers and other hot springs of the Park derive their heat from a deep-seated source is shown by their occurrence along the shores and within Yellowstone Lake itself, an immense body of cold water, beneath which the rocks must have cooled to a considerable depth. The deep-seated source is probably a large body of consolidating magma, a batholith, from which superheated steam issues along fissures; and where this steam meets the ground water, hot springs and geysers are formed.

Harnessing the Volcanic Forces

Fumarole fields have been developed in recent years so as to yield large supplies of steam for power generation. The fumarole field in Tuscany, north of Rome, was the first to be developed. In an area of 140 square miles a large number of fumaroles are giving off superheated steam. From 1818 onward these fumaroles have been utilized to recover the boric acid that they are bringing up from below. Four central power houses, capable of generating 25,000 horsepower, have been built in recent decades, and the electric power is transmitted to Florence, 60 miles away, Pisa, and other cities. Wells have been put down to depths of 600 feet, and the flow of steam, as well as the temperature of the steam, increases as depth is gained. The steam contains 6 per cent by weight of other gases, chiefly carbon dioxide, which is being recovered and used as a refrigerant. It is planned to recover the sulphur dioxide, methane, and helium. The steam is thus being fully utilized, both thermally and chemically.

At " The Geysers " in the Coast Ranges of California, 75 miles north of San Francisco, is an area of 35 acres containing a few feeble fumaroles and some small but very hot springs. The name " Geysers " is a misnomer, however, as none of the hot springs is eruptive.[2] In 1921 the idea was conceived of drilling wells in this area to develop a flow of steam for power purposes. So far eight wells have been put down, the deepest being 650 feet, and copious supplies of superheated steam have been developed. In fact, it is estimated that four of the wells will deliver on the average more than 1300 horsepower each. As in Tuscany the deeper a well is drilled the greater the flow of steam and the higher its temperature.

[2] Some of these steam vents, by suitable control of their outflow, have recently been converted into artificial geysers.

Fumarole fields in Java also have been investigated for their power possibilities, but many more remain to be tested in Java, as well as others in the near-by islands of Sumatra and the Celebes.

Volcanology and Human Affairs

The human race shows an astonishing pertinacity in living close around volcanoes and even high up on their slopes. Vesuvius, at once the pride and terror of Naples, is surrounded by towns and villages and is covered with gardens, groves, and vineyards that extend far towards its summit. The vaster Etna, in Sicily, is cultivated up to an altitude of 4000 feet — intensively below an elevation of 1500 feet, where it is luxuriant with orange and lemon groves, vineyards, and oleanders, all contrasting vividly with the black lava flows poured out in historic times. Monte Rosso, 700 feet high, the largest cinder cone on Etna, built in 1669 during the most disastrous eruption in the history of Etna, is now green with vineyards half way to its summit. From time to time the volcanoes overwhelm some unfortunate village. Along a main highway on the lower slopes of Etna at the terminus of the lava outbreak of 1929, can be seen stone houses partly engorged by the advancing flow, grim reminders of an ever-threatening danger.

Java is distinguished for its many highly active and destructive volcanoes — in fact, its volcanoes surpass all others in the amount of fragmental material they have ejected since 1500. Nevertheless, Java because of its 45,000,000 people is the most densely populated area of its size on the globe. Here the social or societal aspect of volcanology has been most fully recognized. The Netherlands government has established a Volcanologic Service, which by prognosis and warning of impending outbreaks and by defensive measures reduces the dangers of volcanism. The volcano Keluit broke out in 1919 after a dormancy of eighteen years. A crater lake had formed during the quiet interval, and its water now rushed down the valleys, killing 5500 people. A tunnel has since been driven into the crater, draining the lake and making repetition of the disaster impossible. Coming eruptions are often indicated by local, volcanic earthquakes and especially by increasing temperature of the fumaroles. Instruments for recording earthquakes have therefore been installed at critical localities and systematic measurements are made of the temperatures of the fumaroles. At Merapi, a notably active volcano, when the temperature of its fumaroles reach 600° C., danger of an eruption impends.

A lava flow, issuing from Mauna Loa in 1935 at an elevation of 9000 feet, was bombed by the U. S. Army Air Service, in order to turn the lava from its course. It was flowing toward the town of Hilo, threat-

ening to destroy the town and its harbor, the second most valuable in the Hawaiian Islands. The attempt was reported to have been successful. It is the hope of volcanologists in Hawaii and in Sicily that, if proper measures are taken, such as, for example, the construction of embankments, lava flows that threaten to flood productive land can be diverted into unproductive areas.

A brilliant example of diagnosis and prediction was given by Perret during the eruption of Mont Pelée in 1929-1932. After the eruption had continued five months, during which hundreds of peléan clouds h[illegible]

Dikes. A *dike* is a tabular mass of igneous rock that fills a fissure in pre-existent rocks. Consequently, it has walls that are parallel or nearly so. Dikes occur in rocks of all kinds — igneous, sedimentary, or metamorphic — and they are said to "cut" the rocks that inclose them. Dikes inclosed in layered rocks by definition cut the layers at an angle; for if a tabular intrusive mass is parallel with the layers it is termed a *sill.*

Dikes range in length from a few yards to many miles; they range in thickness from a fraction of an inch to thousands of feet. Three

dikes that cut a series of stratified rocks at right angles to the stratification are shown in Fig. 185.

Some fissures at the time they were formed opened at the Earth's surface, and the magma, rising along these channelways, welled forth as streams of lava. This, as we have seen, commonly occurs at active volcanoes. After the discharge ceased, the magma in the fissures solidified and thus formed dikes that reached to the Earth's surface.

Other dikes, however, did not extend to the surface, and their present exposure to view is the work of erosion. Some dikes fill the channels through which were fed intrusive bodies occurring higher in the crust, such as the sills and laccoliths next to be described.

The rock of some dikes is divided into blocks or columns by joints, and these columns are perpendicular to the walls of the dike, resembling a pile of cordwood, an arrangement whose origin is described later under *columnar structure*.

Dikes, especially those cutting sedimentary rocks, are adjoined on each side by a zone of hardened rocks, baked as the result of the high temperature to which they were subjected by the molten magma. Similar effects have been produced by all intrusive masses on the rocks in which they occur, and these effects give us a means for determining whether a given igneous mass is of intrusive origin.

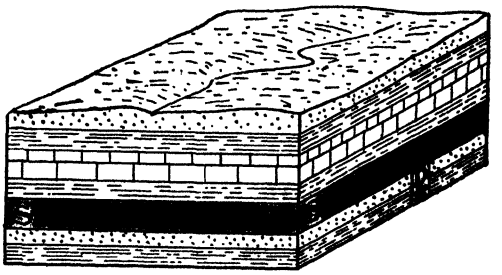


FIG. 186. The sill *SS* is intrusive between horizontal strata; the dike *D* represents the conduit through which the magma was forced up. Vertical joints were formed as the sill cooled. The block is about 1 mile wide, the sill 500 feet thick.

Sills. A *sill* is an intrusive sheet of igneous rock that is parallel with the layers inclosing it (Fig. 186). The inclosing layers are most commonly either sedimentary strata or lava sheets. Sills range in thickness from a foot or so to several thousand feet. In forming a sill, magma insinuated itself between two layers and lifted the overlying rocks through the distance now represented by the thickness of the sill. It can be easily appreciated that the magma of a thick sill, intrusive deep within the crust and having an areal extent of several thousand square miles, must have been injected by an enormous impelling force.

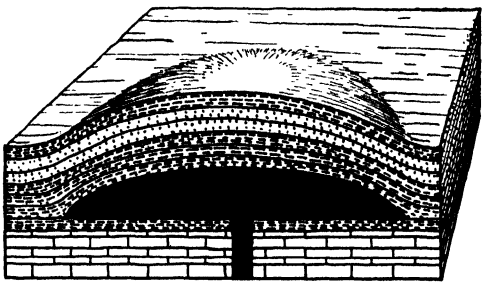
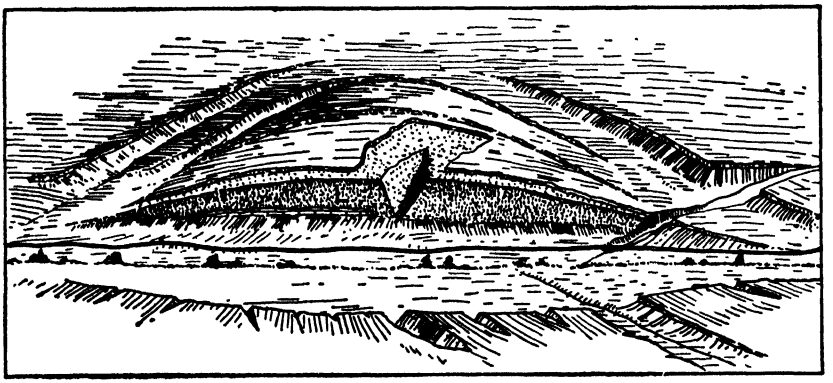


FIG. 187. Laccolith, showing the typical form of the igneous mass and the doming of the overlying beds. The block is about 2 miles wide.

Laccoliths. A *laccolith* is typically a lens-shaped mass of igneous rock intrusive into layered rocks. It has a flat floor and is more or less circular in ground plan. If the magma, after having insinuated itself between the layers in the form of a sill, arches up the overlying layers instead of continuing to spread laterally away from the supply channel, a lens of liquid rock is produced, and this lens on solidifying forms a laccolith. A section of an ideal laccolith is given in Fig. 187, in which is shown the dome-shaped mountain formed by the lifting of the rocks that overlie the laccolith.

Laccoliths are conspicuous features in many parts of western North America (Fig. 188). They were first discovered in the Henry Moun-

tains of southern Utah, where they rise above a plateau of undisturbed horizontal strata. They form a complete series that comprises all the progressive stages of denudation: from laccoliths that are still covered by their roof-rocks and whose presence in depth is inferred from the dome-like hills made by the up-arching of the strata, to laccoliths so deeply dissected as to show the floor of undisturbed horizontal strata underneath them.



L. V. Pirsson.

FIG. 188. Laccolith (*L*), from which the roof-rocks have been partly stripped off by erosion. Warm Spring Creek, cutting across the laccolith, has exposed the horizontal floor on which the laccolith rests. The laccolith is about 1 mile in diameter. Judith Mountains, Montana.

Volcanic Necks. When a volcano becomes extinct, its conduit leading upward from the depths becomes filled with a solidified mass of magma or with a chaotic mass of angular blocks, large and small. This filling, as already mentioned on page 224, forms a cylindrical mass known as a *volcanic neck* (Fig. 189). It is circular in ground plan and may be from a few hundred yards up to a mile in diameter. The rocks surrounding a volcanic neck are generally cut by a system of dikes that radiate out from it as a center, and if the rocks are stratified they contain many sills that were injected into them.

Batholiths. A *batholith* is a huge intrusive body of igneous rock. Large size and intrusive relation to its inclosing rocks are its distinguishing features (Fig. 190). Furthermore, a batholith enlarges downward and appears to extend indefinitely downward into the Earth's crust; it is without a known floor, in contrast to a laccolith, which rests on a floor. To qualify as a batholith, an intrusive mass should exceed 40 square miles (= 100 square kilometers) in area; if smaller than this, the mass is called a *stock*, but some authorities hold that the delimitation should be at 10 square miles.



SPENCE AIR PHOTOS.

Fig. 189. Shiprock volcanic neck, 1400 feet high, with dikes extending out from it. Near Farmington, New Mexico.

Batholiths, like other intrusive bodies, become accessible to human observation only as the result of their exposure by erosion. Accordingly, the size of a batholith as we customarily speak of it depends on the extent to which it has been uncovered by erosion. The largest batholith in the United States is the Idaho batholith of central Idaho, exposed over an area of 16,000 square miles. Had erosion stripped off less of the roof-rocks that originally covered the batholith, its exposed area would be smaller; and had erosion extended a mile or two deeper its visible portion would have been much larger. Another great batholith is the Coast Range batholith, which extends for 1100 miles from the Canadian border northward into Alaska and has an exposed width of 80 to 120 miles.

W.E.D. 19.....

Many mountain ranges have batholithic cores, or backbones of igneous rock. Most batholiths are in the world's mountain belts, in the zones of closely folded strata. The enormous bodies of magma rose from the depths either at times of acute folding of strata, during a mountain-making revolution, or shortly after. A batholith intrusive during such a revolution tends to have concordant contacts, *i.e.*, the roof-rocks arch over the top of the batholith just as the roof-rocks arch over a laccolith; whereas a batholith intruded at the end of a crustal revolution has discordant contacts: it breaks across the general structure of the rocks it has invaded (Fig. 190). Structurally, then, there are two types of batholith: *concordant* and *discordant*.

Granite is the chief rock of which discordant batholiths are composed, and granite gneiss (a modification of granite due to the roughly

parallel arrangement of its component minerals, chiefly expressed by the orientation of the biotite flakes) makes up the concordant batholiths.

As granite is formed at some depth in the crust, it is exposed at the surface only after erosion has stripped off the covering rocks; hence it is seen chiefly in those parts of the continents bared by erosion — that is to say, in mountains or in regions so deeply eroded that the roots of the mountains are visible.

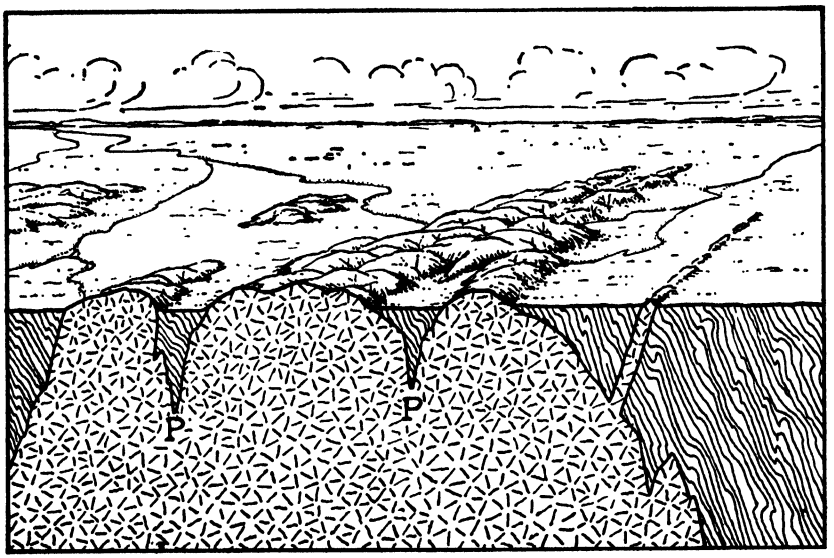


FIG. 190. Batholith, partly uncovered by erosion; P and P' are masses of invaded country rock that project deeply downward into the batholith. At P the downward projecting mass is continuous with the main body of country rock (represented by the wavy lined pattern); but at P' the connection has been destroyed by erosion, leaving the mass of invaded rock as an island in a sea of igneous rock. The batholith is of the *discordant* type, as it cuts across the structure of the invaded country rock. The block is about 20 miles wide.

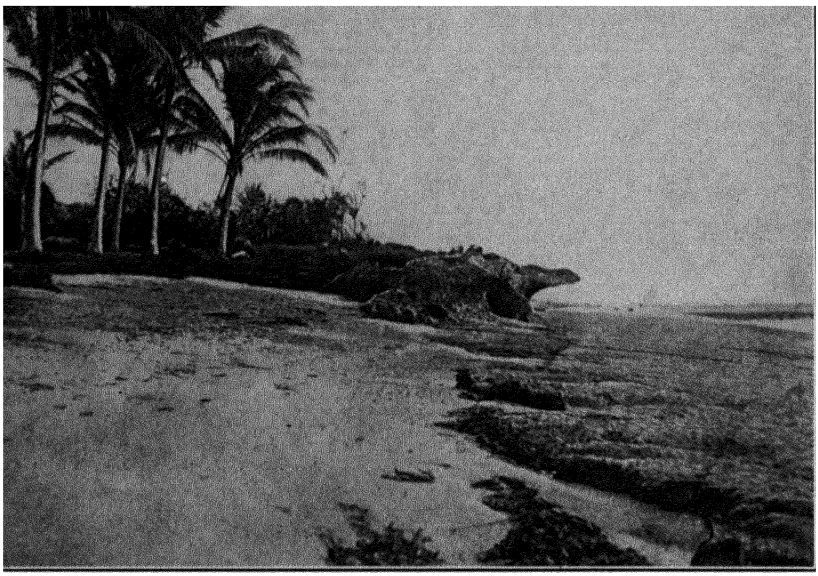
Granite forms the foundation of the continental masses. These foundation granites occur as batholiths of very ancient origin and constitute a floor upon which the sedimentary rocks of later age were deposited. Granite of younger age also occurs as colossal batholiths that are intrusive into the younger rocks, for epochs of granitic intrusion have occurred time and time again during the long span of the Earth's history. The Idaho and Coast Range batholiths already cited are outstanding examples of such younger vast intrusive masses. On account of its prevalence in the crust, granite is by far the most voluminous of the intrusive igneous rocks.

Relation of Batholithic Intrusion to Other Geologic Processes. The preparatory stages for a mountain-making revolution are outlined on page 305. In the late stages of such a revolution, or shortly after, the batholithic granite magmas rise from the depths and solidify. As an accompaniment of this solidification, pegmatite magmas, which are granite magmas of a specialized type, are formed, and are injected into any fissures that open as a result of shrinkage due to cooling. The pegmatite dikes thus formed are of particular interest in that some of them contain the radioactive minerals that are used in determining the ages of rocks (p. 9). Furthermore, the granite magmas as they solidify give off their dissolved gases and other volatile matter, and, if these gases become confined to definite channels, they are likely to form ore deposits of economic value (p. 331). A period of batholithic intrusion is therefore likely to have been followed by an epoch of ore deposition.

CHAPTER 13

BENDING, FRACTURING, AND METAMORPHISM OF ROCKS

In Sweden and other countries near the Baltic Sea an uplift of the land has been under observation for a long time, and its rate has been measured by marks along the shores. In some places the elevation has been as much as 3 feet in a century; but the rate decreases in all



G. A. F. Molengraaff.

FIG. 191. Emerged coral reefs on the Island of Letti, Netherlands East Indies. Two stages of emergence are recorded. The reefs at the level of the palms were lifted above sealevel and were then undercut by the waves. The lower reefs (sloping to the right) grew while the sea was forming the undercut cliff; they also are well above the present sea (shown at extreme right), in which new reefs are now growing.

directions from a central area in northeastern Sweden. Elevated shorelines around the Baltic Sea indicate that the region has been domed up gradually for a long time, and that the central part of the wide dome is at least 900 feet higher than it was at the close of the Ice Age, some thousands of years ago. Similar uplifts in some tropical

regions are indicated by the presence of fresh coral reefs (p. 181) high above sealevel (Fig. 191).

There is abundant evidence in all continents that parts of the land surface have been elevated and other parts depressed. Sedimentary rocks containing shells and bones of marine animals now lie at various altitudes, up to 2 or 3 miles above sealevel in high mountain belts. On the other hand, the edges of some continents have subsided, allowing the sea water to extend great distances inland along stream valleys; the large estuaries on the coast of Maine furnish an excellent illustration. Many of these up-and-down movements of the crust have no doubt proceeded slowly through long time intervals. However, occasional abrupt and violent movements have occurred within historic times. In 1899 a stretch of the Alaskan coast, at Yakutat Bay, was suddenly lifted nearly 50 feet. Instantaneous movements of this kind are accompanied by destructive earthquakes (Chap. 14).

"Terra firma," therefore, is not absolutely stable, and rocks are not indefinitely strong. Probably all parts of the Earth's crust have been moved many times, and some parts have experienced violent disturbance. Much of the bedrock has been fractured, bent, and mashed, and in general the oldest rocks give the most eloquent testimony of crustal unrest, because they have been subject to disturbance repeatedly during geologic time. Rocks that were subjected to intense pressure and heat at great depths have been radically changed or metamorphosed. These altered rocks are now visible over wide areas of old mountain zones, where they have been exposed by long-continued erosion.

Crustal movements that have occurred in late geologic time are recorded in surface features, such as the uplifted shorelines in Scandinavia. With the passage of time these features are destroyed by erosion, and the only remaining clues to ancient crustal movements are then to be found in the bedrock itself, in the form of structural features that resulted from the movements. The principal kinds of such features are warps, folds, fractures, and foliation.

Broad Warps

In the Colorado Plateau of Arizona, Utah, and New Mexico a thick blanket of old marine strata lies thousands of feet above sealevel and is dissected by deep canyons. In a general way these strata are nearly horizontal; but if any one layer is followed in detail it is found to bow gently upward into irregular domes and bend downward into shallow basins. It is clear that this wide cover of sedimentary beds, many hundreds of miles across, was not lifted up with absolute uniformity, but was gently bent or *warped* from its former nearly horizontal atti-

tude. The original surface of the uplifted mass has been entirely destroyed by erosion; but a record of the warping is faithfully preserved in the form of each layer of stratified rock beneath the former surface.

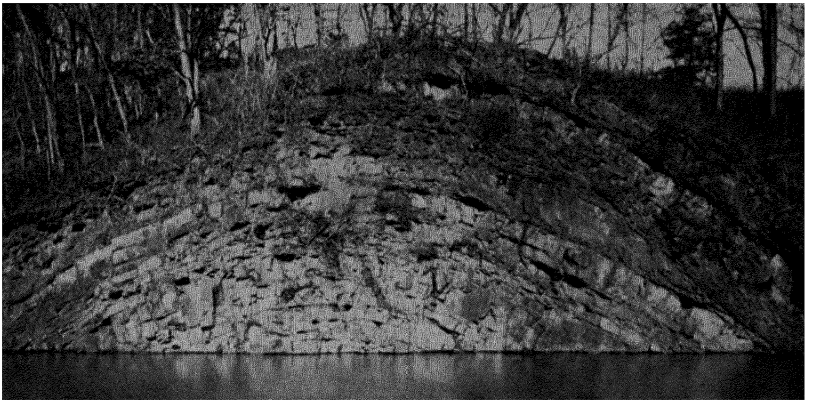
Warping is the commonest form of rock deformation in the outer part of the Earth. All the old marine strata that now lie on the continents are in some degree warped, where they have escaped still more violent disturbance, because uplift of the former sea floors was greater in some places than in others. Large-scale downwarping probably is as common as warping that causes widespread uplift; an example is the region including San Francisco Bay, California, where gentle downbending of the crust has permitted the sea water to flood far inland.

Folds

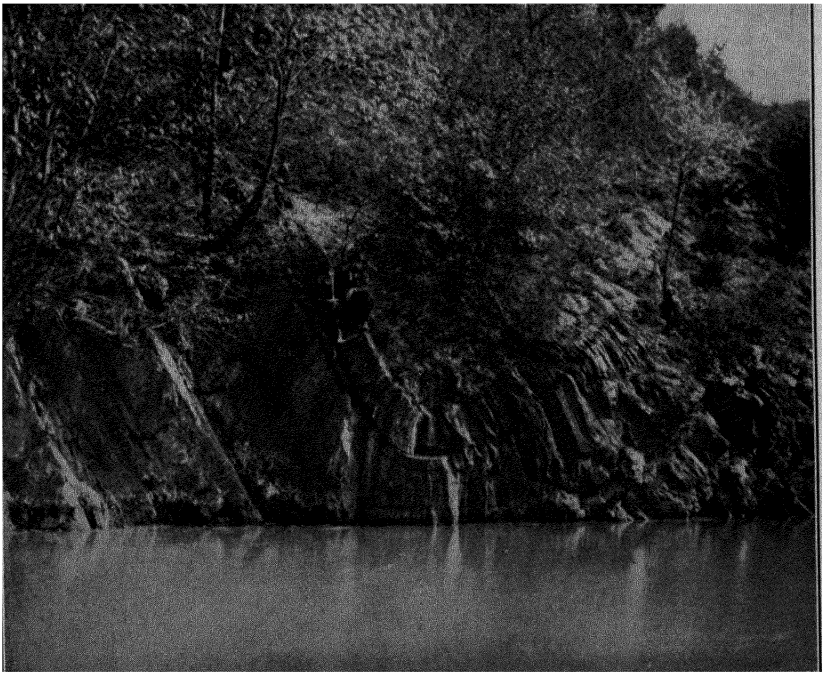
Form of Folds. In many places the stratified rocks have been buckled into more or less regular *folds*. Some of these are on a small scale and can be seen directly (Figs. 192, 193); but commonly the folding is on such a great scale, and exposures of the rocks are so discontinuous, that it is necessary to study and piece together the structure of certain distinguishable layers over many miles before the form of the folds becomes clear. The nature and scale of the folds in mountain regions can be appreciated best by study of maps and cross-sections that have been prepared by geologists in the field.

Two terms are used constantly in descriptions and discussions of folds. Like regular swells on the sea, rock folds ordinarily occur in a series, with alternating crests and troughs. The crests of the folds — that is, the upfolds — are *anticlines;* the troughs, or downfolds, are *synclines* (Fig. 194). Initially the anticlines form ridges, the synclines form valleys; but if the original surface crests are subsequently carried away by erosion, and the whole area is reduced to a plain, we still call the upfolded portions of the layers below the surface anticlines, the downfolded portions synclines, and in imagination reconstruct the missing parts. Thus anticlines and synclines *are features not of surface form, but of bedrock structure.* Not uncommonly the original configuration of the surface is actually reversed by erosion, so that valleys now occupy the positions of the former anticlinal crests, and ridges or mountains are in the places of the synclinal troughs; but the original structural terms of course still apply (Fig. 195).

It is cause for some wonder that strong, brittle rocks can be bent into sharp folds. If we should try to bend a rock slab by compressing the opposite edges in a powerful vise, the slab would be broken in two or



A



B *I. C. Russell, U. S. Geol. Survey.*

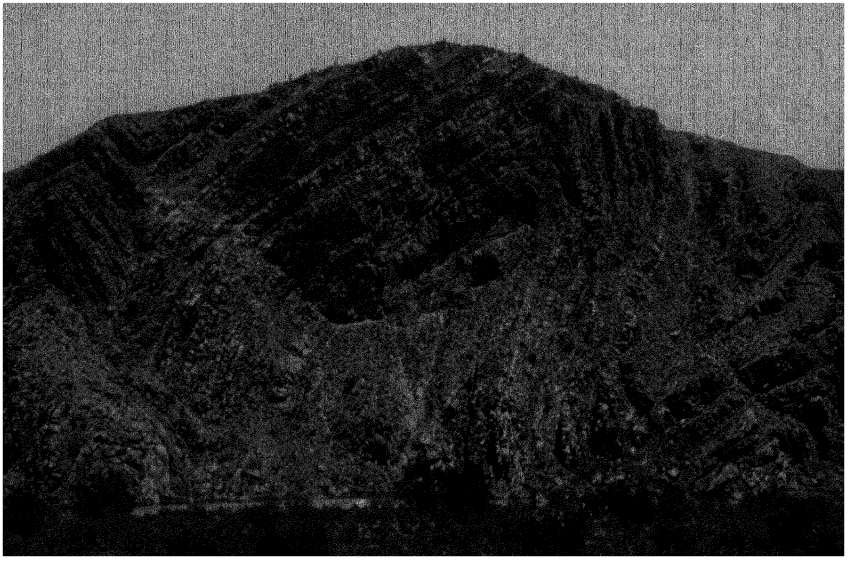
FIG. 192. *A*, top of an anticline; *B*, part of a syncline; both exposed by quarrying operations. Near Hancock, Maryland.

crushed to bits. Probably two conditions are essential for making the rock folds found in nature: (1) The tremendous forces that cause deformation act through very long periods of time, and the rocks yield slowly instead of fracturing abruptly; (2) many of the folded strata that we now see at the surface lay at some depth in the crust when they were deformed, and the confining pressure of the rock above and around them prevented the layers from breaking as the folding took place. If there is sufficient time for adjustment, the most brittle rocks under strong confining pressure can be forced to bend as if they were soft and plastic.

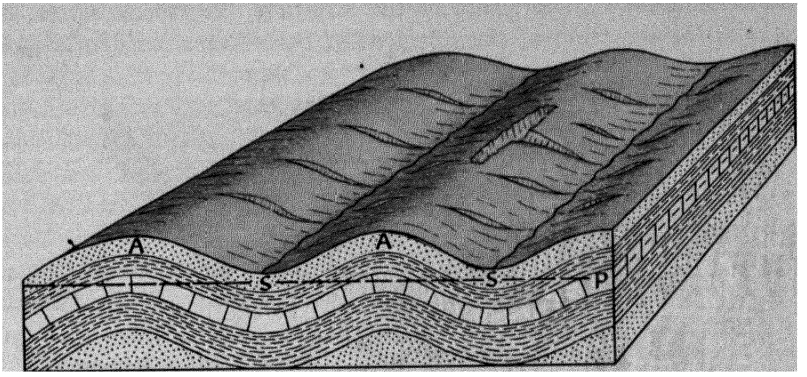
Method of Studying and Mapping Inclined Strata. The varied kinds of deformation through which the rocks have passed in any region determine the *geologic structure* of that region, and it is important that the geologic structure of every country should be known so far as possible and represented accurately on maps. If the surface of the Earth were everywhere naked bedrock, this would be a comparatively easy matter; but since the rocks are largely covered with mantle and vegetation, or with water, snow, and ice, the natural difficulties of the task are great. The structure in a region is determined by a careful

A. W. ROGERS, GEOL. SURVEY, UNION OF SOUTH AFRICA.

Fig. 193. Folded strata along the Buffels River, north side of the Cape Ranges, Cape Province, South Africa. An anticline and an adjacent syncline are overturned toward the right (north).



study and comparison of the outcrops. If the ground were perfectly level and the strata horizontal, the outcrop would be the flat surface of the uppermost rock stratum, and we should learn little from it: but



occurred so recently that running water has had time to cut only a few small valleys in the anticlines. Hence the anticlines form ridges, the synclines form valleys. If erosion persists until a peneplane is produced, as indicated by the broken line through *P*, the folds will still exist as structural features beneath the surface. Length of block about 2 miles.

on slopes and cliffs bordering stream valleys we can inspect the outcropping edges of many horizontal strata, as in the Grand Canyon (Fig. 3, p. 6). On the other hand, if the strata have been inclined

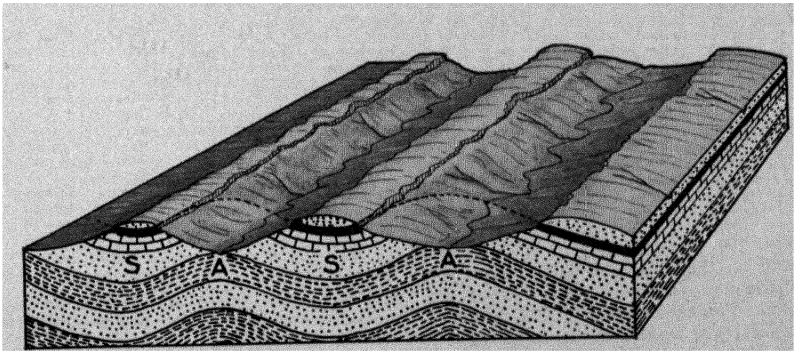


FIG. 195. An advanced stage in erosion of folded strata. Anticlines (*A*,*A*) have been cut down until valleys occupy their crests; a resistant stratum (black) protects the synclines (*S*,*S*), so that ridges exist along these structural troughs. The original position of the resistant stratum across the present valleys is indicated by the broken line. Length of block about 2 miles.

by folding and later eroded, their edges are exposed even on a nearly flat land surface. Commonly the edges of the more resistant beds project to form the more prominent outcrops. (Fig. 70, p. 98).

Dip and Strike of Beds. The inclination of a rock layer is called the *dip*. If the stratum is resistant, its projecting edge trends across flat country as a definite ridge (Fig. 196). The compass direction of this ridge is called the *strike* of the stratum. In precise terms, *the strike is the direction of the line formed by intersection of the plane*

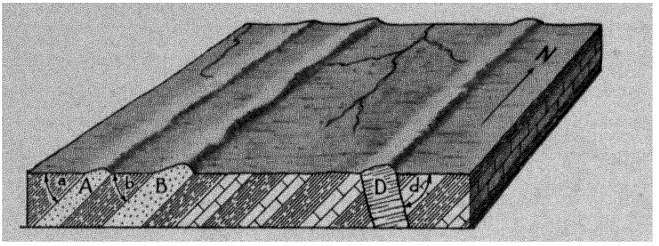


FIG. 196. The *strike* of two resistant strata, *A* and *B*, and of a dike, *D*, is indicated clearly by the trend of the ridge formed by each. The strike in each case is exactly north. *A* and *B* dip west (the dip angles are *a* and *b*); the dike dips east (angle of dip *d*).

of bedding with the horizontal plane. In Fig. 196 the strike of all the strata and of the dike is north-south. The dike and the two strata *A* and *B* are resistant and so form prominent ridges whose direction is easily determined.

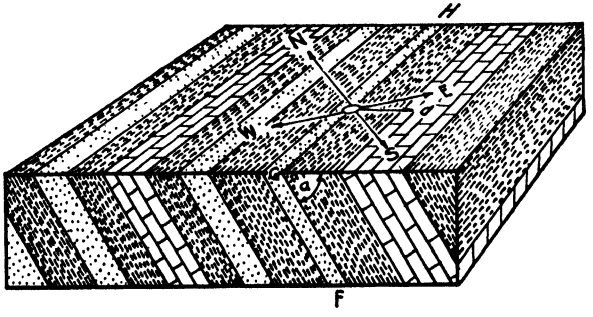


FIG. 197. Determination of strike and dip of inclined strata. The compass (*O*) is placed on the edge of a bedding plane of the stratum *FGH*. The arrows (*N,E,S,W*) indicate compass directions. Arrow *d* indicates the *direction* of dip, at right angles to the strike. The strike (angle *NOH*) and the direction of dip (angle *SOd*) are read with the compass; the *amount* of dip (angle *a*) is read with a clinometer.

The inclination or *dip* of a rock layer is the angle between the surface of the layer and the horizontal plane. In Fig. 197 the surface of the ground is supposed to be horizontal. Then the angle *a* (60°) gives the amount of dip of layer *FGH*. But it is important to give the direction as well as the amount of dip. In Fig. 196, *A* and *B* dip 50° *west*, *D* dips 80° *east*. The direction of the dip is at right angles to the strike.

The amount of dip is determined with a clinometer, which is essentially a pendulum swinging over a graduated arc. For geologic purposes the compass and clinometer are combined in one instrument, to permit ready determination of the strike and the direction and amount of dip. Dip and strike are represented on geologic maps by a conventional sign ⊢, in which the direction of the bar, as placed on the map, indicates the direction of strike, and the arrow points in the direction of dip. Ordinarily the amount of dip in degrees is written in; *e.g.*, ⊢ 30°.

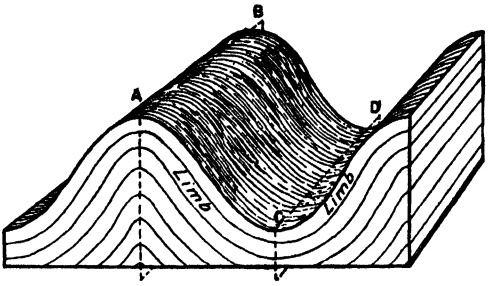


FIG. 198. Simple upright folds. The line *AB* is the axis of the anticline; *CD* is the axis of the syncline. The imaginary planes indicated by broken lines are the *axial planes* of the two folds.

Variations in Fold Structure. An imaginary plane passed through the middle of a fold, as in Fig. 198, is called the *axial plane* of the fold; this plane bisects the angle between the sides or *limbs* of the fold. If the fold is upright the plane is vertical (Fig. 199). However, some folds are not upright but have been pushed over until the axial planes are inclined. A fold of this kind is said to be *over-*

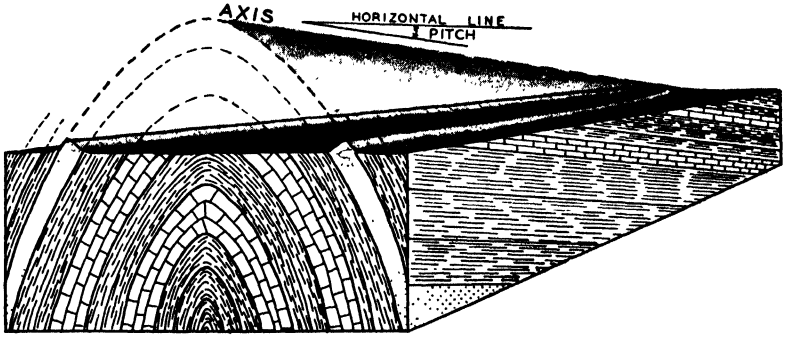


FIG. 199. An anticline tilted along its axis and eroded to a nearly level surface, except for a " hairpin " ridge marking the edge of a resistant sandstone layer, *SS*. The surface of this layer as it appeared before erosion is shown by shading. The *pitch* of the anticline is the angle made with the horizontal by the inclined axis.

turned (Fig. 193). In some folds the overturning has gone so far that the axial plane is nearly or actually horizontal; and the fold is then termed *recumbent*. In the Swiss Alps, where deformation of thick

sedimentary strata is extremely complex, there are many large recumbent folds.

The line along which the axial plane intersects the top of an anticline or the bottom of a syncline is the *axis* of the fold (Figs. 198, 199). When folds that have horizontal axes are eroded deeply, the ridges

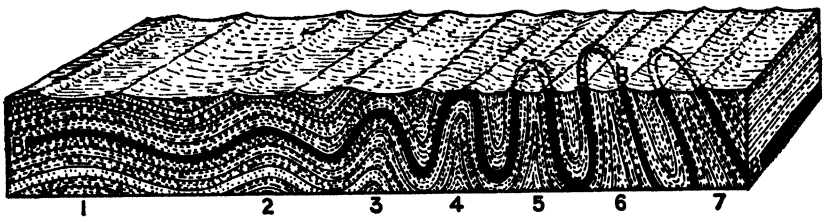


FIG. 200. Folded strata, considerably eroded. The anticlines 1 to 5 are upright; 6 and 7 are overturned. Each fold from 5 to 7 has its limbs essentially parallel as they are seen at the surface; these folds are *isoclinal*. Length of block about 25 miles.

made by the edges of resistant strata are nearly parallel, as shown in Fig. 195; but if the axes are not horizontal, on a nearly flat erosion surface the outcropping edges of strata in the limbs of any anticline or syncline converge and finally meet (Fig. 199). The result is a hairpin turn in the outcrop in either kind of fold; but there are two general ways of distinguishing one from the other. In the ordinary syncline, dips are consistently inward toward the axis, and the younger strata lie inside the hairpin; in an ordinary anticline, dips are outward from the axis, and the older strata lie inside the hairpin (Fig. 199).

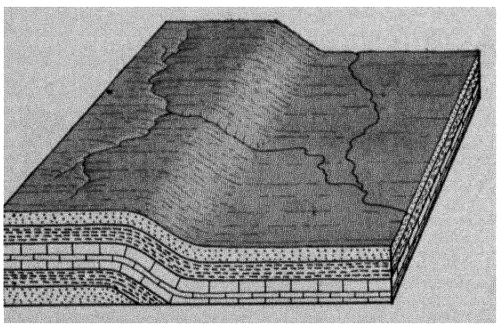


FIG. 201. A monocline. It is assumed that the fold developed rapidly and recently, and therefore is almost unmodified by erosion.

Folds whose axes are not horizontal are known as *pitching* folds.

In *isoclinal* (equal-inclination) folds the strata are compressed until, on both sides of a fold, and perhaps throughout a number of successive folds, they are parallel and have the same dip (Fig. 200). When the crests of such folds are cut away by erosion, considerable skill is required for correct interpretation of the structure, since there is no difference in general appearance between anticlines and synclines.

A special kind of fold is the *monocline,* in which the strata are bent in one direction only (Fig. 201). A true monocline is a one-limb flexure, on either side of which the strata are horizontal or have uniform gentle dips. Monoclines are particularly well developed, as isolated features, in the nearly flat strata of the Colorado Plateau in northern Arizona and New Mexico.

Geosynclines and Geanticlines. Long belts within a continent or on the sea floor have been warped down to form *geosynclines,* whose dimensions are measured in hundreds of miles. Correspondingly great upwarps are called *geanticlines.* The prefix in each case (from the Greek word *geos,* meaning Earth) emphasizes the scale of these features. In contrast with ordinary folds, the flexures responsible for geosynclines and geanticlines are very gentle.

The geosynclines of the past have been the great basins for the accumulation of sediments like those exposed in the Appalachians (Fig. 246, p. 307) and the Alps. Slow downwarping of the floor of a geosynclinal basin continues as sediments accumulate, until in the middle portion the thickness of deposits reaches several miles. It is only by the later uplift of these deposits and their partial destruction by erosion that the original nature of the geosyncline is revealed. Thus a geosyncline has peculiar features other than its great size to distinguish it from an ordinary syncline in a belt of folding. The geosyncline is a great downwarp in the Earth's crust; sedimentary strata that accumulate in the subsiding basin are a logical but incidental effect of the subsidence (p. 306). The first layers of sediment deposited on the sinking floor become flexed downward as the movement continues; but strata formed during the later stages may be essentially horizontal (Fig. 246, p. 307).

Geanticlines also grow slowly, and their crests are gradually destroyed by erosion as the warping continues. A good example, on a moderate scale, is the Cincinnati Arch in Ohio and Kentucky, where in an area 250 miles wide the strata dip gently in opposite directions from a median axis.

Fractures in Rocks

In the outer shell of the Earth the rocks are traversed in all directions by fractures, which vary from microscopic crevices to important breaks on which large displacement has occurred. Such fractures have great geologic importance, because they are clues to important events in the history of a region, and particularly because they give aid to various geologic processes. We have considered the large influence of fractures on the weathering and erosion of rocks (Chap. 2),

and on the circulation of subsurface water (Chap. 6); and we shall consider their importance also in connection with mineral deposits (Chap. 16).

A fracture on which there has been no appreciable displacement parallel with the walls is a *joint*. If there has been relative displacement of the walls parallel with the fracture, so that corresponding points on the two sides are distinctly offset, the fracture is known as a *fault*.

Joints. Field examination shows that joints are common, but that they are much more numerous in some places than in others. Where



I. C. Russell, U. S. Geol. Survey.

FIG. 202. Joints cutting horizontal beds of limestone. There are two sets of joints, nearly vertical and at right angles to each other. Drummond Island, Michigan.

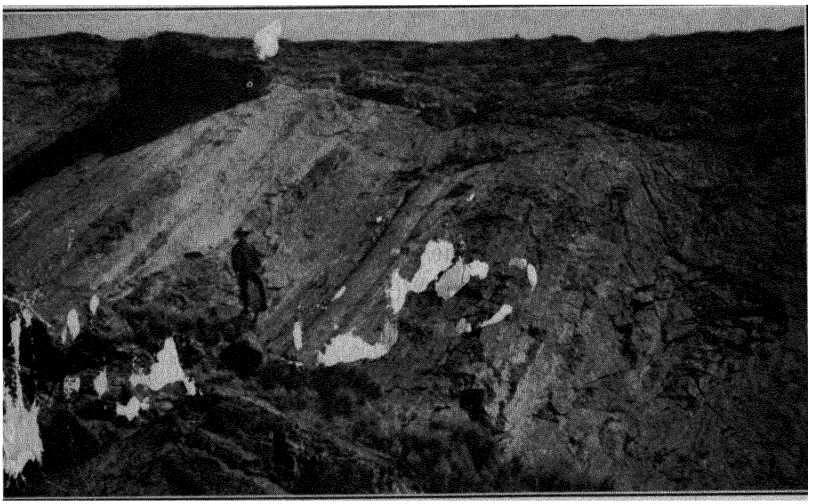
they are abundant, commonly they are arranged in more or less definite *sets;* that is, the divisional planes running through the rock fall into groups according to direction. In many places there are at least two prominent sets of joints, intersecting at a large angle (Fig. 202). Such a combination of two or more intersecting sets constitutes a joint *system*. Combined with natural divisional bedding planes, a well-defined system of joints divides stratified rocks into series of closely fitting blocks. The finer the grain of the rock, as a rule, the more perfect the jointing and the more sharply defined the resulting blocks. In some beds of shale and limestone the jointing is exceptionally perfect.

Some jointing probably results from the tension caused by contrac-

prisms have a variable number of sides, but commonly they tend to be hexagonal, and some of them have remarkable regularity of form. They range from several inches to a number of feet in diameter, and up to 500 feet in length. The Giant's Causeway on the north coast of Ireland is one of the most celebrated examples of this columnar structure; there are many fine examples also in western United States (Fig. 203). The columns form at right angles to the chief cooling surface, and consequently in a level sill or a lava flow they are vertical, whereas in a vertical dike they are horizontal.

General Features of Faults. Displacement of rock masses along a fault may occur at the time of the break, or at some later time. Faults are common features in rocks of all kinds. They are most evident in stratified formations, since the offsetting of definite layers makes a break conspicuous and directly measurable. However, massive igneous rocks are faulted as well. Since mineral veins and other features of economic value have been displaced and locally concealed by movement on such fractures, it is extremely important from a practical as well as a scientific standpoint that the nature of faults be well understood.

A surface of fracture along which movement and dislocation have occurred is often spoken of as a fault plane. Although a limited part of it may be nearly plane, it is rarely flat for any considerable distance,



C. R. Longwell.

FIG. 204. Part of an old fault surface, with slickensides, uncovered by erosion. The striations and flutings indicate that the movement was directly down the dip of the surface. Spotted Range, Nevada.

but more or less curved and irregular. Therefore it is better, and causes less misapprehension, to term it a *fault surface*. Rather commonly a faulting movement occurs, not upon one surface, but upon a number of more or less closely adjacent breaks, producing a *fault zone*, in which the various offsets make in the aggregate the total displacement. The masses of rock involved in fault movements generally are of such size and weight, and are so compressed together, that the motion of one fault face on the other takes place under tremendous pressure. As a result of the friction the rock faces are smoothed and striated, and not uncommonly receive a high polish (Fig. 204).

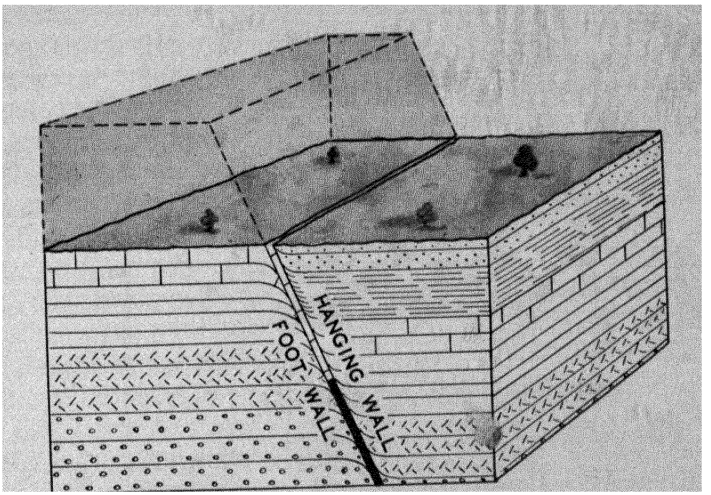
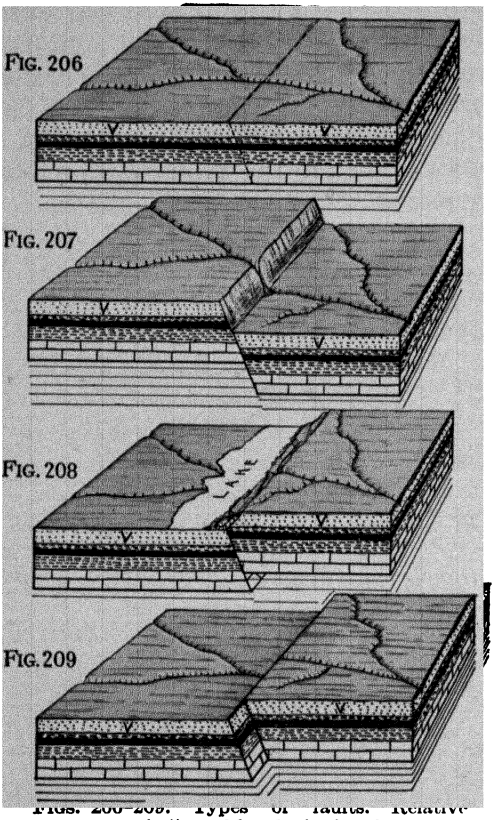


FIG. 205. Fault relations and terms. Horizontal strata were displaced by faulting, and a vein of valuable mineral (black) was formed along the fracture. Mining operations have removed the mineral to a considerable depth, and the space thus formed is kept open by timbers at right angles to the walls. The strata were dragged upward in the hanging wall and downward in the footwall by frictional resistance to movement on the fault. A large mass of rock on the upthrown side, indicated by broken lines, has been removed by erosion since the faulting occurred.

The line of intersection of the fault with the plane of the horizon is called the *strike* of the fault, just as we speak of the strike of inclined strata. The surface of faulting is rarely exactly vertical, usually it is inclined, and in some important faults it approaches horizontal. The angle between the fault surface and the horizontal plane is the *dip*. In an inclined fault the face that overhangs is known as the *hanging wall*, the other as the *foot wall* (Fig. 205). If one were to descend along a fault, as in an inclined shaft of a mine, the appropriateness of these old mining terms would be impressively evident.

The features explained so far have to do chiefly with faults as seen below the surface of the ground. Ordinarily a fault breaks the surface as well as the rocks beneath; and if one side of the fault is elevated with relation to the other, the result is a cliff, or *fault scarp* (Fig. 207). With the passage of time the original scarp is modified or even obliterated by erosion.



FIGS. 206–209. Types of faults. Relative movement indicated by the broken bed *V–V*.

FIG. 206. Before movement. Position of the fracture shown by broken line.

FIG. 207. Simple normal fault, making a scarp which the stream descends in a cascade.

FIG. 208. Reverse fault. The projecting edge of the hanging wall slumps under its own weight. The stream is obstructed and forms a lake.

FIG. 209. Strike-slip fault, with no vertical displacement.

Movements on Faults. Generally there is no means of telling how much actual movement there has been on either side of a fault. Even if a definite, recognizable object, such as a crystal or pebble in the rock, has been cut in two by the fracture and the halves carried apart a measurable distance, we can not determine whether one side of the fault stood still while the other side experienced all the displacement, or whether both sides shared in the movement. Nevertheless an attempt is made to classify faults according to the apparent or relative displacement on the two sides as indicated by offset strata, dikes, or other recognizable features. Thus in Fig. 207, it is evident from the displacement of the layer *VV* that the hanging wall has gone down with relation to the foot wall (although actually the foot wall may have moved up while the hanging-wall block stood still, or both blocks may have moved). A fault that has this relation between hanging wall and foot wall is called a *normal* fault. If the hanging wall appears to have been crowded up over the foot wall, as in Fig. 208, the fault is called a *reverse* fault.

Generally the movement on a fault surface is more or less oblique, instead of straight up or down the dip of the surface. Not uncommonly the motion is chiefly or entirely horizontal, parallel with the strike of the fault (Fig. 209). Such a fault is called a *strike-slip* fault. If it cuts only horizontal strata, there is no measure of the movement except in displaced features on the ground, since the strata are not offset. Displacement of a steeply inclined dike, however, would record both the direction and the amount of movement.

Varying Magnitude of Faults. The scale of faulting varies within wide limits; displacement varies from a fraction of an inch up to thousands of feet, or even several miles. In the Plateau region of Arizona and Utah, several faults of great magnitude extend in a north-south direction, some of them crossing the Grand Canyon. Each of the largest fractures in this group can be followed 100 miles or more, and each has a displacement measured in thousands of feet. The Great Basin region presents the phenomenon of faulting on a colossal scale. In the area between the Sierra Nevada on the west and the Wasatch Range on the east, the crust is divided into huge blocks by gigantic fractures; and differential displacement of these blocks, together with erosion, has resulted in mountainous topography (Fig. 241, p. 301).

Most of the great fractures mentioned above are normal faults. Detailed study of eroded mountain areas has disclosed reverse faults of enormous displacement, some of them with an exceptionally low angle of dip. Such faults are commonly known as *thrust* faults, or simply *thrusts*. The surface on which movement has occurred is spoken of as the thrust surface, or less accurately as the thrust plane. Great thrusts are present in the Alps, in northwestern Scotland, in Scandinavia, in the southern Appalachians, in the Rocky Mountains, and in many other mountain regions. Lower, older formations have been shoved over younger rocks as much as 25, 30, or even 40 miles in individual thrusts (Figs. 254–257, p. 312).

The deciphering of these great thrusts is one of the triumphs of modern geologic research. It has led to rational interpretation of mountain structure that before seemed illogical and chaotic.

Fault Scarps. Displacement of the Earth's surface by a normal or a reverse fault gives rise to a cliff or scarp. Within historic time, movements that caused severe earthquakes have resulted in new scarps from a few feet to nearly 50 feet high (Fig. 210). Many other cliffs and mountain fronts, some of them hundreds or thousands of feet in height, are recognized as fault scarps, but it is not probable that any one of these was formed by a single displacement. There

is strong evidence that the stress responsible for slipping on a fault is relieved temporarily by abrupt displacement of a few feet or tens of feet, and then accumulates for years or even hundreds of years before the movement is repeated. Thus every high fault scarp is a very old feature judged by human standards, although it is youthful from a geologic viewpoint.

Erosion starts to modify a fault scarp as soon as faulting begins, and the upper portion of every high scarp is considerably cut back, both because that part has been subject to erosion since the scarp was



Eliot Blackwelder.

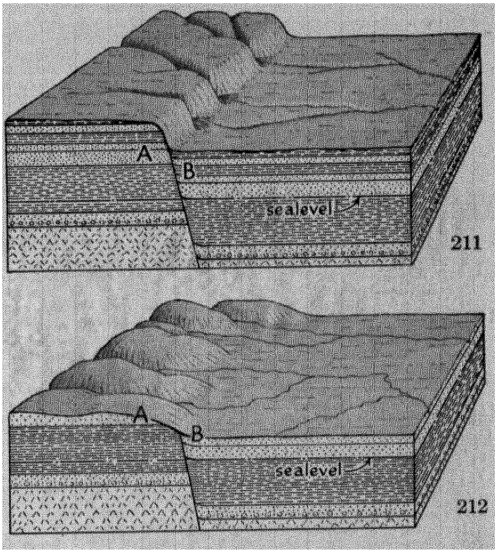
FIG. 210. Result of recent faulting at the base of the Sonoma Range, Nevada. The new scarp, which appears as an irregular band extending across the view at the top of the alluvial slope, is about 20 feet high. This scarp was about 3 miles distant from the camera.

first initiated, and because erosion is most effective at the higher altitudes (Fig. 211). After the faulting has ceased, the entire scarp is continuously lowered, and slowly retreats from the position of the fault. As erosion progresses the scarp passes through the stages of youth, maturity, and old age, and finally, on peneplanation of the region, differences in elevation on opposite sides of the fault almost or entirely disappear.

A large fault displacement as a rule brings together, on opposite sides of the fault, rocks that differ materially in composition and resistance. As erosion proceeds the initial scarp is eventually destroyed, but so long as the entire region has considerable altitude the

position of the fault is marked by a cliff or steep slope because weak rock on one side is removed faster than resistant rock on the other. Many old faults are now marked by scarps that were formed entirely by such differential erosion and not directly by displacement of the surface of the ground (Fig. 212).

In several of the western States, where large crustal movements have occurred in late geologic time, and where climatic conditions favor the development of excellent outcrops, there are many fine examples of fault scarps. The east slope of the Sierra Nevada and the west slope of the Wasatch Mountains are fault scarps that are youthful in a geologic sense. At the base of each of these ranges some of the movement has occurred so recently that scarps exist almost uneroded in the fans of weak alluvium brought down by the streams (Fig. 210). The last recorded movement along the east base of the Sierra Nevada took place in 1872. These two great mountain fronts have grown by many successive displacements, each of moderate extent, and the upper part of each scarp has been greatly eroded.



FIGS. 211–212. Evolution of a fault scarp with continued erosion.

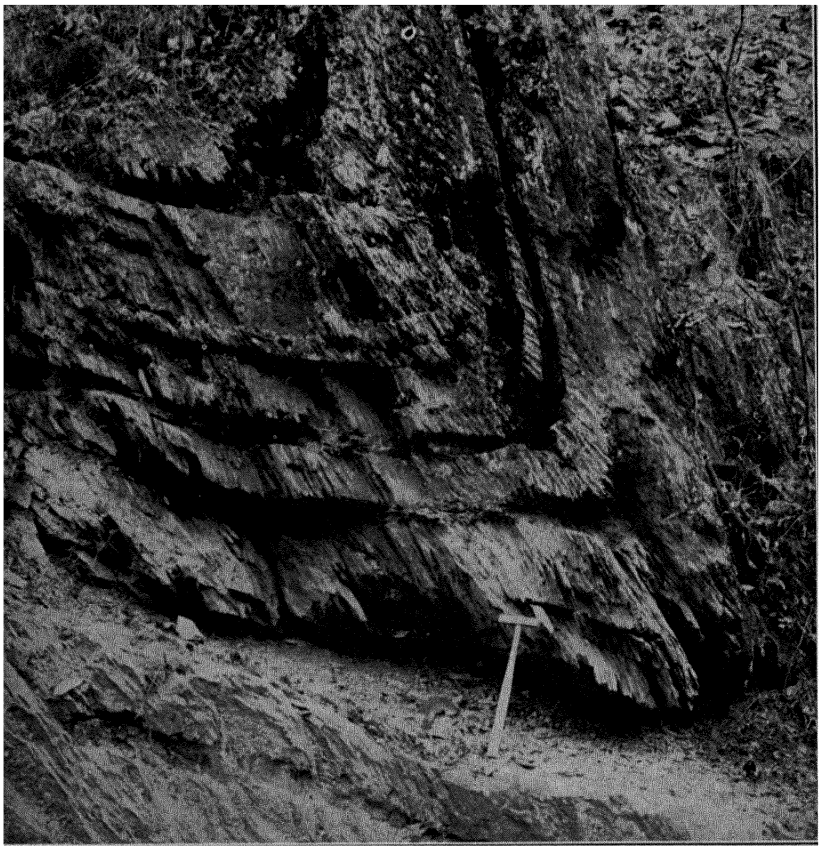
FIG. 211. Scarp made directly by faulting. Only a little of the topmost stratum has been eroded from the uplifted block, but streams are cutting deep valleys into the high mass, spreading the debris on the downthrown block.

FIG. 212. The same fault shown in Fig. 211 at a later stage in the cycle. *A* and *B*, points at the top and the base of the scarp at this stage, were beneath the surface when the initial scarp existed (Fig. 211). Thus the initial scarp has been entirely destroyed, and the ragged scarp at this later stage exists only because the sandstone layer at *A* continues to resist erosion.

METAMORPHISM

Changes in Folded Stratified Rocks. Slate used for roofing and for blackboards is quarried in many parts of the Appalachian region, and in other mountain belts that have been eroded deeply enough to expose at the present surface rocks that once were thousands of feet underground. Examination of slate in its natural occurrence reveals a

type of structure different from any of those described on earlier pages. Typically the rock is in distinct layers, which are folded into ordinary anticlines and synclines; but cutting across the beds, in a direction parallel with the axial planes of the folds, are the *cleavage*



Arthur Keith, U. S. Geol. Survey.

FIG. 213. Slaty cleavage cutting across the beds of an overturned syncline. Cleavage parallels the axial plane of the fold, dipping 60° from left to right. Walland, Tennessee.

planes of the slate (Figs. 213, 214). These planes are closely spaced, and so remarkably parallel that they permit splitting of the slate into uniform smooth plates of any desired thinness.

Ordinary slate, therefore, is distinguished from folded sedimentary strata only in having the additional feature known as slaty cleavage, which generally cuts across the bedding planes at a considerable angle.

Since the cleavage planes are closely parallel to the axial planes of folds, it is a logical inference that the cleavage was in some way acquired at the time of deformation by folding, and hence was not an original feature of the rock. This inference becomes conviction after thorough study of a slate belt. Traced in the direction of decreasing intensity of folding, the slaty cleavage grows less distinct; and where it disappears, the beds are recognized as shale, in many places containing marine fossils. The slate, therefore, came into existence with development of cleavage in connection with intense folding of the shale. The cause of the cleavage is revealed by the microscope: it is the result of innumerable closely spaced minute flakes of micaceous minerals, mainly white mica and chlorite. These mineral flakes have an excellent cleavage parallel to their flat directions (p. 22); and since the flakes are closely parallel, the cleavage of the slate is merely a summation of the cleavage capacity of the tiny mineral particles of which the rock is composed.

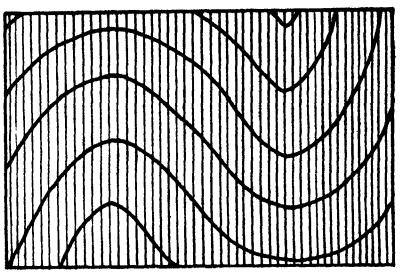


FIG. 214. Slaty cleavage (represented by vertical lines) cutting across folded beds.

Some of the fossils contained in the original shale were squeezed and deformed in the slate, with distinct flattening in the direction of cleavage. It is inferred, therefore, that the mineral flakes grew in their present positions in response to the intense pressure that folded the shale beds. This inference is strengthened by other evidence found in mountain belts. In many places slate grades, by insensible changes, into a more lustrous cleavable rock, phyllite, which differs only in larger average size of the microscopic flakes; and the phyllite in turn grades into mica schist, in which the parallel mica plates are visible to the unaided eye. If a piece of the brilliantly spangled mica schist is placed beside dull, lusterless shale, it is difficult to believe that the two rocks are closely related. However, confronted in the field with the complete gradational series, shale — slate — phyllite—mica schist, the geologist can not escape the conviction that the schist was originally shale, and that the present coarse-grained texture resulted from slow growth of the individual micaceous mineral grains under the control of intense pressure. Such radical change in the nature of rocks is *metamorphism*. Slate, representing the stage of least change in the series described above, is a metamorphic rock of *low rank;* mica schist,

the product of more extreme change, is a metamorphic rock of *high rank*.

The evidence cited above indicates that strong pressure in the crust is a large factor in changing shale into slate, phyllite, and mica schist. It is not known, however, how important temperature may be as a second factor in the process. We know from observations in deep mines and wells that temperature increases with depth below the surface. Some heat must be developed also by friction during the folding of strata by powerful pressures. Perhaps, therefore, the original shale was metamorphosed so extremely as to become coarse mica schist only where it was most deeply buried, or where high temperatures developed because of exceptionally rapid folding. Disregarding this unknown element, we have good evidence that folding pressures played a large part in the type of metamorphism described above, which therefore is termed *dynamic* or *kinetic* metamorphism, to emphasize the evidence of internal *movement* in the rocks while the changes were in progress.

A few minor points should be mentioned here, to avoid possible misunderstandings: (1) Some slaty rocks have been developed by metamorphism of fine-grained rocks other than shales — volcanic tuff, for example. However, shale is the rock most commonly transformed into slate. (2) Mica is one of the common minerals in granites and other coarse-grained rocks formed by cooling and crystallization of igneous magma. Mica formed by metamorphism of shale, though indistinguishable in appearance from mica of igneous origin, was developed by slow crystallization in the solid state, without ever having been heated to the melting point. (3) Shale contains all the chemical elements necessary to form white mica. Therefore the mica schist and the original shale, in spite of their sharply contrasting appearance, represent exactly the same rock material arranged in different forms. (4) Some rocks that have been closely folded show no metamorphic effects.

Contact Metamorphism. The rocks that border an intrusive igneous mass — dike, sill, volcanic neck, laccolith, or batholith — generally show conspicuous change from the normal condition of the same rocks at some distance from the mass. They have been metamorphosed as a result not of pressure but chiefly of the high temperature to which they were subjected by the magma and the hot gases that were given off from the magma as it solidified. Changes are most pronounced at the contact with the igneous mass, and fade away outward from the contact; hence metamorphism of this kind is called *contact* metamorphism. One of the most impressive illustrations is a coal bed that has been converted into a layer of coke by a sill injected parallel with the coal bed just above or below it.

Contact metamorphism commonly shows the effect of only one factor — temperature — uncomplicated by other effects. Moreover, the transition from highly metamorphosed rock near the contact to the original unaltered rock at some distance from the contact can usually be traced. In this way we learn which new minerals form at high temperatures and which at more moderate temperatures, and thus we can work out a comparative scale for measuring the intensity of metamorphism.

Extent of the Metamorphic Zone. The thickness of a contact-metamorphic zone depends on the size of the igneous mass, the sus-

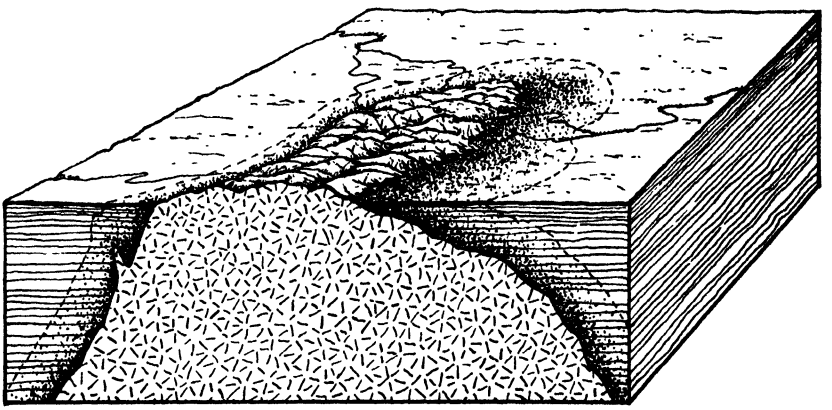


FIG. 215. Stock of granite, intrusive into horizontal strata and partly uncovered by erosion. The width of the contact-metamorphic zone (stippled) as measured on the Earth's surface is seen to depend on the dip of the contact surface; the zone is widest at the right, where the dip of the contact surface is gentlest. Scale is roughly 3 miles to the inch.

ceptibility to change of the surrounding rocks, and other conditions. The most extensive zones surround large, deep-seated masses such as batholiths; distinct effects extend as much as a mile from some intrusive bodies. Adjacent to small dikes and sills, the thickness of the zone is measured in inches or feet. The attitude of the surrounding beds — whether they dip toward or away from the intrusive body — affects the distance to which metamorphism extends, because heat is transmitted more readily along the bedding planes than through the beds themselves. Even if the contact zone is of uniform thickness, its actual width on the land surface will vary with the form of the igneous mass. Thus in Fig. 215, which represents a large igneous body intrusive into a series of horizontal strata, the contact zone as exposed at the surface is narrowest where the contact plunges steeply downward, and widest where the contact is least inclined.

Variations in Contact-Metamorphic Effects. The nature of the rocks invaded by the igneous body is of first importance in determining the metamorphic effects. Ordinary sandstones are not changed in composition, but near the contact are converted into quartzites through cementation of the grains with silica. Shales are baked into a hard, flinty rock that resembles basalt. Pure limestones are transformed into sparkling snow-white marble, visibly crystalline to the unaided eye. Limestones containing clay or sand as impurities are also turned into marble; but high temperature causes chemical reactions between the impurities and the calcite, with the result that the marble produced in the contact zone becomes studded with conspicuous new minerals, such as garnet, pyroxene, and amphibole.

Normally the total chemical composition of the rocks does not change as a result of contact metamorphism; under the stimulus of high temperature, some minerals already present grow to larger size (as in the change of limestone to marble), and new minerals form by recombinations of certain chemical elements. Thus the normal process is merely a "redistribution of wealth" originally present in the contact zone, with no addition of new wealth. However, there are notable exceptions to this general rule. Some igneous masses give off gases that carry iron, copper, silicon, boron, and other elements from the magma into the surrounding rocks. Limestones in particular react with these newly introduced substances, and many beautifully crystallized minerals result. Locally this process has formed valuable ores of metals, such as iron, tungsten, and copper.

Foliated Metamorphic Rocks. Rocks of contact-metamorphic origin are as a rule easily recognized by their relation to igneous bodies, and also by certain distinctive minerals contained in them. There is an immensely larger group of metamorphic rocks that have been formed by other processes; probably they have resulted chiefly from high pressures (as explained on p. 263), aided by high temperatures deep in the crust. The most distinctive feature of these rocks is that they are *foliated* — that is, they have a banded or platy structure, along which they tend to split into slabs or flakes. Slates, phyllites, and schists have close-spaced foliation or cleavage which is well developed. Gneisses generally have coarser grain than these types of rock, and their foliation is poorly defined (p. 40).

Gneisses occur in vast quantities and numerous varieties. Some were formed from granites and other coarse-grained igneous rocks; some from conglomerate and arkose; others by injection of igneous material in thin bands along the foliation of pre-existing mica schist. Many gneissic rocks bear evidence that they "flowed" as plastic ma-

terial, though they are now strong and brittle. For example, in some gneisses formed from conglomerates the pebbles were squeezed into thin lenses, many times their original length and only a fraction of an inch thick. Deformation of this nature could have occurred only under enormous confining pressure, when the rock was at great depth in the crust. Similar flow of solids has been brought about in laboratory experiments. Ice, which is as brittle as glass under ordinary conditions, can be placed in a steel jacket fitted with a piston, and made to flow through a hole in the jacket by exerting strong pressure on the piston. Similarly a cylinder of limestone placed in a specially constructed hydraulic press, and subjected to pressure that is great on all sides but strongest at the ends, slowly changes its form by growing shorter and thicker (Fig. 216). Testing and microscopic examination of the deformed cylinder reveal no loss of strength and no fracturing; under the unbalanced pressure the rock has flowed, just as a weak substance such as beeswax can be molded with the hand. There is no difficulty, therefore, in accepting the concept of rock-flowage on a large scale at depths of many miles where pressures are enormous.

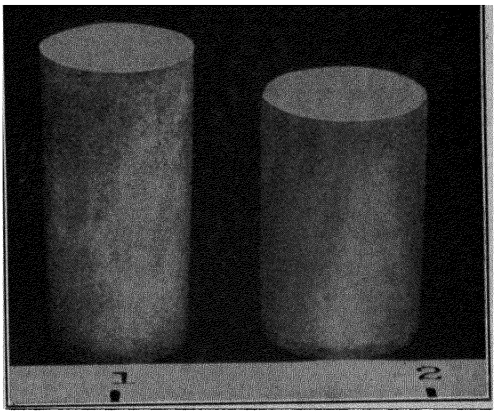
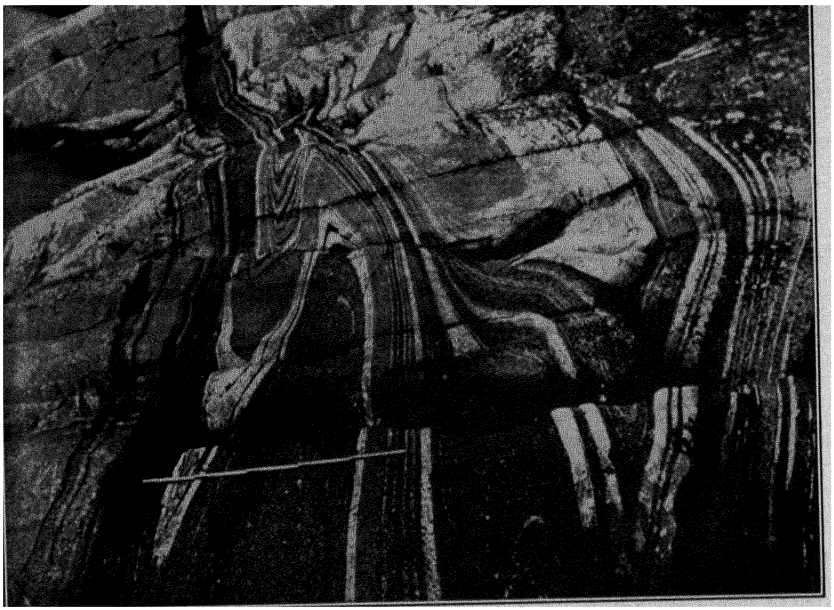


FIG. 216. Result of a laboratory test by D. T. Griggs. The longer cylinder, made of limestone, was placed in a specially constructed press, and pressure up to 185,000 pounds per square inch was applied to the ends of the cylinders, while liquid around the sides of the test piece maintained a uniform confining pressure of 150,000 pounds per square inch. The cylinder was shortened and thickened by plastic flow without fracturing. Scale has one-inch divisions.

Distribution and Significance of Foliated Rocks. Gneisses and schists are widely distributed over the Earth. They are exposed in vast areas of eastern and northern Canada, along with numerous large batholiths of granite intrusive into the metamorphic rocks, many of which were originally conglomerates, sandstones, shales, and limestones (Fig. 217). Since the granites as well as the older gneisses, schists, and marbles testify to an origin deep underground, it is a clear inference that a thick cover of rock has been removed, by long-continued erosion, from all of eastern Canada. For the most part, the metamorphic rocks of that region bear the marks of kinetic metamor-

phism, related to intense folding in ancient mountain belts. However, there are also important zones of contact metamorphism bordering the granitic masses.

Foliated metamorphic rocks are exposed also in long belts in the Appalachian, Rocky, and other mountain chains, where there is clear evidence that a thick cover of younger rocks has been removed by vig-



J. P. Holmquist.

FIG. 217. Folded gneisses and interbedded layers of marble (white). Near Stockholm, Sweden.

orous erosion. In large part the foliated rocks in these mountain belts are geologically old, and their metamorphism took place long before the present mountains were formed. However, in every great mountain belt some of the slates, schists, and other foliated rocks now exposed were actually formed during the mountain-making movement, along with the folding and faulting of the younger rocks nearer the surface.

UNCONFORMITY, A RECORD OF ANCIENT CRUSTAL MOVEMENTS

Sedimentary deposits, especially those laid down on sea floors and later elevated above sealevel, give a faithful record of the history of their times. In general the persistence of nearly uniform conditions,

without any disturbance by crustal movements, results in continuous deposition of parallel strata with similar composition or with gradual change from one type of material to another, as from sandstone to shale. The strata in such a series are said to be *conformable* with each other. But if crustal movement causes uplift and erosion of sedimentary beds, any later series of strata deposited above them is *unconformable* with them (Fig. 218). The *unconformity* of one group of rocks with another is evidence of a definite succession of events and therefore is a significant part of the geologic record.

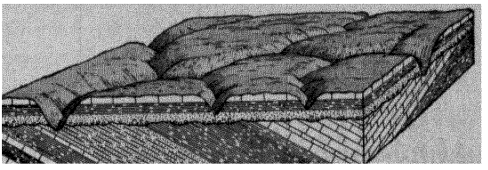


FIG. 218. Angular unconformity between two series of marine strata. The lower series was deposited as a conformable sequence, then tilted and eroded; later submergence allowed deposition of the upper series, after which the area was lifted above sealevel and the present drainage system was developed. The area represented covers several square miles.

The most conspicuous unconformities result when old eroded mountain regions, with their truncated folds and steeply tilted sections of sedimentary strata, are buried beneath later sediments. At practically every point the edges of the older beds form a considerable angle with layers in the later series, and therefore the term *angular unconformity* is appropriate (Fig. 218). Two or more angular unconformities in the same section indicate repeated severe crustal disturbances, each followed by long-continued erosion and a later period of quiet when sediments accumulated.

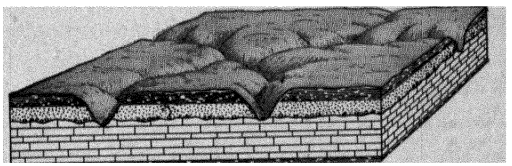


FIG. 219. Disconformity between two series of formations. No tilting has occurred; but the lower series was uplifted uniformly and eroded before deposition of the upper strata. Compare Fig. 218.

On the other hand, suppose a wide shallow-sea basin is warped up almost uniformly to make a land surface. Erosion sets in, and a considerable thickness of the marine strata is stripped away over the entire area. If the sea again invades the district, new strata are deposited above the old erosion surface, and a later upwarping, with consequent cutting of stream valleys, brings to view the older as well as the younger rocks (Fig. 219). As the older strata were not appreciably tilted by the warping, they are essentially parallel with the younger series of beds above them; but the two series are separated by the buried erosion surface. The unconformity between the two groups of strata is important, because it represents a crustal movement of wide extent

and a long time interval during which no sedimentary record was being formed in the region, while part of the earlier record was being destroyed. However, an unconformity of this type is not so conspicuous as an angular unconformity, which attracts attention at once by the divergence of beds above and below. In view of this striking difference, the special name *disconformity* is applied to an unconformity that is not characterized by any angular divergence between the two groups of strata.

A distinguishing characteristic of disconformities is the parallelism of the younger and older strata; but it is not essential that the beds shall be horizontal or undeformed. Commonly there has been disturbance, either slight or severe, at some time after the younger formation was deposited. Since both groups of beds are deformed together they remain parallel (Fig. 220).

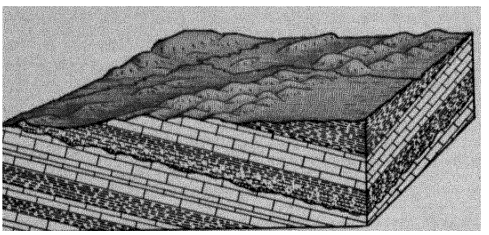


FIG. 220. Disconformity between two series of strata, both series tilted together. A large part of the upper series was destroyed by stream erosion in developing the present surface after the tilting occurred. Compare Fig. 219.

Although the conception of unconformity is inseparable from sedimentary processes, the old surface on which strata are unconformably laid may be developed on rocks of any kind. Granite and other massive rocks, as well as metamorphic rocks of all kinds, have been bared by erosion in wide areas and later covered with sediments. The contact is a surface of unconformity if the sediments were deposited on it. If the contact between rock masses of unlike character is due to faulting or to igneous intrusion, however, the term unconformity does not apply.

Since every unconformity involves some degree of erosion before deposition of the younger sedimentary series, the surface at the base of this series is more or less irregular. If the old land surface on which deposition began was hilly, the buried hills and valleys can be recognized, provided the unconformity is well exposed. Generally the old lands were worn down to low relief before any permanent deposits were formed. If the unconformity represents invasion of the land by the sea, it is probable that submergence occurred very slowly and wave action near the migrating shoreline had opportunity to plane down the most prominent irregularities.

Usually the sediments deposited on a surface of unconformity are distinctly different in character from any sedimentary formations be-

neath. Whenever the sea invades the land every part of the submerged area is passed over by the migrating shore zone, with its characteristic deposits of pebbles and coarse sand. As a common result a *basal conglomerate*, composed in part of the beach materials, lies directly above the old land surface.

Whether the first sediments in the younger series were deposited by the sea or by streams, as a rule some pebbles in the lowest layer had their source in the rocks on which the deposits rest. The presence in a conglomerate of pebbles obviously derived from granite beneath proves clearly that the granite is older than the overlying strata and therefore that it was not intruded into them.

Larger Significance of Unconformities. A study of unconformities emphasizes the close relationship between crustal movements, erosion, and sedimentation. The lands are being worn down and sediments are accumulating continuously. But slowly the scenes shift. Folding or faulting in a geosynclinal basin, or upwarping at the edge of a continent, brings to light the strata built up during former ages. At once the forces of erosion attack the strata of shale, sandstone, and limestone, and in the act of destroying them reveal the record they contain. Streams cut deep valleys in which are exposed angular unconformities that testify to severe folding in remote geologic periods, or widespread disconformities that indicate ancient upwarping of large areas. As erosion bares these secrets the streams carry away the new waste and deposit it, perhaps on a land surface recently submerged. Thus construction in one place supplements destruction in another; the whole complex record shows the constant struggle between deep-seated forces that produce the major relief features, and processes at the surface that strive to keep the lands featureless and low.

Economic Aspects of Geologic Structure

Correct solution of problems encountered in folded and fractured rocks is of the utmost importance to mining geologists and others concerned with the recovery of mineral products. In most oil fields the occurrence of petroleum and natural gas has a definite relation to flexures in sedimentary beds, as explained in a later chapter (p. 323). Many of our coal deposits, particularly the valuable anthracite and other high-grade coals of the Appalachian region, are in belts of complicated folding and faulting. In Fig. 200, the folded black layer *BB* may be taken to represent an important coal bed in one of the Pennsylvania fields. From hasty examination, guided only by the surface exposures, it may appear that there are six or more separate beds of

coal, each extending downward indefinitely. A skilled geologist, however, will recognize the evidence of folding, and will be able to estimate the quantity of available coal. In the famous Homestake gold mine of the Black Hills, South Dakota, the formation containing the ore is complexly folded, and precise determination of the structure is necessary for the most efficient and profitable mining as well as for any dependable estimate of the quantity of ore still in the ground.

Joints and other fractures are a matter of great importance in all quarrying, tunneling, and mining operations where large-scale rock work is necessary, since the intersecting fractures greatly facilitate the task of excavation. Without them, every rock fragment would have to be broken or blasted loose from bedrock. The fractures may of course be a serious inconvenience in some situations, if exceptionally large blocks of quarried stone free from defects are desired. Mining geologists have particular interest in fractures because joints and faults have commonly been the channels along which ore solutions have found their way and deposited valuable metallic minerals (p. 332). The famous copper-bearing veins at Butte, Montana, were formed in successive stages along sets of great faults that intersect and offset each other to form a baffling complex of blocks. Efficient mining of these broken veins requires intensive study of the faults, to determine the order of their formation, directions and amounts of displacement, and other facts necessary for guiding the miners in their expensive tunneling operations. The " losing " of a vein where it has been offset and thus hidden by faulting is one of the commonest difficulties encountered in mining.

The occurrence and recovery of subsurface water, one of our greatest and most vital natural resources, are controlled to an important degree by geologic structure. The Dakota and similar artesian systems (p. 108) depend on the warping of water-bearing strata in such a way as to furnish hydrostatic pressure. Knowledge of the structure is necessary for proper location of any deep wells. Faults cutting across some artesian systems have brought impermeable rocks across the faulted edges of important aquifers, thus diverting the flow of water to form artesian springs (Fig. 221; p. 107). Joints and other fractures provide the only water-containing capacity in great masses of igneous and metamorphic rocks (p. 108), and a full understanding of this principle is required for intelligent planning of water supply in the vast areas in which such rocks are exposed. Too frequently wells are drilled with the thought that an abundant supply, perhaps even an artesian flow, can be obtained by deep drilling, regardless of the kind and structure of bedrock.

Most economic problems involving the structure of metamorphic rocks are difficult, but many of them can be solved if the principles of metamorphism are understood. Some schists and other foliated rocks formed by metamorphism of sedimentary strata retain at least traces of the original bedding, which betray the forms of folds or the positions of important faults. Such features are of large assistance in mining the gold ores in the complex metamorphic rocks of Canada. Knowl-

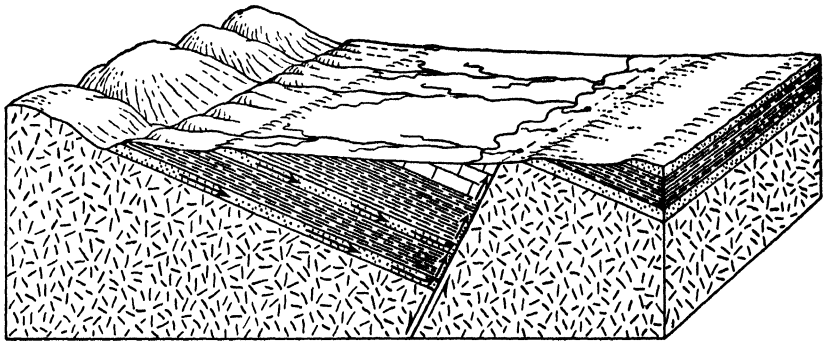


FIG. 221. A line of springs along a fault. The diagram represents an area about 20 miles long. After the strata were faulted and tilted, erosion reduced the upthrown block (at right of fault), and the present drainage became established. Artesian conditions (p. 106) exist in two sandstone formations; water rises from these aquifers along the fault (see full arrows), issuing as springs at the most favorable points. Since the granite at the right of the fault is almost impermeable, nearly all the water in the two aquifers is diverted to the Earth's surface. Springs of this type are called fault-dam springs. (Direction of fault movement indicated by half-arrows.)

edge of the principles that control the development of slaty cleavage is often used as the key to reveal the major folds and faults of metamorphosed bedrock.

Many widespread unconformities have large economic importance. Deposits at the base of a marine sedimentary series often represent near-shore conditions while the sea was advancing across a subsiding land. Students of petroleum are convinced that such near-shore marine deposits formed in past ages have contained exceptionally large quantities of the substances from which oil and gas were generated. Moreover, a younger series of beds may have sealed off and prevented the escape of petroleum generated in an older folded and eroded series (p. 325), and therefore an unconformable contact may be a critical zone to be located in the search for oil. In Oklahoma and other oil-producing regions, recent deep drilling has tapped large oil and gas reservoirs not suspected during earlier drilling confined to younger series of rocks above unconformities.

Summary

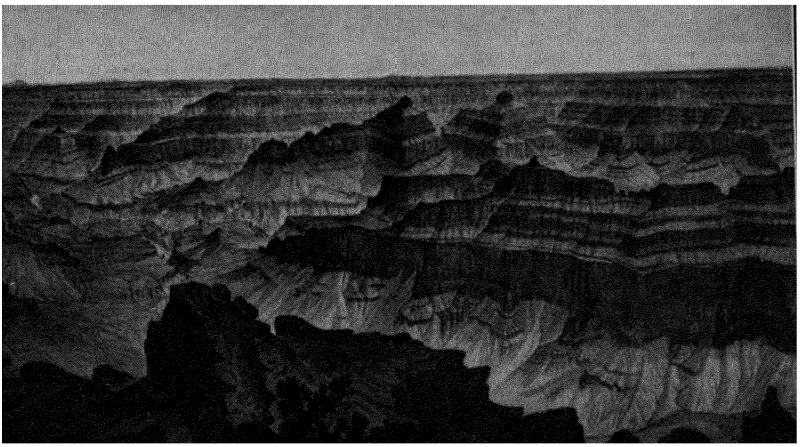
Movements of the Earth's crust, some slow and affecting large areas, others abrupt and localized, have occurred within historic time. Numerous ancient movements have left their records in deformation of the bedrock. Strata that originally were nearly horizontal are now warped into the form of broad domes and basins; other strata are strongly folded into anticlines and synclines. Rocks of all kinds have been fractured, and on many of the breaks, known as faults, there have been displacements of rock masses, both vertically and horizontally. Many fault movements have been small and unimportant; others, amounting to thousands of feet, or even many miles, have played a large part in the uplift of mountains.

Ordinary folding and fracturing of rocks occur in a comparatively thin outer zone of the Earth's crust. At greater depths the rocks have been mashed and made to flow under high confining pressure. As a result the rocks in the deeper zones have become foliated and so changed from their original characters that they are called metamorphic rocks. Metamorphism of a special kind has occurred under high temperatures in rocks at or near the borders of intrusive igneous masses. Metamorphic rocks now exposed widely at the Earth's surface bear witness to deep and extensive erosion.

Important geologic events are recorded in the unconformable relation of a series of sedimentary strata to the rocks beneath them. Broad warping is indicated if sedimentary beds are nearly parallel in the older and younger rock series. Pronounced angular discordance between two series records strong deformation of the older rocks and a long erosion interval before deposition of the younger series. Unconformities emphasize the close relation between crustal movements, erosion of lands, and deposition of sediments.

An understanding of folds, fractures, unconformities, and other structural features of the bedrock is essential in mining operations and in drilling for oil, gas, and water.

The Appalachians, an excellent example of such "second-generation" mountains, are explained in some detail in a later part of the chapter (pp. 305–311; Figs. 246–249).



Drawn by W. H. Holmes.

FIG. 238. Part of the Grand Canyon seen from Point Sublime, showing dissection by erosion of the plateau mass into ridges and pyramid-shaped buttes of mountainous size.

ROLE OF CRUSTAL MOVEMENTS

All highlands, except those built up directly by volcanism, owe their high altitudes to crustal movements. All have been changed in form — some only slightly, others drastically — by erosion since uplift occurred. However, crustal movement was the fundamental process in creating the highlands, whereas erosion played the part of a sculptor's tool in fashioning details of form.

Many types of movement have taken part in the changes of level responsible for mountains and plateaus. Probably the commonest type has been widespread upwarping, which involves gentle bending of the crust over a wide area, with little deformation of bedrock. Usually, however, warping on a large scale is accompanied by local fracturing, with displacements on steep faults amounting to hundreds or even thousands of feet. In some regions, movement of great crustal blocks along numerous faults has been much more important than bending. The great mountain belts are characterized by severe folding of strata and development of great thrust faults, in addition to simpler deformation by warping and normal faulting.

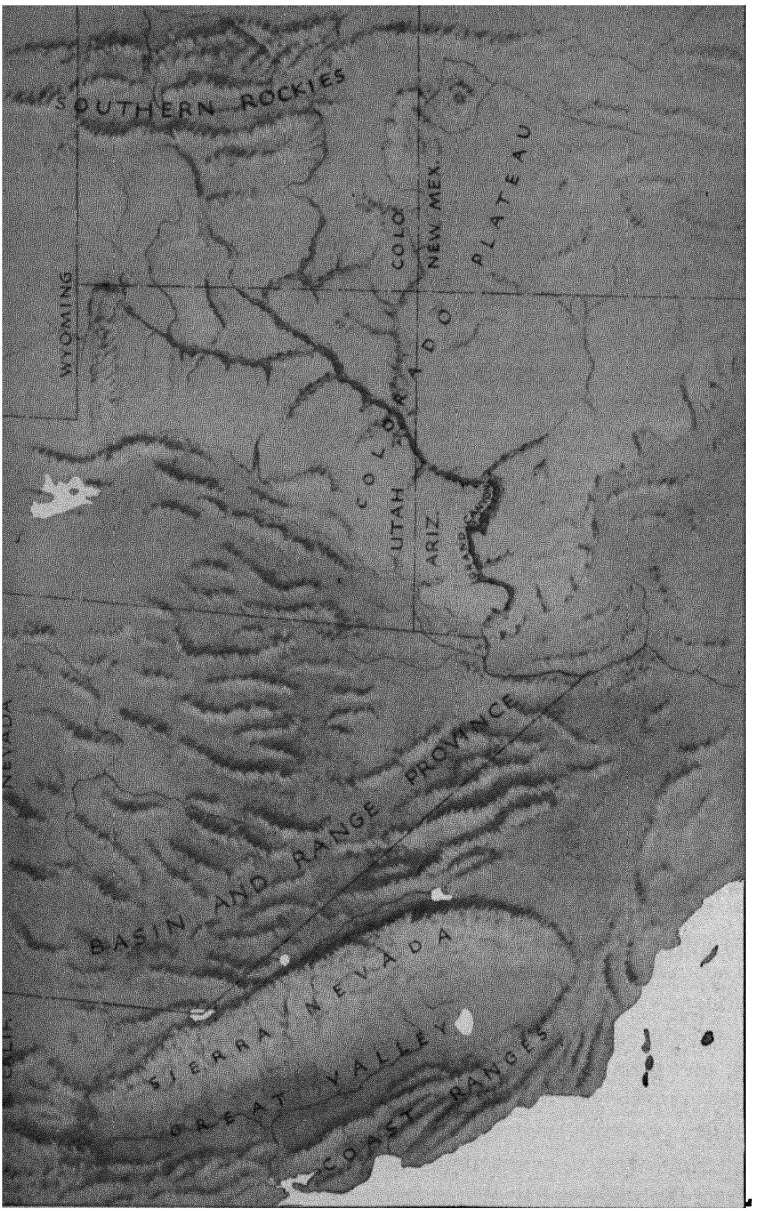


FIG. 239. Mountains and plateaus of southwestern United States. The principal units at this latitude are, from east to west, the Southern Rocky Mountains, the Colorado Plateau, the Basin-and-Range province, the Sierra Nevada, and the Coast Ranges. Numerous details omitted, to avoid obscuring of major units.

The several kinds of crustal deformation are illustrated by major highland units discussed below. Even the simplest of these units have had complex histories, involving more than one kind of crustal movement.

WARPING AND FAULTING

The Colorado Plateau. A vast area in Utah, Arizona, New Mexico, and southwestern Colorado is characterized by high average elevation, on bedrock composed chiefly of sedimentary strata that are almost horizontal except for some bending and fracturing at widely separated localities. This great unit, which is cut across diagonally by the Colorado River, is the Colorado Plateau province (Fig. 239). It is sometimes described as a *tabular* mass, because it resembles an immense table or plate that has been lifted almost uniformly. Many large expanses of the plateau, almost free from marks of erosion, are strikingly flat; these even surfaces correspond to the nearly flat attitude of the sedimentary strata beneath them (Fig. 240).

Except in the deep canyons cut by streams, altitudes in the plateau range from 5000 to about 11,000 feet. Since the stratified rocks in the area originated for the most part as deposits on the sea floor, it is clear that the plateau resulted from uplift amounting to several thousands of feet. Considerable warping attended the uplift, in spite of the general appearance of uniformity. Strata which near the Grand Canyon are at the plateau surface (Fig. 238) as much as 8000 feet above sealevel dip gently but persistently northward beneath younger beds; and 100 miles north of the canyon these same strata are below sealevel, thousands of feet under the plateau surface. The structure is varied also by several abrupt monoclinal bends (Fig. 201, p. 252), and by a number of large normal faults. The Hurricane fault in southern Utah and northern Arizona is more than 100 miles long; its position is marked by a steep west-facing scarp. Another great fault marks the precipitous western border of the plateau (Fig. 239). It is not surprising that a tabular mass so extensive — 130,000 square miles in total surface area — should have been broken and flexed to some extent while it was being forced upward.

Uplift of the Colorado Plateau was a recent geologic event; the few large valleys cut into the mass are youthful in form (Fig. 240), and the wide intervening areas are nearly untouched by stream erosion (p. 90). Excavation of the Grand Canyon may not have required more than a million years — a short life for a great stream valley. By analogy with other plateau regions farther advanced in the fluvial cycle, we can foresee that the tributaries of the Colorado will continue to cut



SPENCE AIR PHOTOS.

Fig. 240. Looking east across the Painted Desert, Arizona. This part of the Colorado Plateau has vast areas that are nearly level, between a few youthful and deeply incised valleys. In the foreground the valley of the Little Colorado River is about 3000 feet deep.

their way headward until they destroy the identity of the plateau surface. After a long time has elapsed, there will remain only an intricate maze of mountainous buttes and spurs, like those now within the canyon walls (Fig. 238).

Fault-Block Mountains. Directly west of the Colorado Plateau is a wide region in Utah, Arizona, Nevada, and California, covering one-tenth the area of the United States, in which long, narrow mountain ranges alternate with basins at much lower altitudes. This region is appropriately known as the Basin-and-Range province (Fig. 239). It has had a complicated history, and no simple generalized statement of structure applies accurately to all the ranges; but in large part the ranges are bounded by steep faults, between which the ranges have

been elevated with relation to the adjacent basins (Figs. 241, 242). It is not known, however, whether the ranges actually moved upward after the faults were formed. Conceivably a large part of the region

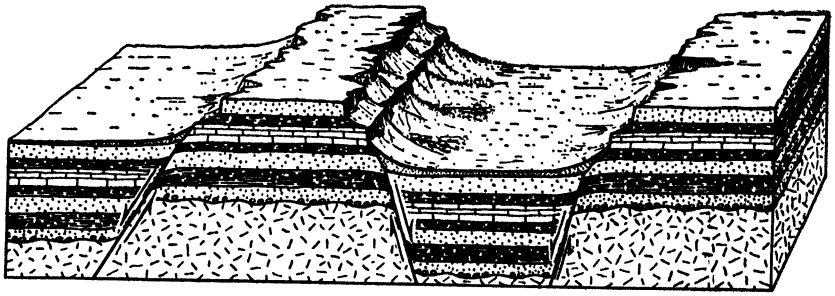
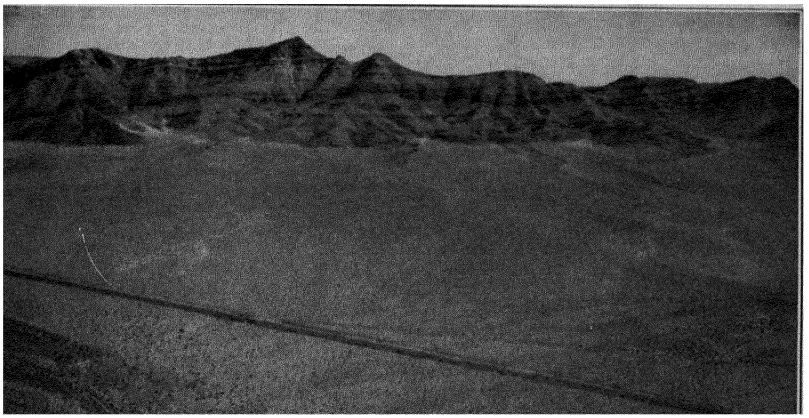


FIG. 241. Mountain ranges formed by large-scale normal faulting. Uplifted blocks form the ranges, depressed blocks the basins. The bedrock consists of nearly horizontal sedimentary strata unconformable on granite.

was once continuous with the high Colorado Plateau and, after the great faults came into existence, blocks sank to form the present basins, leaving the intervening blocks as ranges. However, structure as simple



Spence Air Photos.

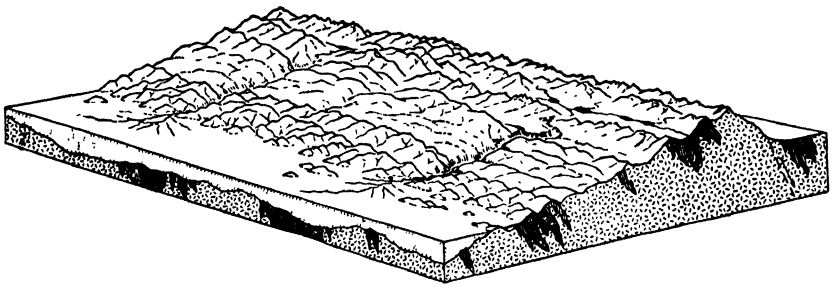
FIG. 242. Front of a fault-block mountain range, south of Goodsprings, Nevada. The Union Pacific Railroad tracks (shown in foreground) are near the base of a slope built up of debris eroded from the range. A large fault is concealed near the top of this slope. The highest peak is about 3000 feet above the foreground.

as that represented in Fig. 241 is exceptional. Most of the ranges in the Basin-and-Range province have been tilted, one edge being elevated and the opposite edge depressed. Whatever the exact nature of the

faulting movements, ranges bounded by faults are termed *fault-block mountains.*

All fault-block mountains have been more or less modified by erosion. Debris worn from the high masses finally buries those that are lower (Figs. 241, 242). In time the combination of erosion and deposition nearly or entirely obliterates the mountain relief, especially in a region of interior drainage (p. 95). This tendency is defeated so long as the fault scarps are renewed by recurrent movements (Fig. 210, p. 260).

The Sierra Nevada of California is a tilted block 400 miles long and about 60 miles wide (Figs. 239, 243). Its eastern edge has been up-



F. E. Matthes.

FIG. 243. Part of the Sierra Nevada, California, looking northeast, showing the general form and structure. The steep east front is an eroded fault scarp; the gentle western slope follows the tilt of the uplifted block. Remnants of folded rocks (dark) engulfed in granite record ancient crustal movements and enormous igneous intrusions, after which long-continued erosion formed a peneplane. In late geologic time the present range was formed by tilting uplift along the great fault. Glaciation shaped the rugged peaks at the summit and enlarged the valleys on the western slope.
Vertical scale considerably exaggerated.

lifted 2 miles or more, to form an abrupt scarp facing eastward. Roads from the east ascend this precipitous front with difficulty; but west of the crest they descend on a long, gentle slope — the tilted upper surface of the block. In the Great Valley of California, sediments thousands of feet deep, eroded from the high part of the block, have accumulated on the depressed part of the tilted mass.

DOMING

Some large uplifts have the form of domes, with ground plans either almost circular or elliptical. Bending of the rocks to bring about these uplifts is too strong and systematic to be classed as warping.

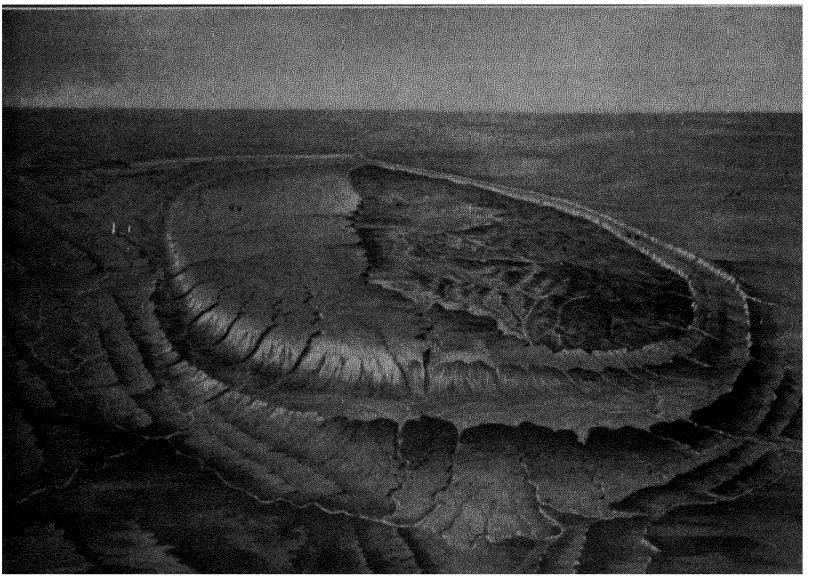
The simplest and best understood uplifts of this kind are laccolithic domes, made by the bowing up of strata above thick, lens-shaped in-

trusions of liquid rock (p. 239). Ordinarily a dome of this kind that is high enough to be called a mountain has lost more or less of its original cover through erosion; and commonly the resistant igneous mass, almost completely denuded, stands within circular or elliptical ridges formed by the upturned edges of the more resistant strata (Fig. 188, p. 240). There are several excellent examples east of the Rocky Mountain front in Montana and Wyoming, and others in the Henry Mountains of Utah, where domes of this type were first recognized and described.

The Black Hills. Dome-shaped uplifts much larger than any known laccoliths are illustrated by the Black Hills of South Dakota. In a casual journey through this mountain group the traveler may gain an impression of disordered arrangement; but a good map or a relief diagram of the entire unit reveals a remarkable symmetry of structure, involving an elliptical area about 100 miles long and 50 miles wide (Fig. 244). A thick section of sedimentary strata, chiefly of marine origin, has been uplifted by bending into the form of a great dome (Fig. 245). The higher strata have been entirely eroded from the top of the structure, and their eroded edges now form a frame around the central mass. This frame is made more distinct by the fact that weak formations of shale have been reduced to valleys between prominent hogbacks and cuestas formed of resistant sandstone strata. The innermost valley, which is particularly well developed, is known as "The Race Track."

In a large area at the top of the dome, all the sedimentary rocks have been removed, and stream erosion has cut into underlying schists, gneisses, and granites, which are much older than any of the strata in the former cover. These ancient rocks have been carved into ridges and peaks, including Harney Peak (7242 feet above sealevel), the highest point east of the Rockies. A lower peak of similar granite is Mount Rushmore, on which the likenesses of four American statesmen have been sculptured. As shown in Fig. 245, these old igneous and metamorphic rocks lie beneath the entire region but are hidden by the sedimentary cover except at the crest of the dome. At scattered localities on and around the dome there are younger igneous rocks, which intrude even the youngest of the deformed sedimentary beds. Some of the intrusive masses are small laccoliths, which make subsidiary domes that are tiny in comparison with the main uplift.

The principal events in the history of the Black Hills are clearly indicated. Seas covered the region and deposited essentially horizontal beds of sandstone, shale, and limestone, which eventually formed



H. Newton, U. S. Geog. and Geol. Survey.

FIG. 244. Diagram of the Black Hills uplift, South Dakota. View looking north, generally along the axis of the elliptical dome. All sedimentary strata have been stripped from the eastern part of the dome, exposing granite and metamorphic rocks. Edges of resistant strata form hogback ridges encircling the dome.

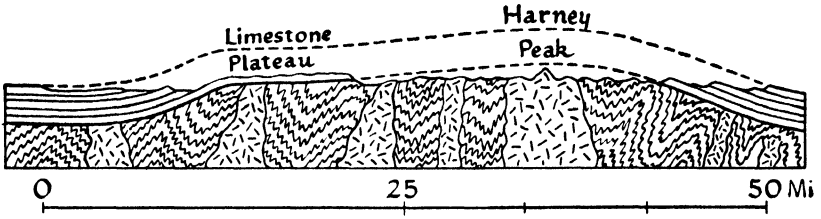


FIG. 245. Cross-section, west to east, showing the structure and major surface forms of the Black Hills. Sedimentary strata that once were continuous across the dome have a total thickness of 5000 feet; broken lines indicate position occupied by these strata before erosion removed them from the crest of the uplift. Older rocks beneath these strata consist of folded and metamorphosed sedimentary formations, cut by bodies of granite.

a thick cover on the ancient " basement " of schist and granite. Strong doming then occurred, accompanied by intrusions of magma which formed laccoliths in the sedimentary strata. Possibly a large deep-seated body of magma played some part in lifting the great dome; but

this is a speculative matter. Since the uplift occurred, erosion has removed sedimentary formations thousands of feet thick, exposing part of the old basement rocks and fashioning details of the present topography.

FOLDING AND THRUST FAULTING

All the great mountain chains of the Earth include strongly folded sedimentary rocks as a conspicuous part of their structure. Thrust faults are commonly associated with the folds, and, in some mountain belts, thrusts on which there have been enormous displacements are the most prominent structural features. Both folds and thrusts indicate shortening by pressure, and therefore the structure of great mountain systems suggests that powerful compressive forces, acting horizontally, have buckled and sheared the crust in the formation of these belts of highlands.

The deformed beds of sandstone, shale, and limestone, now exposed on the flanks and even on some of the highest summits of great mountain ranges, represent deposits in former seas, on deltas, and in swamps bordering the sea. Owing to the strong folding and faulting, these strata, once nearly horizontal, are now steeply inclined or vertical, and erosion has revealed their full thickness (Fig. 249). In some mountain belts these thicknesses are truly astonishing; 4, 5, or even 6 miles are by no means exceptional values, and maximum totals are more than 8 miles. Since these remarkable piles of strata are characteristic of all the great mountain belts, whatever their geologic age, it appears that accumulation of exceptionally thick marine deposits has always been an essential preliminary to large-scale failure of the Earth's crust by folding and thrusting. This seeming paradox — the development of great highlands from areas that had been persistent sea floors for long geologic periods — is well illustrated by the evolution of the Appalachian Mountains. Since this mountain unit is in many ways typical of great mountain systems formed in all continents at widely separated geologic dates, a brief outline of its complete history is more illuminating than an abstract discussion of mountain structure and development.

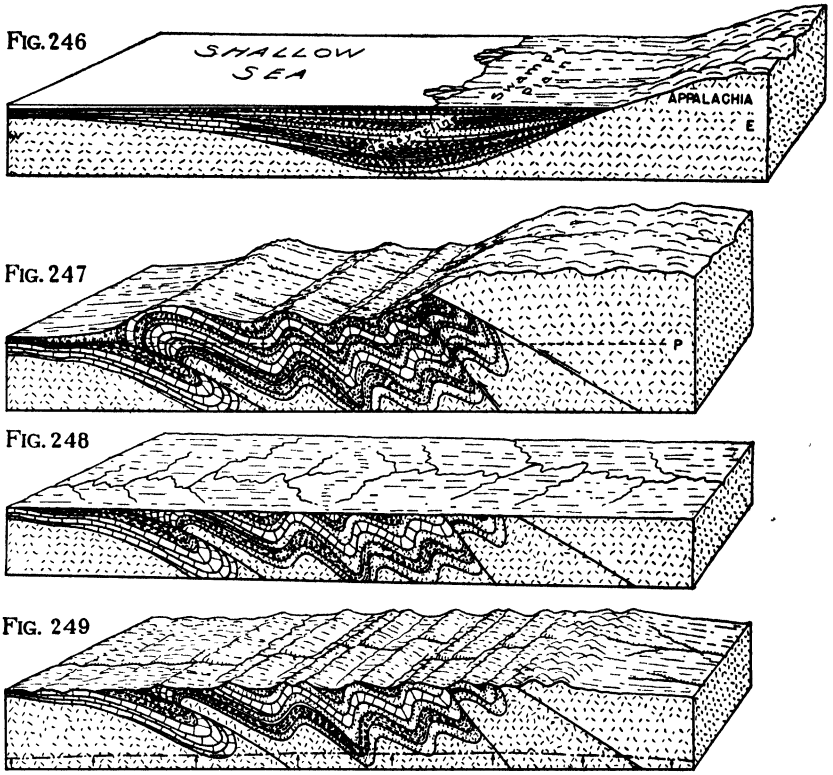
Structure and History of the Appalachians. Figure 249, which represents a sample of the Appalachian region at the present time, shows three chief structural divisions. (1) On the east a belt of highlands, sloping generally toward the Atlantic coast, has bedrock composed of ancient gneiss, schist, and granite. These rocks form a great crustal block that has been thrust westward against and partly over (2), strongly folded and thrust-faulted sedimentary strata that underlie a belt 100 to 150 miles wide. The folded strata have been greatly

eroded, and generally the edges of thick sandstone formations stand up as long mountain ridges, whereas weak shales and limestones have been worn down to form valley floors. By piecing together the thicknesses of the numerous formations, exposed in various parts of the folded belt, we find that the total thickness of strata in this belt is several miles, with a maximum of 38,000 feet. (3) Directly west of the folded belt is a plateau of moderate height, beneath which the strata are weakly folded or only slightly warped. Sedimentary formations in this plateau, corresponding in age to all the formations in the folded belt, total only a few thousand feet in thickness. Throughout the Appalachian region, the stratified rocks have their maximum thicknesses near the middle of the folded belt, and grow conspicuously thinner as they are traced westward. In the Mississippi Valley the average thickness of the flat-lying strata totals no more than 4000 or 5000 feet — about one-eighth the thickness of corresponding formations that are strongly folded in the Appalachians.

The Appalachian Geosyncline. Figure 246 represents an ideal restoration of the rocks in the entire region to their condition shortly before the folding and faulting occurred and while the sea still covered part of the surface. A first interpretation of this restored section might assume that the sea was initially several miles deep in the present area of the folded belt, and that the deep trough was progressively filled with sediments to form the total thickness now exposed. However, careful study of the sedimentary beds reveals that all of them, from the bottom to the top of the seven-mile-thick section, were formed by deposition of sediments either in a shallow sea or on deltas and floodplains actually above sealevel. Throughout the section there are many beds with ripple marks and mud cracks, indicating deposition in very shallow water and occasional exposure of the muds to sunshine and air. Coal beds in parts of the section originated as peat deposits in swamps (p. 125). In beds of undoubted marine origin, fossils are of shellfish and other kinds of animals that now live only in shallow water near the shore. This combination of evidence proves that the sea floor sank slowly, and accumulating sediments kept the trough nearly full, or at times actually crowded the sea water out in large areas, where deltas and marshy ground were built slightly above sealevel. Thus in Fig. 246, the original sea floor, represented by the lowermost sedimentary layer, was near the position of the highest layer shown in the restored section. Subsidence occurred slowly, but sediments were spread out rapidly enough to keep the water shallow. As the sinking and filling continued, probably with variations in speed and with some temporary halts, eventually the oldest layers were bowed downward, whereas the

upper beds at any stage in this part of the history were essentially undeformed.

The Appalachian trough of sedimentation was a typical geosyncline (p. 253). Thick deposits accumulated on the sites of the Rocky Mountains, Andes, Alps, and other great mountain units, before fold-



FIGS. 246–249. Four stages in the evolution of the present Appalachians. Views looking north. Each block is about 200 miles long.

FIG. 246. The geosyncline and the edge of the old land Appalachia, composed of granite and metamorphic rocks.

FIG. 247. Folding and thrust faulting of the rocks in the geosyncline. The form and height of the surface are entirely hypothetical; it is not known how much uplift resulted directly from the folding or to what extent erosion kept pace with the uplift. After several geologic periods had elapsed the region was worn to a peneplane, indicated by the broken line at *P*. The thickness of rock above this line suggests the vast work of erosion in reducing the original mountains.

FIG. 248. General appearance of the peneplaned Appalachian region near the close of the Mesozoic era. The eastern part of the region was submerged and received a veneer of coastal-plain sediments; possibly this veneer covered most of the folded belt, and has been removed by erosion.

FIG. 249. During Cenozoic time the region was warped up, as indicated by arrows at the bottom of the block; belts of weak sedimentary rock were eroded faster than the resistant strata, which therefore make the present ridges. (The broken line corresponds to the base of the block in Fig. 248.)

ing and thrusting disturbed the rocks that have been elevated to form these highland belts. It appears to have been a general rule, therefore, that a sinking trough, flooded by the sea and loaded with tremendously thick deposits of sediments, prepared the way for the forces that created each great mountain system. In every case the development of the geosyncline required a long span of time. The Appalachian trough was slowly sinking and receiving sediments for nearly 300 million years before its history was ended by the folding and thrusting that brought the original Appalachian Mountains into existence.

The Old Land Appalachia. Study of the sedimentary rocks in the Appalachian folded belt reveals other surprising facts regarding the ancient geography of the region. The distribution of the sediments indicates clearly that a large land mass lay east of the old geosyncline and supplied the gravel, sand, and mud carried by streams into the sinking trough. Conglomerate beds in the eastern part of the folded belt grade westward into sandstones, and these in turn give way to mudstones, which are succeeded still farther west by limestones deposited in the sea far from land. Thick sections of sandstone and shale that are abundantly mud cracked, ripple marked, and cross-bedded, and contain numerous fossils of land plants, are recognized as deposits in deltas and floodplains of large streams that flowed westward into the geosyncline. One of these old deltas, now exposed over a wide area in northeastern Pennsylvania and in the Catskill Mountains of New York, was so immense that its building required a stream of exceptional size. A land large enough to nourish such a stream, and to supply the vast quantities of sediment now exposed throughout the length of the geosyncline, must have extended well east of the present Atlantic shoreline. This old land, now represented by the belt of metamorphic rocks and granites near the continental margin, is known as *Appalachia* (Figs. 246, 250). It is a "lost Atlantis" for which there is abundant unquestionable evidence.

Birth of the Appalachians. The long history of the geosyncline was ended by a movement which, although it probably went on slowly, produced such great effects that it is spoken of as a *crustal revolution.* Under powerful lateral pressure the thick section of strata was buckled into folds, and great slices of the old rocks in Appalachia were driven westward over the margin of the geosyncline (Fig. 247). Under the high pressures and the increased temperatures, many of the shale beds folded in the deeper parts of the disturbed zone were metamorphosed to slate (p. 263). At still greater depths, vast quantities of molten rock invaded the crust and later solidified to form batholiths of granite

(p. 240). The former geosyncline was elevated to mountain heights, although there is no certainty as to exact altitudes of the original mountains.

Development of the Present Appalachians. The Appalachian revolution occurred about 200 million years ago. There is no record that seas ever again flooded the area of the old geosyncline, except in its southern part, where the Appalachian folds now disappear under

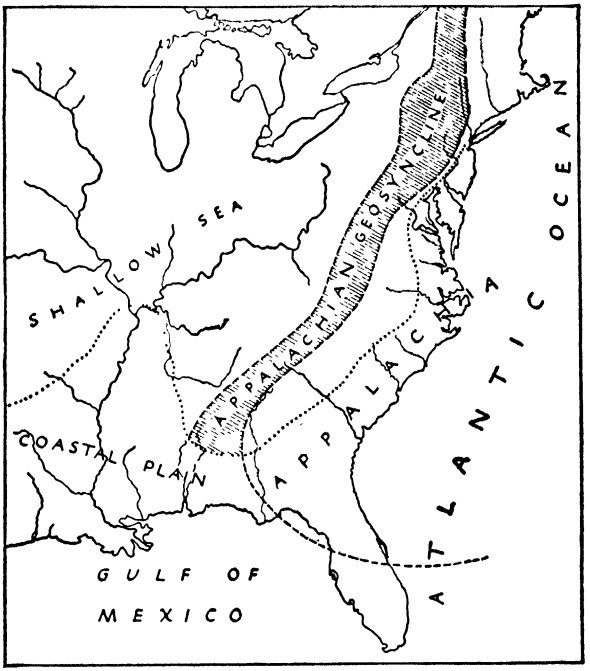


FIG. 250. Map showing general location of the Appalachian geosyncline and of the old land Appalachia. The area between the dotted line and the present shoreline is the Coastal Plain, where young sedimentary deposits conceal the older rocks; the folded strata that had their origin in the geosyncline disappear southward under this younger cover, and hence the full length of the geosyncline is not known. That part of old Appalachia now above sealevel is indicated by shading; however, the full extent of the old land in present New England has not been determined.

younger strata of the Gulf Coastal Plain (Fig. 250). Therefore the Appalachian Mountain belt has been subject to continuous erosion through long geologic periods. Even the highest mountains, built of the most resistant rocks, would have been swept away within a fraction of this extended regime. How then are the present high Appalachian ridges to be explained?

A study of the surface forms in the folded belt gives a large part of the explanation (Fig. 251). The ridges, formed by outcrops of the most resistant rock formations, have even summits, broken here and there by water gaps (*WrG*) and wind gaps (*WdG*). One group of these ridges reaches nearly a common plane at a high elevation (*I*, Fig. 251), and another group stands at a nearly uniform lower elevation (*II*, Fig. 251). The lowlands (*III*, Fig. 251) between the ridges are a network of small hills whose summits have nearly the same height. They are drained by small streams that flow into larger meandering streams (*SSS*, Fig. 251) following the strike of the strata,

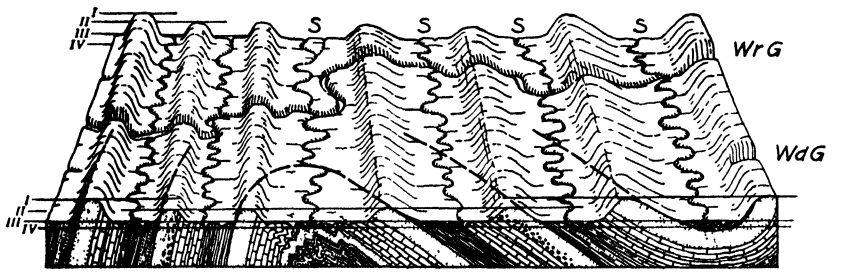


FIG. 251. Ideal segment of a part of the central folded Appalachian region. The main stream trenches seven ridges of resistant rock through seven water gaps (*WrG*). A former stream course, long abandoned, is indicated by a wind gap (*WdG*). Control by four successive baselevels (I, II, III, IV) is indicated by two series of accordant ridge tops, an accordant group of hilltops in the weak-rock belts, and the present stream profiles.

and all the meanders are incised. These meandering streams, developed along belts of weak rocks, are tributary to great streams that flow indiscriminately across resistant-rock ridges and weak-rock valleys.

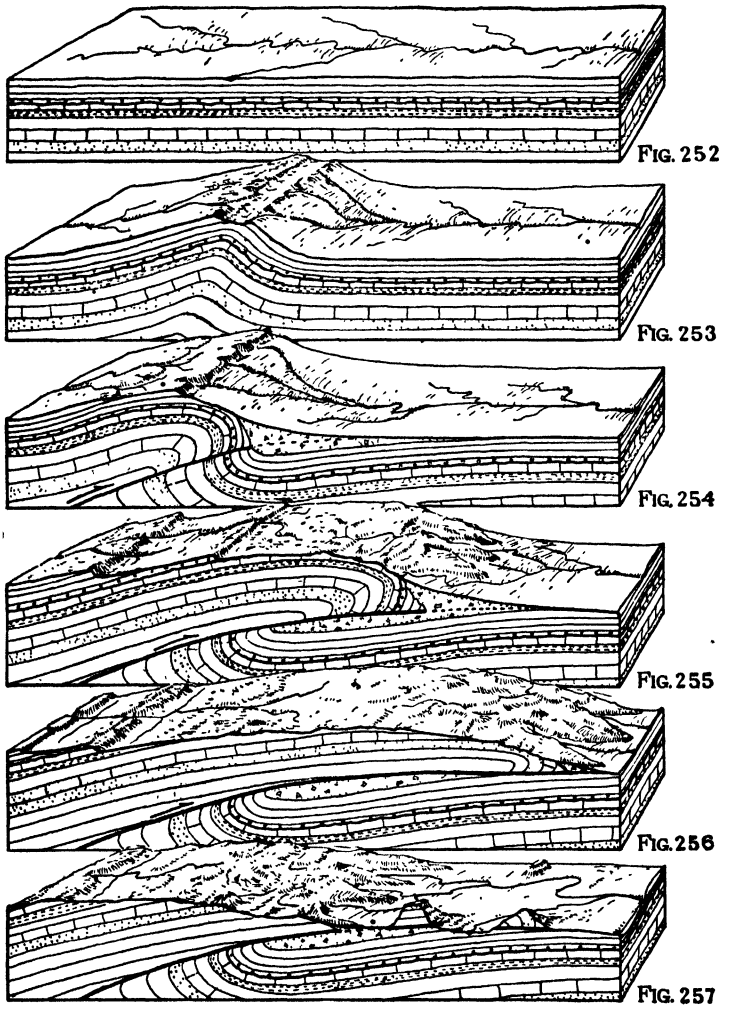
The high ridges on resistant rocks could have acquired their uniformly even summits only by erosion of the original mountain folds to a peneplane, near sealevel (p. 93). We reason, therefore, that the highest even-topped ridges represent this peneplane, and in imagination we project the weak-rock strata up to this former surface, thus filling the present intermont valleys. The result would be a surface like that represented in Fig. 248. During the long time this peneplane may have existed, the large streams in some way acquired their present courses transverse to the strike of the strata. A slow regional upwarping then occurred, and these main streams began cutting down across the edges of the tilted strata. Tributaries developed most favorably along the belts of weak rocks, and, as these rocks were cut down toward the new baselevel, the resistant formations were etched into relief and came to form ridges between the larger tributary streams.

In the course of stream adjustment to the weak-rock belts, some stream courses across the strike were abandoned through capture (p. 99), and water gaps in the abandoned courses became wind gaps (*WdG*, Fig. 251). Upwarping ceased for a considerable time and a large part of the surface was reduced to low relief (*II*), leaving only the ridges on the most resistant rocks to mark the position of the peneplane (*I*). A second upwarping started a third fluvial cycle, during which the weak rocks were further reduced, and only some ridges on rocks of moderate resistance remained to mark the height of the second erosion surface (*II*). After the streams on weak-rock belts had opened wide valleys and had developed meander patterns, a third upwarping caused another rejuvenation, and parts of the old valley floors (*III*) now stand well above the incised stream courses (*IV*).

Warping has not been entirely uniform throughout the Appalachian region, and the number of rejuvenations indicated in Fig. 251 to illustrate principles can not be applied literally to all parts of the mountain belt. The essential points are that the original mountains formed by the crustal revolution were peneplaned, and the present mountain relief resulted from differential erosion after broad upwarping converted the peneplane into a plateau (p. 299). However, the later erosion has been guided by the pattern of folds and faults impressed on the region by deformation of the Appalachian geosyncline 200 million years ago. Many other mountain chains, some much older than the Appalachians, have gained a new lease on life by upwarping and differential erosion long after the initial mountain forms disappeared.

Variations in Mountain Structure. Differences in structure between separate mountain systems and between distant parts of any one unit are caused by variations in kinds and thicknesses of stratified rocks, in the intensity of deforming forces, and probably in other factors. Appalachian structure in Pennsylvania is characterized by fairly regular folds, which in the eastern part of the section are closely compressed and overturned, but farther west are upright, with gentler dips (Fig. 195, p. 249). Thrust faults grow more numerous in sections taken successively farther south, and in southwestern Virginia numerous thrust slices have been driven from the southeast one above another, like gigantic shingles. In parts of the Rocky Mountains, great thrusts dominate the structure, almost to the exclusion of ordinary folds. Not uncommonly a thrust plate has been driven forward as much as 10 or 20 miles, and exceptional displacements are even greater (Figs. 252–257). When a widespread plate of this kind is greatly eroded, remnants of large size are left standing far in advance of the main mountain front, with relations to underlying rocks that appear illogical until the

origin by thrusting is recognized. Isolated erosion remnants of this kind, numerous in the Alps and in western North America, are termed "mountains without roots" (Fig. 257).



FIGS. 252–257. Development of a great thrust fault. Length of block about 50 miles.

FIG. 252. Undisturbed strata before the movement has begun.

FIG. 253. Horizontal compression has formed a fold, overturned to the east.

FIG. 254. The fold has developed into a thrust fault. Debris eroded from the rising structure has accumulated in the synclinal depression at the base of the range.

FIG. 255. The mass is pushed out over the land surface, and overrides some of its own alluvial debris.

FIG. 256. The thrust reaches its maximum extent.

FIG. 257. After movement has ceased, erosion has full sway. The thrust mass is cut down and back. Note the isolated remnants of the older rocks.

Possible Cause of Crustal Movements

When it was believed that the Earth consisted of a relatively thin crust resting on a hot molten interior, it seemed easy to explain deformation of the crust by assuming that there was steady contraction of the Earth's mass as the result of cooling. The already cold outer crust would be folded up as it gradually sank upon the shrinking core, very much as the skin wrinkles upon an apple that contracts from drying. This view in its original simple form can no longer be held, because it is known from seismic evidence that the Earth is rigid, at least in the outer half of its radius.

Nevertheless a view commonly held to account for crustal deformation assumes contraction because of cooling. This is a survival of the idea mentioned above, but changed to accord more nearly with later knowledge. It assumes that the Earth, though rigid, is very hot within and that progressive cooling causes slow shrinkage below a comparatively shallow depth. An English scientist has shown that this mechanism would account for a large amount of buckling in the outer shell, provided we make certain reasonable assumptions as to the temperatures in the interior. However, serious objections to this hypothesis have been raised. Theoretically, a comparatively thin crust collapsing on a shrinking interior would fail by buckling simultaneously in a large number of places, and not in a few widely separated mountain belts. Furthermore, continuous contraction of the Earth would account only for features of compression, such as folds and thrust faults, and not for regions of block faulting such as the Basin-and-Range province (Fig. 239).

Within the last few years some geologists have suggested that whole continents shift horizontally through long distances. It is claimed, for example, that Africa moved northward against the old Mediterranean geosyncline and crushed it to form the Alps and neighboring mountains; that the great mountain chains of India were caused by southward shifting of Asia; and that the vast mountain belt extending from Cape Horn to Alaska, along the western sides of North and South America, is the result of slow, long-continued westward drifting of those two continents. It is urged that no other explanation will suffice in view of the stupendous shortening recorded by mountain folds and thrusts. Further, part of a moving continent might be held back and broken into large fault blocks while the forward edge was being crushed and buckled to form a great mountain belt. Students who favor the hypothesis of "continental drift" point out considerable geologic evidence which, in their view, strongly supports the concept. For example, if the maps of North and South America, as they appear on a globe, are moved eastward

against Europe and Africa, not only do the continental margins match remarkably, but also some old mountain belts in America — among them the Appalachians — appear to be continuous with mountain belts of the same geologic dates in lands east of the Atlantic. But what would furnish the motive power for breaking up and transporting continental masses?

It must be admitted that the cause of crustal deformation is one of the great mysteries of science and can be discussed only in a speculative way. The lack of definite knowledge on the subject is emphasized by the great diversity and contradictory character of attempted explanations. It is a fascinating problem, but lengthy discussion of its various aspects has no place in this volume. The facts and relationships of mountain structure present a large field of study in themselves, aside from the problem of ultimate forces.

Equilibrium in the Crust

The irregularities of the Earth's surface are small in comparison with the length of the radius, but some of them probably are nearly as large as the rocks of the crust will bear. Rock is not indefinitely strong. Under great stress it adjusts itself to a condition of equilibrium, as does any other material. For this reason the Earth does not have the form of a cube or other angular figure, but is nearly spherical, with an amount of bulging at the equator and flattening at the poles determined by the rate of rotation.

How high can a mountain mass rise above the general surface? Certainly not to unlimited height, because above a critical point the strength of rocks would be exceeded and the mass would tend to flatten out. The Himalaya Mountains of Asia are exceptionally high and massive. Is their enormous weight held up merely by the strength of the crust beneath them? At least a partial answer to this question is found in the results of gravity measurements that have been made at numerous localities. By the swinging of a delicate pendulum, the gravitative pull at any place can be determined with great accuracy. Such measurements made at stations in high mountains show values of gravity considerably less than are to be expected in comparison with the values obtained at low altitudes. The logical inference is that the average density of rocks beneath high areas is less than it is beneath lower areas. In other words, parts of the Earth's crust that contain large quantities of light rock stand high in order to balance adjacent portions that have heavier rock, just as an iceberg must project above the surface of water in which it floats. According to this view, a great mountain system like the Himalaya is not a load on the crust; it is buoyed up, so to speak, by a great thickness of light rock in the crust beneath.

This conception is illustrated in Fig. 258, which represents blocks of copper, equal in cross-section but of different lengths, floating in mercury. All the blocks float fairly high, because mercury is 13.6 times as heavy as water, whereas copper is less than 9 times as heavy; but long blocks rise higher and also reach to greater depths than short blocks. Applying this illustration to the Earth, we may picture each continental mass as a great plate of granite with variable thickness, resting on a deeper layer of heavier rock (Fig. 259). Under high mountains the granite extends downward farther than under low plains, and thus the different parts of the crust are essentially balanced against each other. The term *isostasy* (from the Greek, meaning "equal standing") is applied to this supposed condition. It is not to be understood, of course, that the Earth's crust is divided into definite blocks, or that there is a liquid substratum at some depth.

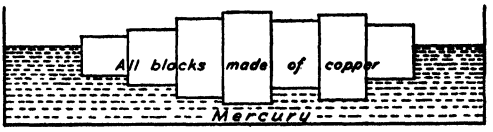


FIG. 258. Copper blocks, equal in cross-section but unequal in length, float in mercury. They sink to unequal depth, and also rise to unequal height. According to this conception of isostasy, a continent is the upper surface of a light-rock shell, essentially uniform in density but with variations in thickness. The thinner portions form low plains, whereas thicker parts project upward as plateaus and mountains. (See Fig. 259.)

Suppose now that a portion is cut from the top of one block in Fig. 258 and placed on another. Equilibrium is disturbed, and adjustment

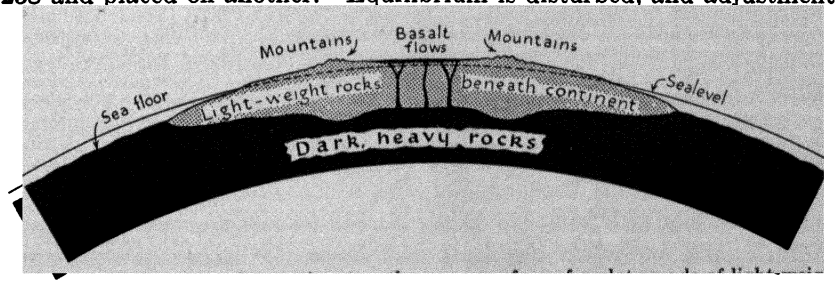
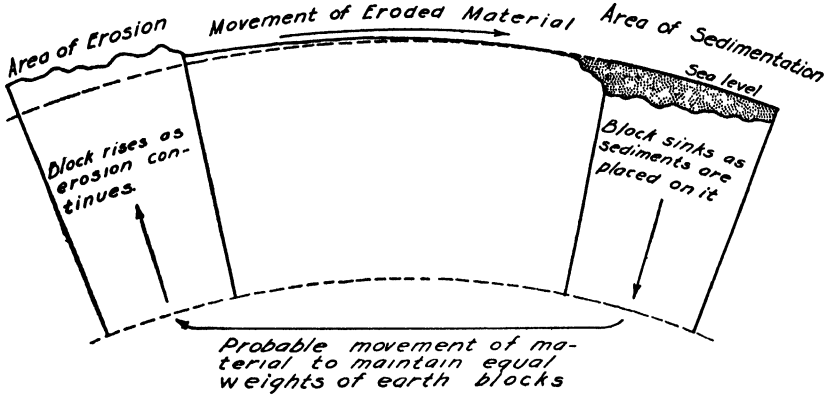


FIG. 259. Concept of a continent as the upper surface of a plate made of light-weight rocks, "floating" high above the heavier rocks on which it rests. Mountains are above the thickest parts of the plate, a plateau above a somewhat thinner part, low plains and continental shelves above still thinner parts. Great mass eruptions of basalt are represented as rising through the entire thickness of the continental plate from the continuous substratum of heavy rock (p. 293). Vertical scale greatly exaggerated.

takes place by sinking of the loaded unit and rising of the lightened one. In a liquid this adjustment is immediate and perfect. How can the principle apply in the Earth? No continuous zone of liquid rock exists; but we know that under sufficiently high pressure solid rock behaves as a plastic substance. Hence we infer that, when any part

of the crust is heavily loaded, it sinks, displacing the deep rocks by plastic flow and thus causing lighter parts of the crust to rise. The operation is much less perfect than in a liquid, and of course requires a much longer time.

This inferred mechanism for preserving balance in the crust is illustrated by Fig. 260. A mountain mass is eroded deeply, and the debris is transported across an adjacent low plain, to be deposited on a sea floor. As it loses mass by continued erosion the mountain segment becomes abnormally light; the surrounding crust, and especially the



Modified from W. Bowie.

FIG. 260. Diagrammatic explanation of the supposed mechanism by which balance is restored when load is shifted on the surface by erosion and deposition. The eroded area, at the left, continually loses weight, which is added to the low area at the right (shaded section represents sediments). In time this loaded part of the crust sinks, and forces deep-seated rock to move horizontally by slow plastic flowage. This material moves underneath the eroded " block " which rises to a position of proper balance. The plains area, across which eroded sediments are transported, is neither depressed nor uplifted. The representation is highly artificial, as there probably are no definite, freely moving " blocks " in the crust.

part newly loaded by the sediments, forces deep-seated rocks to move laterally and buoy up the lightened segment. Repeated uplift of mountain belts — as in the Appalachians (p. 310) — in large part undoing the slow work of erosion, finds a logical explanation in this way. At first thought it may appear that this mechanism would make it impossible for erosion ever to wear highlands to a low level, as there would be constant rejuvenation. However, since the deep rocks are denser than those near the surface the amount of uplift can not equal the thickness of lighter rock removed; therefore mountains can finally be brought low, though only by long-continued erosion.

A striking confirmation of the isostatic theory is furnished by the areas in North America and Europe that were covered by great ice

sheets in late geologic time. As the ice disappeared, the sea invaded much of the glaciated area, but was excluded by later uplift. Uplifted wave-cut cliffs, beaches, and other evidences of this late submergence, are found in the region of Lake Champlain and Montreal several hundred feet above present sealevel; and similar evidence is found in Scandinavia. The clear inference is that the mass of ice was a great load which depressed the land. After the load was removed, some time was required for restoration of balance by slow plastic flow in the rocks at depth. Before adjustment occurred, the sea invaded the depressed area; and as balance was gradually restored by regional uplift the sea was expelled. Although it is thousands of years since the ice disappeared, probably the adjustment is not yet complete, as parts of Scandinavia are still rising at the rate of 2 or 3 feet in a century (p. 244).

The general fact of isostasy appears to be established; but many uncertainties are connected with the subject. We do not know the depth at which plastic flow occurs during adjustment, though from several lines of reasoning it is argued that this depth is only a few tens of miles. The size of a load necessary to start the mechanism of adjustment is not known. These and other problems are likely to be solved by continued study.

Summary

Some mountains and plateaus are built up directly as heaps of lava, ash, and other volcanic materials. Mountainous forms originate also as erosion remnants of plateaus, whatever the origin of the plateaus may have been. Most highlands are created primarily by movements of the crust, and later are modified by erosion. Several kinds of crustal movements are responsible, and the form of a highland mass reflects in important measure the nature of the movements that created it. (1) Broad warping and displacements on steep faults have co-operated to produce great plateaus such as the Colorado Plateau. Differential movement of blocks on a set of steep faults, perhaps following regional upwarping, has resulted in fault-block mountains like those in the Basin-and-Range province. (2) Strong doming above laccoliths has formed isolated mountains; larger-scale doming, not visibly related to igneous bodies, has developed small plateaus like the Black Hills uplift, which is now a rugged group of mountains because of erosion. A common feature of a dome-shaped uplift is a frame of hogback ridges. (3) Structure of the great mountain belts has resulted from large-scale folding and thrust faulting. These movements in each major belt have been preceded by prolonged sinking and filling of a geosyncline. Erosion of the intensely folded strata reveals their great thickness, and

numerous features of the sedimentary deposits make it possible to restore the relations of land and sea as they were during the long geosynclinal history. The present Appalachians have been developed by differential erosion; the original mountains were eroded to a peneplane, this surface later was warped into a broad plateau, and the weak-rock belts were then reduced to low elevation, leaving high ridges made of resistant formations.

Forces that deform the crust are a subject of much speculation. A time-honored hypothesis represents the interior of the Earth as a slowly contracting mass, on which the outer shell collapses like the skin of a shriveling apple. A newer theory suggests that the continental masses have moved horizontally, and that weak zones have been crushed and elevated by pressure from these "drifting" masses. Whatever their origin, the great features of relief are nearly in equilibrium, the lighter parts of the crust standing high with relation to heavier parts. This condition of balance, termed isostasy, presumably is restored by some deep-seated mechanism when great loads are shifted at the surface by erosion and deposition, by formation of ice caps, or by any other process.

Chapter 16

MINERAL RESOURCES

Relation of Mineral Resources to Geology

Modern civilization is strikingly dependent on mineral resources. Many mineral products are essential in peace and in war, and those essential minerals in which a nation is not self-sufficient are coming to be termed strategic minerals. The United States, more fortunate than other nations, is deficient only in about seven essential mineral supplies: manganese — the "vitamin" of the steel industry — tin, platinum, nickel, and a few others.

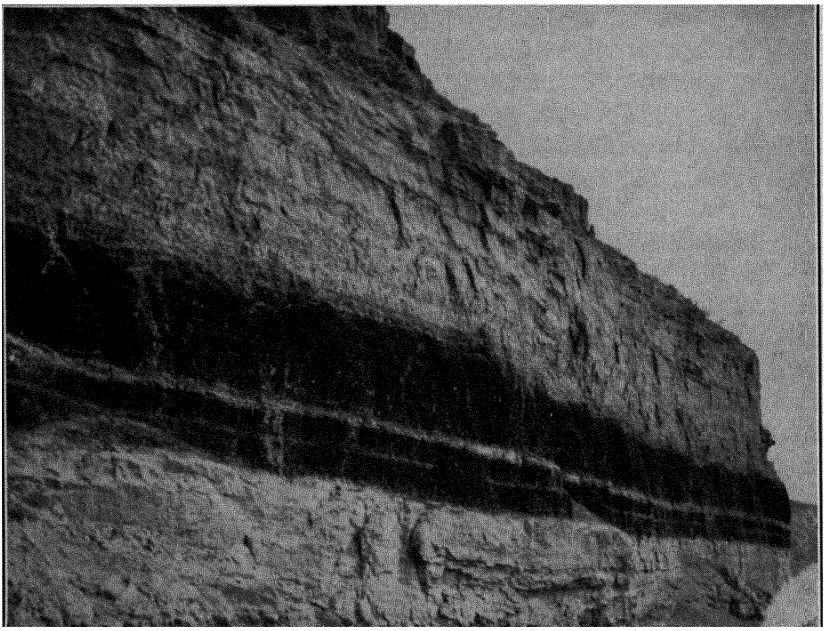
The world's mineral supplies are being consumed at an unprecedented rate. The amount mined during the first quarter of the present century was greater than that in all previous history. This enormous draft on our mineral resources means that the known supplies are being rapidly depleted and that as fast as they are depleted new supplies must be discovered in order to maintain the present rate of production. The easily found mineral deposits have already been found, so that more ingenuity and more work are necessary to find new deposits. Therefore the cost of finding new deposits is steadily rising. It is the counsel of prudence, then, to enlist all possible aids to minimize the financial risks of the search and discovery of new deposits. Applying the principles of geology to the search for valuable mineral deposits is one of the main functions of economic geology. To aid in this search there have recently been developed powerful auxiliaries, such as the seismograph for "seismic prospecting," the torsion balance, and other geophysical instruments. We call these instruments auxiliaries advisedly, because the results obtained by their use must be interpreted in the light of the geology of the area that is being explored before the results can be practically applied.

Even more important than the aid given by applied geology to the finding of new deposits is its power to guide intelligently the development and exploitation of the deposits already found.

Coal

Occurrence and Nature of Coals. Coals are compact masses of carbonized plant debris. Peat, the embryonic form of coal, has already been described (p. 125). Between peat and anthracite there is a complete series of gradational varieties of coals, and this gradation leads

to the conclusion that all coals, no matter how structureless and amorphous they may seem, consist of carbonized plant remains. This conclusion is confirmed by the results of microscopic study, which show that coals are not amorphous but consist of plant debris in various stages of alteration. Fragments of wood, bark, leaves, roots, spores, seedcoats, and lumps of resin have been recognized in coals. Even in such highly carbonized material as anthracite the plant ingredients can be made visible, and, unexpectedly enough, are found to be so well preserved that the species of many of the plants can be identified.



M. R. Campbell, U. S. Geol. Survey.

FIG. 261. Coal bed, 8 feet thick, containing two partings of clay. Glendive, Montana.

Coals occur in beds which are generally inclosed between strata of sandstone and shale (Fig. 261). Their occurrence between strata of this kind harmonizes with the other evidence that most coal beds accumulated in freshwater swamps. Limestones are rare, either immediately above or below a coal bed, and where they do occur they indicate that the coal-forming swamp was near the sea and at sealevel and therefore was likely to be inundated at intervals by the sea.

Most beds of coal are underlain by a layer of clay, the underclay, which, because it contains the roots of plants, is interpreted as a fossil

soil. Stumps of large trees, with their root systems penetrating the underclay, are abundant in some coal fields. These features support the prevailing idea that most coal beds were formed from plant matter that accumulated where it grew.

Chemical Composition of Coals. It is customary to ascertain the chemical composition of coals to determine their value as fuels, and ordinarily the following constituents are reported: (1) fixed carbon, which is the carbon left after the gas has been driven off; (2) volatile matter, mainly combustible hydrocarbons (gas) but including some inert gases, such as carbon dioxide; (3) water; (4) ash; and (5) sulphur. The value of a coal as a fuel depends on its content of fixed carbon and volatile combustible matter, whereas the water, ash, and sulphur are undesirable ingredients. Coals containing much ash are termed low grade.

Classification of Coals by Ranks. Coals are classified according to *ranks* by a combination of their fixed-carbon content and their physical properties. As there is a continuous gradation from low-rank to high-rank coals, the divisions adopted are necessarily arbitrary.

The lowest-rank coals are the *lignites,* so called because of their obviously woody appearance, or *brown coals,* in reference to their color. They are highly immature coals. When taken from the mine they may appear to be perfectly dry, but may contain as much as 30 to 40 per cent of water. On exposure they lose most of this water; they slack and crumble to pieces and are likely to take fire spontaneously.

The medium-rank coals are the *bituminous.* They do not slack on exposure and generally have a prismatic jointing perpendicular to their banding. As there is no hard and fast line between lignite and bituminous coal, the intermediate varieties are termed *sub-bituminous.* Their black color and nonwoody structure distinguish them from the lowest-rank lignites, and their tendency to slack distinguishes them from the high-rank bituminous coals.

The highest-rank coal is *anthracite.* It differs physically from the bituminous varieties by its conchoidal fracture and absence of cross-jointing. Water and volatile matter are extremely low, and nearly all the carbon is fixed carbon.

The increase in the rank of a coal, then, is marked by the progressive increase in the fixed-carbon content and by the diminution of the content of water.

Relation of Rank of Coal to the Geologic History of the Coal. Coals have formed in all the geologic periods since floras began growing on the lands. Most of them have formed in forested coastal swamps. The requisite conditions for the accumulation of a coal bed

are at least two: (1) the swamp must be stagnant, hence the water cover under which the plant remains are accumulating is poorly aerated, thus preventing the plant debris from being oxidized to carbon dioxide; and (2) the swamp must be slowly sinking, thus permitting progressive accumulation of the plant remains.

The nature of the environment in which the coals were formed is inferred from the botanical character of the coal-forming flora and from the character of the inclosing sedimentary strata. Modern analogues of coal-forming swamps are the Dismal Swamp of Virginia, the Everglades of Florida, and, above all, the dense mangrove swamps of coastal Sumatra.

There are two stages in the transformation of plant matter into coal. The first stage consists of a bacterial fermentation (p. 125), which after a longer or shorter interval becomes arrested by the toxic products formed during the bacterial activity. During this stage the plant debris is carbonized and compacted; it is transformed to peat (p. 124).

In the second stage the further changes in the immature coals are determined by geologic activities. If the coal beds remain geologically unacted upon — if they remain horizontal, undisturbed — the coal does not advance in rank. The most influential factor in raising the rank of a coal is folding of the inclosing strata, which raises the rank of the coal by eliminating the water and volatile combustible matter. Nowhere is this better shown than in the Appalachian belt. In Ohio and western Pennsylvania the coal-bearing strata are horizontal, but eastward across the coal belt they become more and more closely folded (p. 306). Concurrently the fixed-carbon content of the coal rises more than 40 per cent. The anthracite fields of Pennsylvania, which furnish 99.9 per cent of this country's supply of anthracite, are in the highly folded portion of the Appalachian coal field, and the coal of these fields consists almost wholly of fixed carbon, the moisture and gas having been nearly completely eliminated.

Oil and Gas

Oil, or petroleum as it is more formally called, consists of liquid hydrocarbons containing dissolved gaseous and solid hydrocarbons. As there are many of these hydrocarbons (compounds of carbon with hydrogen) and as they are mixed in various proportions, the oils of the various oil fields differ markedly. A distinction is commonly made between *light oils,* those much lighter than water, and *heavy oils,* which are near water in specific gravity. The light oils have a high content of gasoline, whereas the heavy oils are low in gasoline. As the gasoline

content largely determines the commercial value, the light oils command a considerably higher price per barrel than the heavy oils.

Requisite Conditions for the Occurrence of Oil. Four conditions must be fulfilled in order that oil can accumulate in the rocks. First, a *source rock* must be present containing the necessary carbonaceous matter from which the oil can be formed. Experience has shown that marine bituminous shales are the most common source rocks; limestones rarely are source rocks. Why rocks of freshwater origin have not given rise to valuable accumulations of oil has not yet been ascertained, but the fact that they are unfavorable is of great practical interest, for it excludes from consideration areas underlain by freshwater strata as most unlikely to contain valuable accumulations of oil.

The second requisite is a *reservoir rock* in which the oil can accumulate. Most commonly the reservoir rock is a sandstone whose pores are large enough to allow the oil to move freely through it. Less commonly limestone and dolomite serve as reservoir rocks. In sandstones the average pore space is 15 per cent, and the range is from 5 to 40 per cent; in other words, a sandstone of maximum porosity can contain eight times as much oil as one of minimum porosity.

The third requisite is a favorable structural arrangement of the strata, which is the condition that determines the place where the oil collects in the reservoir rock. The most simple form of such a favorable geologic structure is an anticline. It was the first structure that was recognized as controlling the accumulation of oil, but now nearly twenty kinds of structural traps are known to occur in the world's oil fields.

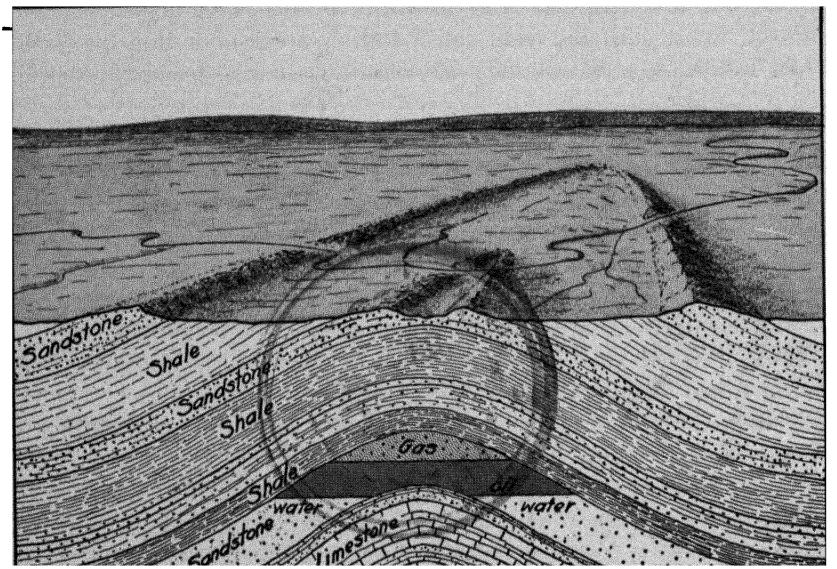
The fourth requisite is an impermeable layer, generally shale or clay, which overlies the reservoir stratum, and prevents the escape of the oil. As the result of the anticlinal structure and the overlying impermeable layer, the reservoir stratum forms a *deformational trap* in which the oil is held.

All four conditions are fundamental for the occurrence of oil; without any one of them commercial accumulations of oil are impossible. Inasmuch, however, as structure controls the actual underground position of an oil accumulation, and therefore in commercial practice the structure is determined as accurately as possible in advance of putting down a well, the structural requisite is of major practical importance. The mode of occurrence of oil in an anticline is shown in Fig. 262.

If, because of insufficient pressure, free gas occurs with the oil (under heavy pressure all the gas would be dissolved in the oil), there will be this triple arrangement: gas fills the pore space in the reservoir rock

in the arch of the anticline; below it oil fills the pore space in the reservoir rock; and below this occurs water, generally so charged with salts as to be termed a brine. The arrangement is thus according to specific gravity: the brine, which is heaviest, is at the bottom; and the gas, which is lightest, is at the top. The oil that fills the body of porous rock forms what in popular parlance is called the "oil pool."

If the sedimentary strata contain no water, the oil instead of occupying the upper parts of the anticlines occurs in the bottoms of the



Modified from Hewett and Lupton, U. S. Geol. Survey.

FIG. 262. Occurrence of gas, oil, and water in an anticlinal structure. The gas, being the lightest, occupies the crest of the arch; the oil, being heavier, lies below the gas; and the water, the heaviest of all, is at the bottom.

synclines. Recognition of the requisite conditions governing the accumulation of oil makes it possible in a given territory to block out the impossibly and improbably oil-bearing areas. Areas of igneous and metamorphic rocks can contain no petroleum, and areas of nonmarine strata, if not impossibly petroliferous, at best are improbably petroleum bearing.

Stratigraphic Traps. The East Texas oil field, the greatest ever found, was discovered in 1930. Up to January 1, 1940, it has yielded 1300 million barrels of oil, and the remaining oil yet to be produced was estimated to be 2650 million barrels. The magnitude of the

East Texas field can be appreciated when we consider that an oil field is regarded as a major field if its total yield during its entire life amounts to 20 million barrels. The conditions that governed th accumulation of oil in the East Texas field differ notably from those in the deformational traps. The oil occurs in the wedge-ends of sandstone layers that have been truncated at an acute angle by an unconformity; it was trapped in the upslope ends of the sandstone layers where they are covered by impermeable beds of the overlying unconformable formation (Fig. 263). Such an oil-bearing reservoir is termed a *stratigraphic trap.*

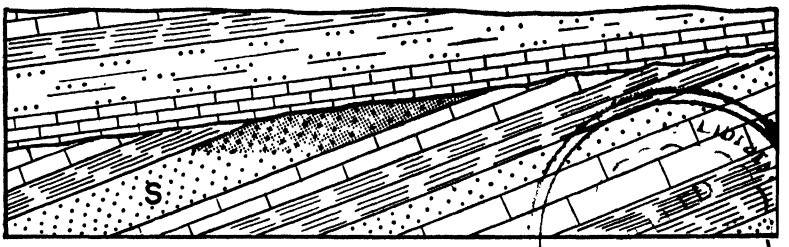


FIG. 263. Stratigraphic trap, showing the occurrence of oil (shaded pattern) in sandstone (*S*) below an angular unconformity. Length of block is about 3 miles.

Future success in finding new oil fields will depend largely on increasing our ability to find more stratigraphic traps, for most of the more obvious, easily found traps — the deformational traps — have now been discovered.

Life of an Oil Well. The gas, oil, and salt water in an oil-bearing structure, such as shown in Fig. 262, have in the course of geologic time attained an equilibrium. As soon as the top of the structure is perforated by the drill this equilibrium is violently disturbed, and the disturbance spreads radially from the well. At first the well produces gas, then it becomes a gusher or flowing oil well, later it has to be pumped, and finally salt water appears with the oil, presaging the extinction of the well. The withdrawal of the gas causes the oil to move to the upper part of the structure, and the water follows up after the oil; not in all pools, but in many of them. Oil, being a fluid, migrates readily in the direction of decreased pressure. Consequently it recognizes no property lines, and if the pool is under divided ownership the wells that first tap the reservoir drain not only the oil within their own tracts but also, if situated near the property lines, the oil from the adjacent tracts. If the owner does not take out his own oil, his neighbors will. This fact accounts largely for the close spac-

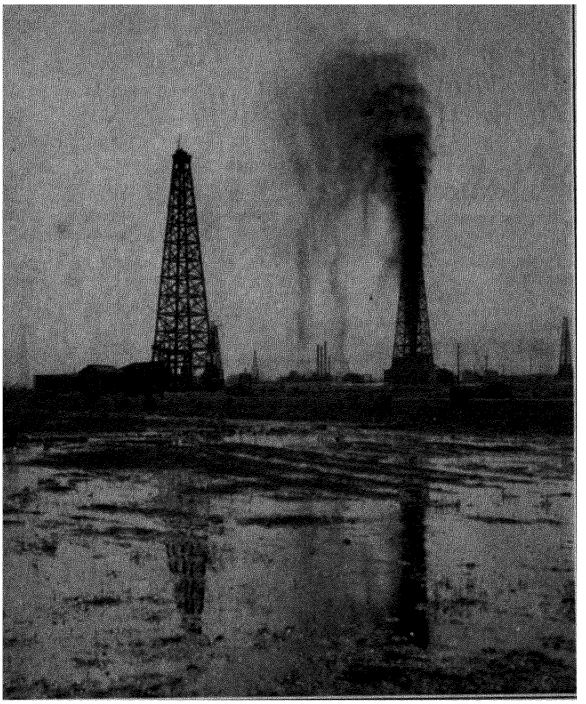


Fig. 264. Signal Hill oil field, southern California.

SPENCE AIR PHOTOS.

ing of wells in certain fields (Fig. 264) and for the great overproduction that ensues soon after the discovery of new fields.

Coarsely porous rocks because of their high permeability yield their oil freely and give rise to extremely productive gushers (Fig. 265). But they become exhausted rapidly — a fast life and a short one go together here. Finely porous rocks hold on to their oil tenaciously



G. S. Rogers, U. S. Geol. Survey.

FIG. 265. Gusher in Sunset field, California, May 10, 1914, shortly after oil was struck.

and so prolong the life of a well into old age. The record-breaking Mexican wells, which yielded as much as 260,000 barrels a day, drew their oil from limestones, which like most limestones contained solution channels and cavities; the oil therefore escaped with enormous rapidity and gave the wells their astounding yields, and for the same reason their period of production was short.

Geophysical Prospecting. One of the most remarkable of the seven major oil regions of the United States is the Gulf Coast field of Louisiana and Texas. The oil is associated with cylindrical or steeply

conical masses of rock salt which, forced to flow plastically under heavy pressure, have punched their way up from unknown depths through the overlying sedimentary strata. These masses are termed *plugs*, and most of them are a mile or so in diameter (Fig. 266). The

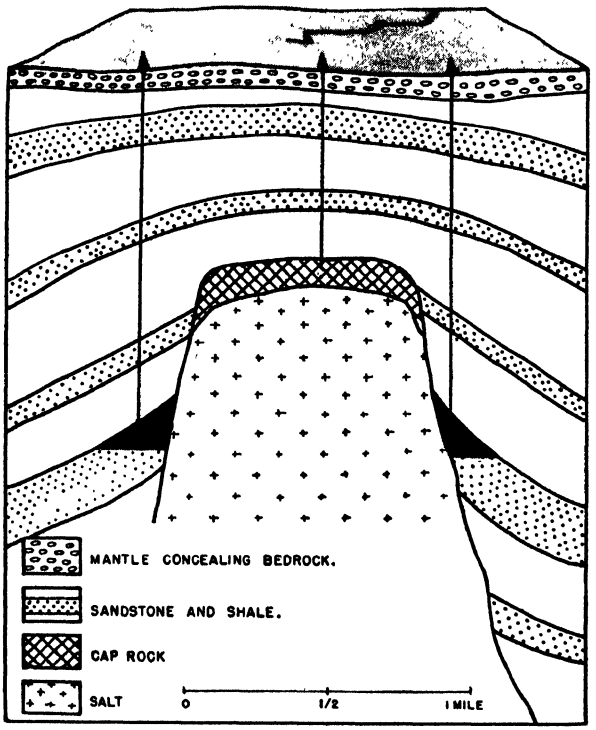


FIG. 266. Salt plug and enveloping strata, showing the occurrence of oil (shaded pattern) in flanking sandstone.

tops of some of the salt plugs are practically at the surface, but many of them are deep below the surface. Oil occurs in three kinds of structural traps: (1) cap rock, a peculiar rock made of calcite, gypsum, and anhydrite occurring as a capping over the tops of the salt plugs; (2) flanking sands, abutting upon and cut off by the salt plug; and (3) super-cap sands, the sandy strata that arch over the tops of the plugs, forming structural domes. Few of the salt-plug fields, however, produce oil from all three structures. The first of these oil fields to be brought in was the famous Spindletop, near Beaumont, Texas, discovered in 1901. Spindletop is a circular mound rising 65 feet above the otherwise level monotony of the Gulf coastal plain. The top of the salt plug is at a depth of 1100 feet, and the mound at the

surface appears to have been due to a renewed upward push by the salt below. Many salt plugs, however, are without mounds or any other indication at the surface that they are present at depth.

In recent years, geophysical methods have been used with brilliant success in locating these hidden salt plugs. In essence the various geophysical methods depend on the fact that the physical properties of the salt differ greatly from those of the surrounding rocks. Use of the seismograph was introduced in the Gulf Coast region in 1924 and has probably been the most successful of the several geophysical methods employed, though the torsion balance, an extraordinarily sensitive instrument for measuring variations in the value of gravitational attraction, is more accurate for detailed work. The seismic method depends on the fact that the speed of earthquake waves is three times as fast through salt as it is through the adjacent strata. Artificial tremors are induced by the explosion of charges of dynamite, and the rate at which the waves travel is determined by appropriately located seismographs; those waves that travel for part of their course through a salt mass have the shortest travel-times. As a result of growing experience the methods are rapidly improving, and depths can be measured by the reflection of the waves. During the early years of seismic prospecting the effective working depth was 2500 feet; it now has increased to 12,000 or 15,000 feet. The Gulf region is being "re-shot" for the third and fourth times to locate the favorable oil-bearing structures formed by the deeper salt plugs. Whereas the discovery well at Spindletop was brought in at a depth of 1100 feet, oil is now being obtained from wells as deep as 13,000 feet, and exploratory wells have penetrated to still greater depths. Geophysical methods were first used in the Gulf Coast region in 1924, and in the next four or five years as many salt domes were found as in the preceding thirty years. In addition to their use in locating deeply buried salt domes, geophysical methods are used in manifold ways in exploring underground structures.

The developments in seismic methods illustrate the reciprocal influence of pure and applied science. The seismograph was devised to study the transmission of earthquake waves, without thought of practical application. It was first used in the search for oil in 1924, and immediately methods and instruments began to improve at an accelerated rate. The technique thus developed in response to practical considerations is now being applied to such matters of theoretical interest as the determination of the thickness of glaciers in the Alps and of the ice sheet in Greenland.

Ore Deposits

In addition to the mineral fuels, industry utilizes many other mineral substances. At present the number is about eighty, but it will undoubtedly grow, for research is steadily finding or creating new uses for mineral products, and minerals considered today to be only of scientific interest may tomorrow become of economic value.

Mineral deposits fall naturally into two classes: *metallic* and *nonmetallic*. The metallic, or more accurately, the metalliferous, include the deposits of the industrial metals (iron, copper, lead, zinc, and others) and the precious metals — gold, silver, platinum, and allied metals. The nonmetallic include the mineral fuels, building stones, ceramic materials, gems, and a host of others. The nonmetallic substances mined in the United States exceed the metallic threefold in value of annual output, and the trend of the times is toward their greater and greater industrial utilization.

Definition of Ore. An *ore* is a mineral aggregate from which one or more metals can be extracted at a profit. The essence of this definition is in the phrase "at a profit," for "ore" is an economic concept. Consequently, many factors influence what is and what is not ore. When, as in 1932, the price of copper sank to 5 cents a pound, far below its long-time average of 13 cents, much copper-bearing material that had been ore fell out of the class of ore. On the other hand, the increase in the price of gold by legal enactment in 1934, from $20.67 to $35 a troy ounce, added enormous tonnages of gold ore to the world's supply and greatly stimulated the production of gold. Metallurgical advances, by making it profitable to work material of lower and lower grade, also influence the status of what is or is not ore. The development of new uses can transform a worthless material into a valuable ore; for example, the discovery that the metal tungsten is one of the most useful steel-alloying elements has changed the status of its chief mineral from an opprobrious impurity to a much-sought constituent.

Mineralogically, an ore consists of one or more metalliferous minerals inclosed in worthless material. Technically, this worthless material consisting of mineral or rock matter is termed *gangue*. The relative proportions of valuable constituent and gangue vary enormously: an iron ore of the highest grade consists solidly of the iron-bearing mineral magnetite, but iron ores at the lower limit of commercial availability consist of 30 per cent of magnetite mixed with 70 per cent of gangue. In contrast, most gold ores contain 0.001 per cent of gold disseminated through 99.999 per cent of gangue. In general,

the amount of gangue in average ores largely exceeds the amount of valuable metalliferous material they contain.

Primary Deposits

Occurrence and Origin of Ore Deposits. Mineral deposits that occur in bedrock are called *primary deposits,* to distinguish them from those derived from them by erosional destruction, which are called *secondary deposits.* The most important of the secondary deposits are the *stream placers,* which are stream gravels carrying valuable minerals that have become concentrated in paying amount during transport by the streams.

Primary ore deposits as a rule do not occur singly but are grouped in small areas, and these mineralized areas determine where the world's mining districts are situated. Many of these districts produce predominantly one metal; indeed some districts produce only one metal. Hence mining districts are usually designated by their principal product, as the Rand gold district of South Africa, which is the world's greatest gold field, or the Butte copper district of Montana, the world's richest metalliferous district, which produces not only copper but also zinc, silver, gold, and manganese.

The habit of ore deposits to be localized in districts — their gregariousness we may call it — is an advantage in many ways. Among these advantages is the fact that an intensive study of a mining district leads to a knowledge of the idiosyncrasies of its ore bodies that is of value in finding extensions of the known ore bodies and in finding the still undiscovered deposits; in fact, this has been the most successful method of ore hunting so far developed.

Most mining districts are situated near, around, or on areas of intrusive igneous rocks. The geographic association of mining districts with igneous rocks early led to the idea that there is a fundamental connection between the occurrence of the igneous rocks and the origin of ore deposits. The fact that at Vesuvius and other volcanoes during times of heightened activity hot gases carrying iron, copper, and lead are given off and visibly form minerals, such as galena and hematite, suggested that the magmas from which the igneous rocks were formed supplied the metals in the ore deposits and that the metals were released from the magma at the time it solidified. Magmas are the ore-bringers.

Most ore bodies formed in connection with igneous action are associated with plutonic rocks that occur as stocks and batholiths. Some are in areas of volcanic rocks, but here the ore-forming solutions as well as the volcanic rocks themselves were both derived from a parent

magma that solidified at a comparatively shallow depth, possibly a mile or two beneath the surface. In a few mining districts the ore deposits occur in volcanic necks. As a general rule the ore deposits genetically associated with stocks and batholiths have a greater vertical range than those associated with volcanic rocks: they persist to greater depths — at present the world's record for depth on an ore body of this origin is held by a gold mine in Brazil whose depth exceeds 8000 feet, whereas the deposits associated with volcanic rocks are likely to give out at depths of 500 to 1000 feet.

The solutions by means of which metals leave the magma are at high temperatures, so high that they are gaseous. While these solutions are moving upward through fissures toward the Earth's surface, they are steadily losing temperature, they are reacting with the wall rocks of the fissures, they are becoming admixed with more or less ground water, and the pressure on them is diminishing. As a result the composition of the solutions changes and certain constituents become insoluble and are deposited in the fissures. Loss of temperature is probably the most potent factor in thus causing precipitation. When the ore-forming solutions leave the magma they probably consist mainly of superheated steam, but during their journey upward they become condensed to water. Such hot-water solutions are the agents by which most ore bodies have been formed, and the ores thus deposited are said to be of *hydrothermal* origin.

Forms of Ore Bodies. The shape or form of an ore body is of great practical importance, for it determines the way in which the ore body can be worked. A tabular mass of ore more or less sharply defined from the rock inclosing it is termed a *vein* (Fig. 267). The ideal vein is bounded by well-defined walls; the overhanging wall, as illustrated on page 257, is the hanging wall, and the other, on which the miner obtains his footing, is appropriately called the foot wall. The ore breaks cleanly from these walls.

Some veins are bordered by zones of mineralized rock rich enough to extract along with the vein filling. These mineralized zones as a rule shade off imperceptibly into rock too poor to mine. Consequently, an ore body of this kind, instead of being bounded by well-defined walls, is bounded by "assay-walls" so called because continuous sampling and assaying to determine its metallic content are necessary in finding the limits of the ore body. Therefore such boundaries fluctuate with the price of the metal.

A *lode* consists of several veins spaced closely enough so that all of them, together with the intervening rock, can be mined as a unit (Fig. 268). All the larger tabular ore bodies tend to have this general



H. G. Ferguson, U. S. Geol. Survey.

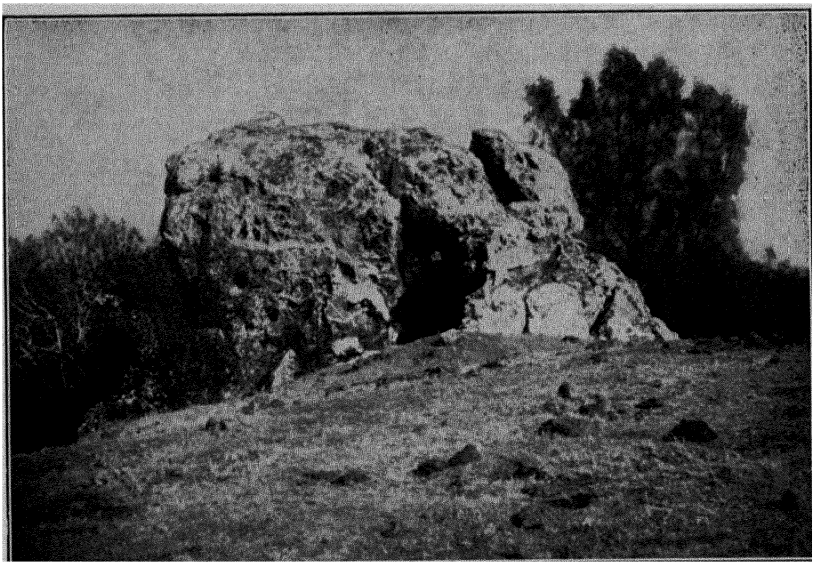
FIG. 267. Gold-bearing quartz vein, Alleghany district, California. The sharply defined white quartz vein is well shown, together with minor veinlets branching from it.



FIG. 268. Gold-bearing lode, a member of the Mother Lode system. Gover Mine, Amador County, California.

character, and there is no sharp distinction between a vein and a lode. A spectacularly large outcrop of quartz, part of one of the gold-bearing lodes of the Mother Lode system of California, is shown in Fig. 269.

Some ore bodies in sedimentary rocks conform to the bedding of the inclosing strata. Such ore bodies are either of sedimentary origin like the inclosing strata, or are of replacement origin (p. 335). Genetically these two modes of origin are wholly unlike, and the distinc-



Adolph Knopf.

FIG. 269. Outcrop of a gold-bearing quartz lode of the Mother Lode system, Mariposa County, California.

tion is of great practical importance although not always easy to make. If of sedimentary origin they are beds; if of replacement origin they are termed *bed veins.*

Fissure Veins. Some ore bodies have been formed by the filling of cavities or openings in the crust, others have been formed by replacement, and others have been formed by a combination of both processes. Openings in the crust are made by fracturing and fissuring. As the walls of a fissure are not rigorously plane but are more or less irregular surfaces, movement along them relative to each other causes open spaces to form along the course of the fissure. These openings become the receptacles of vein matter, and the vein thus formed, when

followed along its course or down its dip, will be found to expand and contract in width — "to swell and pinch," in the language of the miner. The abruptness of this swelling and pinching depends on the original irregularities in the fissure and determines how far the vein departs from the ideal tabular form. By renewal of movement along the vein the fissure may be reopened, and more vein matter deposited in the newly formed openings. In this way many veins have grown in size; the early formed portions of the vein are likely to become crushed during the later movements, and angular fragments of ore that was formed in the early stages may become incorporated in the ore deposited later. Thus the stages of growth of the vein are recorded within the vein, and a sequence in the order of deposition of the minerals can often be ascertained. These facts are not only of theoretical interest but also of practical consequence.

The vein-forming solutions that deposit the minerals in the openings along a fissure soak out into the wall rocks. There they bring about many changes, depending on their composition, on their temperature, and on the composition of the wall rocks. The effects may extend for a few inches up to hundreds of feet from the vein. From the study of these effects, conclusions can be drawn as to the composition and temperature of the ore-forming solutions.

Replacement Ore Bodies. More interesting practically is the ability of the ore-forming solutions under some circumstances to transmute the wall rocks into ore. The vein is then bordered on one or both sides by a layer or layers of ore formed by replacement. The resulting ore body is therefore of dual origin: it was formed in part by the filling of open spaces and in part by replacement.

Many ore bodies are wholly of replacement origin. Limestone is the most common rock thus transformed into ore. In some ore bodies of this origin the evidence of replacement is astonishingly impressive. Although the ore consists solidly of sulphides — galena, sphalerite, and pyrite — it preserves faithfully the bedding and other sedimentary features of the vanished limestone; and on seeing such an ore body underground one often finds it difficult to believe that he is viewing an ore body and not merely country rock. In ore bodies of replacement origin, the ores in contrast to those in the fissure veins were formed by the ore-forming solutions dissolving the country rock and simultaneously depositing in the space thus formed an equal volume of ore. The thoroughness of replacement in many mining districts is impressive, but the immensity of the volume of rock removed during replacement is perhaps even more impressive. The process of replacement is of prime importance to an understanding of ore deposits.

Composition of Ores. In the primary ores of copper, lead, zinc, and silver, the metals were originally deposited in compounds in which they are united with sulphur — in short, as sulphides. Galena (PbS) is the ultimate source of all the world's lead; sphalerite (ZnS) is the chief source of all our zinc; chalcopyrite ($CuFeS_2$) and other copper-bearing sulphides are the ultimate sources of our copper. Gold, it is true, is generally deposited as native metal, but it is almost invariably accompanied by pyrite, that most ubiquitous of all sulphides.

Weathering of Ore Bodies. Certain important consequences follow from the fact that the primary ore bodies generally contain sulphides. As soon as an ore deposit becomes exposed at the Earth's surface by the progress of erosion, the sulphides in it begin to oxidize — to unite with the oxygen of the atmosphere — and the oxidized products begin to unite with water and carbon dioxide. A host of new minerals is formed. Prominent among the changes are those that overtake the pyrite. Pyrite alters to rusty yellowish-brown limonite, which imparts to the outcrops of veins and lodes their characteristic iron-stained appearance. Not only is limonite formed from the pyrite, but powerful solvents, such as sulphuric acid and ferric sulphate, are generated, and as these solvents trickle downward they attack the other sulphides. They dissolve the silver and copper and cause them to move downward. As a result of these changes the ore body at the outcrop is likely to be vastly different from what it is in depth. It differs in appearance, in composition, and in metallic content.

These changes stop at or near the water table (p. 104), because the subsurface water moves slowly below the water table; the supply of oxygen is therefore not rapidly replenished and becomes scant. In humid regions the water table is near the surface; in arid regions it extends as deep as 2400 feet. As the position of the water table is influenced also by the relief of the land, the depth to which the oxidized zone extends is controlled by climate and topography.

At the water table, then, the character of an ore is likely to change drastically. The metallurgical processes adapted to the oxidized ore may be wholly unsuited to the primary sulphide ore. Many a mine, equipped to treat the ore occurring near the surface, has failed from this cause alone. Moreover, the metallic content of an ore body is likely to become either smaller or larger, depending on the nature of the chemical reactions that have taken place in the zone of oxidation. The explanation of why some ores are impoverished and others are enriched depends on the solubility of the metals in the zone of oxidation and involves applying chemistry to the problems of geology, but it would take us too far afield to discuss the details here.

Supergene Enrichment. The enrichment that has affected certain ore deposits just below the zone of oxidation is so important that it merits mention. Copper deposits illustrate the great principle of enrichment most readily. By weathering, the copper in the outcrop and underlying zone of oxidation is rendered soluble; it is dissolved by descending water, and is carried downward. When the copper-bearing solution comes into contact with the unaltered sulphides that occur below the zone of oxidation, it reacts with them and the copper is precipitated as a bluish-black film or coating on the sulphides. The copper content of the primary material is thereby enriched; and in many places, notably Utah, Nevada, Arizona, and New Mexico, the primary mineralized rock, which was too lean to be ore, was enriched sufficiently to bring it up to ore grade. The process is termed *supergene enrichment.* In the States mentioned this process has been effective in forming enormous deposits of copper ore. Although the deposits thus formed are of relatively low grade, the application of mass-production methods makes them immensely productive and profitable and since 1900 has revolutionized the copper industry.

Iron-Ore Deposits. Most ore deposits, as already outlined in the preceding pages, are concentrations of metals brought about by igneous activity. Other methods of concentration, however, are effective in forming ore deposits of economic value. These other methods can be illustrated most readily by means of the iron-ore deposits.

Iron is by far the most useful of the metals, and fortunately its ores are more abundant than those of all other metals. Part of this abundance is due to the fact that iron-ore deposits are formed in more ways than those of any other metal, but largely because many iron-ore deposits were formed by sedimentation, a process that makes far larger ore deposits than any other process of concentration. If we consider that an iron-ore district containing a reserve of more than one billion (10^9) tons of ore is a district of first-magnitude reserves, then there are ten such the world over; and in at least seven of these ten the ores are of sedimentary origin.

In the following sketch of the processes by which iron has been assembled to form commercially valuable ore bodies, four types of deposits are described: first, deposits formed by concentration of the iron within molten magmas and thus originating at high temperature; second, those formed as a result of the iron being carried out of the magma by gases, the iron having been rendered volatile by the presence of chlorine or some other agent, such as we have visible evidence of in the fumaroles at Vesuvius or in the Valley of Ten Thousand Smokes

in Alaska; third, the deposits formed by sedimentation; and fourth, those in which the concentration was effected by weathering.

Iron-ore bodies formed by concentration within molten magmas are rare. Probably the best-established examples, whose mechanism of concentration can most readily be visualized, are in the Bushveld, Union of South Africa. They are inclosed in gabbro as layers of magnetite resembling strata; they are as much as 15 feet thick and extend for hundreds of miles. At a certain stage while the gabbro magma was solidifying, the magnetite began to separate out, and, being heavier than the magma, the grains sank and accumulated in the form of a layer.

In some districts part of the iron of the magma escaped at the time the magma was solidifying, and, if the magma was intrusive into limestones, the iron-bearing emanations reacted with these limestones. In this way ore bodies of contact-metamorphic origin were formed, as outlined on page 266. If the emanations do not meet limestone, they are likely to migrate farther from the magmatic hearth; and, as they move into an environment that is becoming progressively cooler as they travel away from the magma, they form iron-ore deposits of successively different types, which are distinguished by the fact that they were formed at progressively lower temperatures and consequently carry distinctive minerals that indicate the lower temperature conditions under which they were formed. The iron ores of contact-metamorphic origin contain garnet, which is a mineral that is formed only at high temperatures. The iron ores formed at lower temperatures do not contain garnet, but contain other index minerals.

The iron deposits of Lorraine in France are the world's most valuable iron ores of sedimentary origin. They consist of oölitic limonite in nearly horizontal beds interstratified with limestone, shale, and sandstone. Although nearly horizontal, they dip westward at a very low angle. They average 30 per cent of iron — a relatively low content; but because they contain sufficient calcite to form a slag in the furnace (they are "self-fluxing," in technical language), are near supplies of coking coal and also near consuming centers, they are of great commercial value. They contain nearly 2 per cent of phosphorus, ordinarily a highly undesirable impurity in an iron ore; but as a result of the development of the Thomas process of smelting in 1879, the phosphorus is eliminated in the form of a by-product valuable as fertilizer.

In virtue of this sedimentary origin the ore bodies are of large areal extent and of constant composition; consequently the tonnage of ore can be estimated with far higher probability than can be done for ore deposits of any other mode of origin. The reserves are estimated to contain 5000 million tons of ore.

In eastern Cuba are large iron-ore deposits, in which the iron has been concentrated to commercial grade by the chemical weathering of serpentine. The ore occurs on a plateau as a blanket 20 feet thick. In the cuts made by mining with steam-shovels the ore at the surface can be seen to grade downward into the unaltered serpentine from which it was derived. The serpentine contains only 7 per cent of iron; but chemical weathering, by dissolving out almost all the constituents of the serpentine except the iron, has raised the iron content of the residual product to 50 per cent. Iron ores of this kind occur also in Celebes and the Philippines.

In the Lake Superior region, from which the United States obtains 85 per cent of its supply of iron ore, the ore deposits are the results of a double concentration. First there was laid down by sedimentation an "iron formation," consisting of thinly bedded strata of iron-bearing minerals alternating with siliceous strata. In the Mesabi district, Minnesota, which is the most productive iron district in the world, this iron formation averages 25 per cent in content of iron. This is too low in grade to be worked as ore. Fortunately, parts of the iron formation were reconcentrated by weathering, by which the gangue was dissolved and carried away, and the iron minerals, because of their insolubility, were left behind. As a result of this purification the residual product contains 50 to 60 per cent of iron and is therefore valuable ore. This weathering took place not under present conditions of climate and topography but under those of remote geologic antiquity.

In conclusion, then, many diverse geologic processes of concentration have been effective in assembling iron into ore deposits of commercial value. Some of these deposits required a twofold concentration before they became of workable grade, first by sedimentation and second by weathering.

Gold and Other Metal Deposits. The primary ore deposits of gold and of the industrial metals copper, tin, lead, and zinc, unlike those of iron, occur mainly as veins and lodes of hydrothermal origin. Most of these deposits are in the borders of stocks and batholiths of granite or in the rocks in contact with these intrusive masses. The gold lodes hold the distinction of having been followed deeper into the crust than deposits of any other metal, depths of more than a mile having been reached in California and India, 8000 feet in Brazil, and 9000 feet in South Africa.

PLACERS

General Features. A *placer* is a deposit of sand or gravel containing particles of a valuable mineral in sufficient quantity to be workable at a profit. Gold, tin (in the form of its oxide, cassiterite), platinum,

and diamond are the substances commonly won from placers. Most placers are stream gravels. A few, however, are marine beach gravels, such as the famous gold placers of Nome, Alaska, one of which was the present beach of the Bering Sea, and the others were ancient beaches, formed when the Bering Sea had outlines somewhat different from those it has now.

Placers are so easily found and so readily worked without special equipment or capital that they have been sought from the beginning of history by the prospector and explorer. Gold placers have been the strongest incentive to this search, and most of our mining districts have been found by the placer miner. The richer placers are soon worked out, and attention then is directed to finding the bedrock sources from which the minerals in the placers were derived. If these sources prove to be deposits of economic size, they form the basis for a much more permanent industry; and the ephemeral placer-mining camp becomes transformed into the more staid lode-mining district.

Great ingenuity has been applied to the problem of working the leaner placers. The more advanced methods of placer mining—*hydraulicking* and *dredging*—represent the most efficient forms of mining, in the sense that lower-grade material can be worked by them than by any other method. In hydraulic mining a jet of water under heavy pressure is directed against a bank of gravel and the gravel thus loosened is swept by a current of water into a long sluice (Fig. 270); the gold, platinum, or cassiterite, because of its high specific gravity, rapidly settles to the bottom and is caught by appropriate devices at the head of the sluice, and the lighter material—the gravel and sand—is carried through the sluice. In thus concentrating the gold or other valuable material, the miner, using nature's own method, has completed the concentration begun by nature in forming the placer. In California, where hydraulic mining has reached its highest development, gravel containing as little as 3 cents in gold to the cubic yard has been profitably worked.

In dredging, the digging apparatus and the entire concentrating plant are contained on a boat—the dredge (Fig. 271). The dredge floats on a pond; it digs and takes in the gravel at its forward end, and at the rear discharges the tailings—the gravel from which the gold, platinum, or cassiterite has been separated. Thus the pond and the dredge on it gradually travel up the valley. Gold-bearing gravel containing as little as 10 cents in gold to the cubic yard can be worked at a profit by dredging.

Origin of Placers. As soon as the primary ore bodies come into the zone of erosion they are attacked by weathering. If they contain

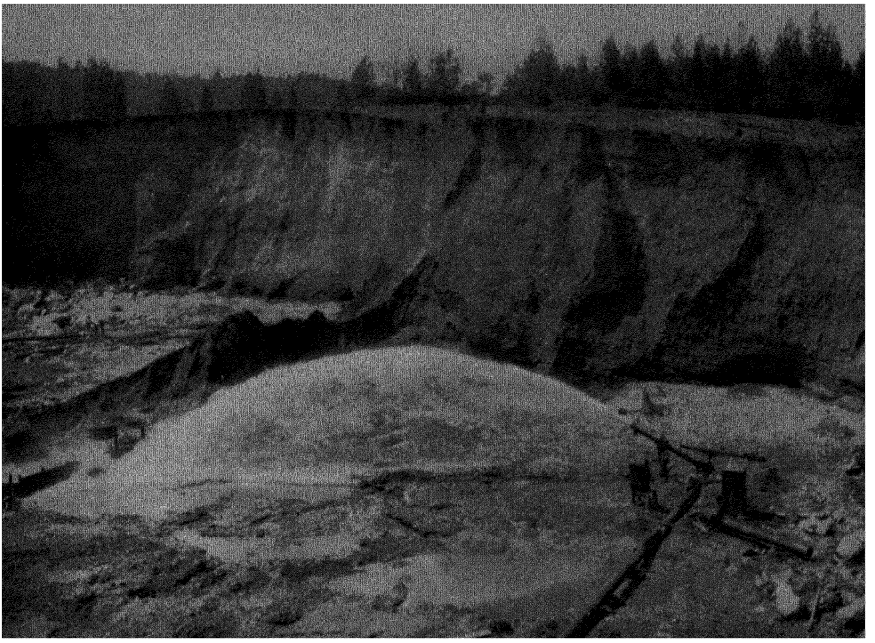
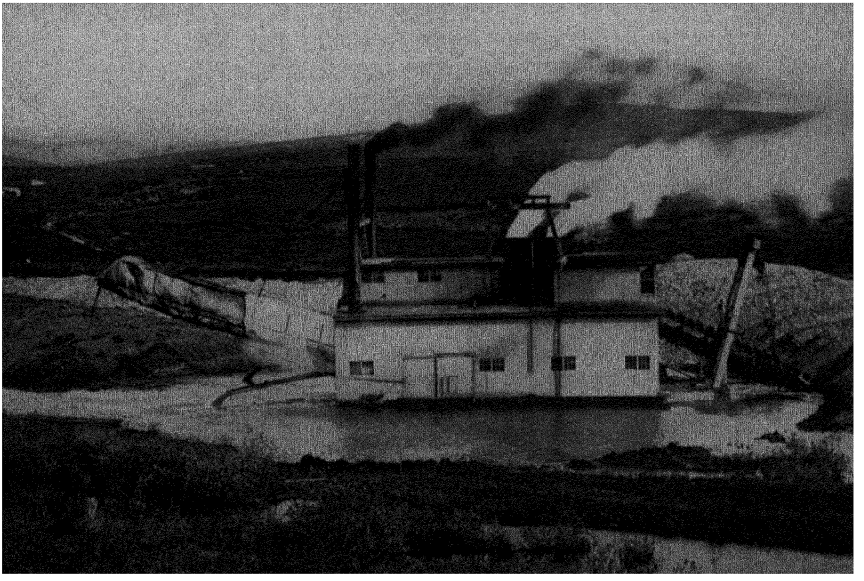


Fig. 270. Hydraulic mining in the Sierra Nevada, California. At the time the picture was taken, the gold-bearing gravel was being swept by a jet of water into the head of the string of sluice boxes shown at the extreme left. [G. K. GILBERT, U. S. GEOL. SURVEY.] *Fig. 271. Dredge at work on gold-bearing gravel. Seward Peninsula, Alaska.* [P. S. SMITH, U. S. GEOL. SURVEY.]



sulphides, they are subject to a peculiarly active form of chemical weathering intensified by the sulphuric acid and other powerful solvents formed by the oxidation of pyrite and other sulphides. Only the most resistant minerals survive this attack. After being set free from their matrix they eventually find their way by creep and rainwash into the streams. Only the tougher minerals withstand the pounding and abrasion to which they are subjected in the streams; the brittle minerals are pounded to minute particles and are swept downstream. The valuable minerals in placers represent survivals of the fittest, where fitness is measured by resistance to chemical attack and to abrasion. Hence it is easy to understand why the minerals commonly won from placers are such indestructible substances as gold, platinum, cassiterite, and diamond.

The gold and other valuable minerals occur in particles ranging from the tiniest grains (flour gold) up to larger pieces termed *nuggets*. According to the distance that these particles were carried downstream from their source in bedrock, they are more or less water worn. Angular, jagged, "rough" gold occurs in placers near where it has been set free; smooth gold is found farther downstream. It is somewhat surprising, however, to see within how short a distance from their bedrock sources gold particles become smoothly water worn. This is due partly to the softness of gold and partly to its great weight, which causes the grains and nuggets to move downstream slowly, with many a halt; and during their slow progress downstream they are pounded and abraded by the passing gravel.

The lowermost few feet of gravel, those resting on bedrock, are much richer in gold than the upper layers of gravel. As the miner puts it, the "paystreak" rests on bedrock. The concentration of gold on bedrock is the result in part of the churning action of streams during high-water stages. The gravel is locally scoured out to great depths during these stages (p. 76), and whatever gold was distributed through the scoured-out mass of gravel becomes concentrated in the bottom of the channel thus formed; and as high water subsides, the scour channel becomes filled with barren gravel. Another method of concentration that causes the gold to move toward bedrock is that resulting from the downstream migration of the meander belt (p. 89).

It can be seen that a knowledge of the laws governing the transport of debris by streams and the laws of the origin of land forms is fundamental to an understanding of the formation of placers. In a region in the early stages of the cycle of erosion the streams are so actively engaged in downcutting that no gravels are laid down in their channels more than temporarily; hence such regions are unfavorable

for the occurrence of placers. As a matter of experience it has been found that regions of uplifted and maturely dissected peneplanes are favorable for the development of gold placers. During the peneplane stage the gold is liberated from the veins and veinlets distributed throughout the region, and after the region is uplifted and the new cycle of erosion is well under way the gold becomes concentrated in the stream gravels of the valleys carved in the old peneplane.

Placer deposits have formed at all times during the history of the Earth. Some of the older placers have been buried by later sedimentary rocks; others have been sealed beneath lavas that flowed down the old valleys in which the gravels were accumulating. In regions in which placers were covered by flows of lava, the streams that formed the placers became dispossessed of their channels and sought new ones. In the course of time a complete revolution in the topography was

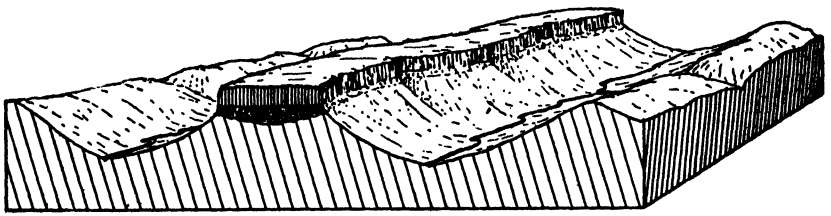


FIG. 272. Ancient stream placer covered by lava flow; occupies the divide between two rivers of the present drainage system. Width of block about 3 miles.

effected, and the placers capped by the resistant lava flows became the divides between the existing streams. What were once the valley bottoms are now the mountain tops (Fig. 272). Such dead rivers, whose gravels are sealed under lava flows, occur high above the present streams in various parts of the world, notably in the Sierra Nevada, where they have yielded much gold.

Although the finding of placers has generally been the prelude to the discovery of veins and lodes in bedrock, it by no means follows that rich placers are necessarily derived from rich deposits in bedrock. Almost the contrary is true. For example, much of the world's platinum has been won from placers in the Ural Mountains, but no workable primary deposits have been found. The platinum in its bedrock sources in those mountains is disseminated through large bodies of rock, which are far too lean to work at a profit. The processes of forming placers are so thorough, however, that the small quantity of platinum distributed through immense volumes of rock has become concentrated in the gravels of the streams that flow out from the mountains. Cubic miles of rock were ground up by erosion, and the platinum in them

has accumulated in commercially valuable amount in the gravels of the stream beds. Similarly, rich gold-bearing gravels have accumulated in many of the world's gold placer districts in which the gold occurs in its bedrock source in gold-bearing quartz veinlets, each individually too small and too widely scattered to be profitably workable. The same disparity between the richness of the placers and the poverty of the bedrock sources is even more generally true of tin deposits and is reflected in the fact that 70 per cent of the world's annual supply of tin is still won from placers. In forming placers, erosion does an extraordinarily efficient job of concentration.

Summary

A mineral deposit of economic value is a concentrated accumulation of substance that originally was thinly distributed through one of the envelopes of the Earth. A coal bed is made up of carbon that was concentrated by the photosynthetic power of plants from the carbon dioxide thinly diffused throughout the atmosphere; an oil pool is an accumulation of petroleum generated from carbonaceous matter thinly scattered through certain sedimentary beds; an iron-ore deposit is an amassment of iron that was disseminated through the Earth's crust. The problem of the origin of valuable mineral deposits is in essence, then, the problem of how the thinly distributed material was assembled in concentrated form. Most of the major geologic processes — igneous activity, sedimentation, weathering, and stream transport — have under favorable circumstances brought about important concentrations of minerals. Many valuable deposits are the results of a single concentration; but some, like the Lake Superior iron deposits, required a two-fold concentration to make them of economic value; and a few, like the extraordinarily rich gold placers of the Sierra Nevada in California, required a triple concentration.

Practically, mineral deposits are classified according to the substance that gives them predominant value, *e.g., copper deposit,* or *garnet deposit;* if two substances determine their value, both are named, as for example, *silver-lead deposit.* The variety of mineral deposits is so great and the ways in which they were formed are so many that a classification based on mode of origin — a genetic classification — which is comprehensive and at the same time simple, is impossible.

A classification not too detailed is:

I. Magmatic deposits, formed by the solidification of molten rock-matter; are not very abundant.

II. Deposits formed by fluids (gases and hydrothermal solutions) emanating from intrusive igneous masses.
    1. Formed at high temperature.
    2. Formed at intermediate temperature.
    3. Formed at low temperature.

III. Deposits formed by subsurface water derived from the Earth's surface.

IV. Sedimentary deposits.
    1. Chemical deposits, *e.g.*, marine iron ores, phosphate rock.
    2. Detrital deposits (placers).

Chapter 17

GEOLOGY AND ENGINEERING

The use of geology in coal and metal mining long ago was recognized as essential. Somewhat later its value in discovering artesian and other underground supplies of water became accepted. At the beginning of the present century its power in finding oil fields and in locating oil wells began to be realized and is now fully appreciated. In fact, the greatest success in the commercial application of geology, as measured in dollars and cents, has been the ever-increasing discovery of new oil fields in every quarter of the globe. Only in recent years, however, has the necessity of geologic examination in advance of construction in great civil-engineering enterprises become widely accepted. It is true that the necessity had long been recognized in principle, but the principle seems to have been more honored in the breach than in the observance. Exceptions of course can be cited, notably that of the Catskill water supply system of New York City, where close co-operation between engineers and geologists was maintained during the entire time of planning and construction, from 1905 to 1917. However, the fact remains that in the United States since 1928 the use of geology has greatly increased in one phase of engineering construction, namely the building of dams. In that year the St. Francis dam in southern California failed, with catastrophic results. It transpired that the dam had been built in complete ignorance of the unfavorable geologic conditions at the site. After this disaster, few important dams have been constructed without adequate geologic examination and approval of the proposed sites.

Engineering Structures and Faults. The most elementary understanding of geology should make apparent that it is unwise to build engineering structures across faults. Aqueducts, tunnels, bridges, and municipal water mains, upon which a city may depend for protection against fire, should not be built on or across faults. Every fault, unless evidence to the contrary is available, is a zone of weakness and is a potential hazard. Although this principle is almost self-evident, it is often unconsciously violated; perhaps the most astonishing example of its violation is a great football stadium that was built without consultation with the geology department of the University, and extends across a well-known active fault.

Sometimes it can be shown that certain faults are inactive and are therefore no longer dangerous. A case in point is a fault near the Boulder Dam, in the Black Canyon of the Colorado River (Fig. 273). Faults are exposed in the walls of the canyon, and it was therefore imperative to determine, before the site for the dam was finally chosen, whether these faults were active or inactive. Expert examination showed that the river formerly flowed at a much higher level and had worn potholes and smooth channels into the hard rocks. This evidence of the work of the river occurs on the brink of the Canyon 900 feet above the present water level. Some of the smooth channels extend across a fault, without dislocation. The evidence is therefore convincing that no movement on this fault has taken place during the long time (humanly considered) required by the river to cut its canyon 900 feet deep. The stability of the dam site was therefore assured.

TOURIST SERVICE BUREAU, BOULDER CITY, NEVADA.

Fig. 273. Preliminary work at Boulder Dam, Colorado River, in 1933. A deposit of sand and gravel, 130 feet thick, was removed before the bedrock floor of the river was reached. At bottom is shown the "inner goree." A trench cut into the broad bedrock floor of the river.



In many places, however, practical considerations make it impossible to avoid active faults. No engineering structure standing across a fault can be built strong enough to withstand being sliced in two when movement along the fault occurs. Provision is therefore made, or should be made, to minimize the damage that will be done when the movement inevitably takes place. Such foresight was shown, for example, during the construction of the Los Angeles aqueduct in southern Owens Valley, California. For a number of miles the aqueduct zigzags across a fault along which a large displacement occurred at the time of the earthquake of 1872. In all probability movement will again take place on the fault. Therefore a storage reservoir was built between the city and the danger spot, so that, while the damage that will be done to the aqueduct is being repaired, the city can draw water from storage.

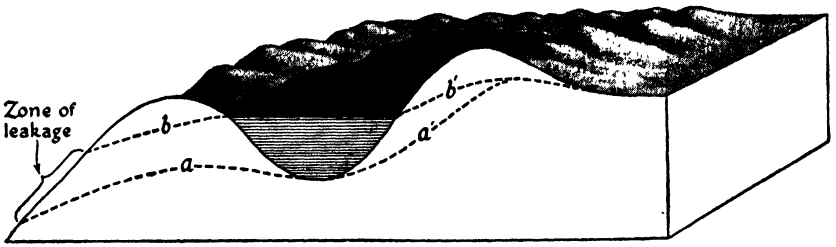
Geology of Reservoirs and Dams. A reservoir, in the engineering sense, is ordinarily a basin in which water is stored behind a dam in order to maintain a water supply for human consumption, or for generating power, or for irrigation, or for flood control. The dam used to hold the water in the storage basin must be a structure that is practically impermeable and that is strong enough to resist the pressure of the water impounded behind it.

In selecting a site for a reservoir it is essential to have a flow of water that can be backed up by a dam, and a natural basin large enough to hold the necessary amount of water and tight enough to prevent the water from leaking away in any considerable amount. Under ideal conditions the basin has an outlet that is narrow enough for a relatively small dam to hold back the water, and the floor of this outlet is in rock firm enough to afford a secure foundation. Unfortunately, such ideal conditions do not commonly exist at the outlets of otherwise highly favorable reservoir basins. In many instances, for example the Fort Peck dam built across the Missouri River in Montana, the conditions for a reservoir basin, except at the outlet, are otherwise favorable and the need for the storage of water supposedly so great that large and costly dams have been constructed.

One of the most important questions that arise in selecting a reservoir site is "Will the basin leak to an extent to make storage of water impracticable?"

A certain amount of water escapes through the bottom and sides of all reservoirs, even through small concrete-lined basins. In regions where the water table is high, a reservoir that occupies a stream valley cut below the water table will have its supply augmented by an inward flow of water. Leakage, however, may take place where the reservoir

basin is separated from a lateral tributary valley by a narrow ridge in which the water table stands lower than the level of the water in the reservoir (Fig. 274). If the intervening ridge in such a place is composed of permeable material, such as basalt, cavernous limestone, or coarse boulder beds, the leakage will be large enough to constitute a problem; such a problem can be predicted from a study of the local geology. In basalt the rate of leakage will not change, whereas in the more readily soluble limestone and in easily soluble material such as rock salt or gypsum the rate of leakage will increase. Therefore



Modified from Kirk Bryan.

FIG. 274. Zone of leakage developed as result of the rise of the water table on filling the reservoir; *aa'* shows position of the water table before filling of the reservoir; *bb'* after filling.

the geologic materials underlying the area that will be flooded by a reservoir are of first importance in determining the availability of the proposed site.

A low water table under a large area indicates that the rocks present are permeable or contain large openings. Such a condition naturally makes for much leakage and has in fact led to the abandonment of some reservoirs in the western part of the United States. Reservoirs can be established in distinctly permeable material only if the accumulated water can gradually saturate the underlying and surrounding ground so that the water table is actually raised. If the ground is not too permeable, this saturation will be attained after some years and the reservoir will then fulfill its function.

One factor of stream erosion can have both an advantageous and a disadvantageous influence upon reservoirs. A stream entering a body of standing water eventually deposits its load of sediment. If the stream entering a reservoir is draining a region of rocks so easily disintegrated that the water is heavily laden with sediment, the eventual silting up of the reservoir will bring the life of the storage basin to an untimely end. If, on the other hand, a stream carrying a considerable amount of silt enters a reservoir surrounded by permeable or fissured

rocks in which the openings are not too large, the silt carried into the surrounding walls may seal up the pores or fissures within a few years and prevent further leakage.

In order to be a successul structure a dam must rest upon a secure foundation without possibility of slippage, and its ends must be tied in to the side walls of the reservoir outlet in such a way that leakage through the walls can not undermine the dam. The security of the foundation depends on the strength of the underlying rock in relation to the load placed on it by the dam; upon the water-tight nature of the underlying material, whether permeable or relatively impermeable; or whether firm rock or unconsolidated material. A dam built of hard material, such as concrete, should be built upon a sound rock foundation. This requirement necessitates cutting through the alluvium on the valley floor until fresh, unweathered bedrock is reached. Therefore one prediction generally demanded by the engineer is "What is the depth to bedrock?," a question whose answer requires expert examination, and whose accurate quantitative answer always requires a series of test drillings. Only where rock ledges in place are visible at close intervals in the stream is it reasonably safe to predict that bedrock is at slight depth. If the stream is flowing on glacial or alluvial material, the likelihood that a buried channel is present makes reliable predictions about depth to bedrock absolutely impossible; numerous, closely spaced test borings are necessary for accurate information. Two notable illustrations are afforded by the Storm King crossing of the Catskill aqueduct (Fig. 277), and by the disaster to the Lötschberg railway tunnel in Switzerland (p. 354).

Dams built upon a narrow base require greater strength of foundation than wide-base dams, because the load upon a narrow base is concentrated over a relatively small area, whereas the load on a wide base, such as that of an earth dam, is widely distributed and is therefore smaller per square foot. For this reason earth dams are preferred where the foundation is soft or permeable. Rocks that are poorly consolidated or are cemented with soluble material are likely to disintegrate completely after being acted on by water for some time. Such rocks can be warned against by the geologist, but the comparison of different kinds of hard-rock foundation, for example, the relative strength of gabbro compared with granite, is a matter that can be determined by engineers and is therefore not within the province of the geologist.

On the other hand, both texture and structure of foundation rocks are important in the construction of dams and can be determined by geologic examination. Clay-filled seams along bedding planes and

joints are potential causes of the failure of dams by slippage along the wetted clay surfaces. Therefore joints and bedding planes should be examined in order to find out whether they are sealed with mineral matter, or with sediment carried into them by the stream, or whether they are open, in which contingency the engineer should seal them with a thin cement mixture forced in under high pressure.

Faults, being an actual or potential source of weakness, should always be avoided, if possible, and if, as is becoming increasingly necessary on account of the gradual exhaustion of more favorable dam sites, a fault zone must be crossed, the consequent hazard should be emphasized, so that all requisite precautions can be taken in constructing the dam.

Horizontally bedded limestone traversed by numerous fractures is an undesirable foundation for a dam. This is illustrated, for example, by the history of the Austin Dam over the Colorado River in Texas; in 1900 the dam failed during a heavy flood, and great difficulties were encountered in reconstructing it because of the essentially unfavorable geologic conditions of the site, which was along a fault and in limestone with horizontal bedding planes along which the solvent action of the water is likely to undermine the foundation of the dam. Although dams have been successfully constructed upon limestone, nevertheless because of its solubility and tendency to contain channel-ways and caverns, limestone should always be regarded with circumspection in all engineering construction.

The material upon which the ends of the dam abut should have, in general, the same qualifications that are required for the foundation rock. Possible leakage is a serious problem, particularly if the ends of the dam are tied to ridges that are not much wider than the dam, because a narrow ridge is more likely to be undermined by the effects of leakage that is a wide abutment. Therefore if the ends of a dam abut on unconsolidated material, the abutment area should be wide. The same principles that governed the selection of a suitable reservoir site apply to the problem of leakage in the material that supports the ends of the dam. However, the area with which a dam is connected is so much smaller than the area surrounding the reservoir that it may be feasible to construct an impermeable blanket to make a water-tight connection between dam and abutment area. This is an engineering problem, but the engineer should be amply forewarned where the material adjoining the dam is subject to leakage or slippage.

Tunnels are used in connection with dams, as spillways to carry off the excess or flood water instead of allowing it to pour over the lip of the dam; as outlet tunnels to conduct water from the reservoir for use; or as by-pass tunnels, such as were used at Boulder Dam to divert the



SPENCE AIR PHOTOS.

Fig. 275. St. Francis Dam, California, 1928, after it had failed The central portion of the dam, on firmer foundation, remained standing in place. Huge blocks of concrete from the broken dam are scattered downstream over the valley floor.

stream during the construction of the dam. The problems that may arise in connection with these tunnels require the same sort of geological investigation that is necessary for tunnel projects of any other kind.

Failure of the St. Francis Dam. The St. Francis Dam was built to impound the waters of San Francisquito Creek, 45 miles northwest of Los Angeles. It was 700 feet long and 205 feet high. One end of it rested on a conglomerate, which when dry is a fairly firm rock but when wet loses all its cohesion and crumbles to pieces. It is amazing that while the dam was being built this fatal property of the foundation rock was not discovered. Moreover, the conglomerate contains many small veins of gypsum, an easily soluble mineral, which would therefore tend to be dissolved and thus further weaken the foundation.

The reservoir was completed on May 4, 1926, and first became full on March 5, 1928; a week later the dam failed (Fig. 275). The con-

crete cracked, and huge blocks weighing as much as 10,000 tons were swept down the canyon for half a mile. Hundreds of lives were blotted out, and great property damage was done. Investigation by a commission appointed by the governor of California showed that the failure of the dam was the result of defective geologic foundations.

The disastrous failure of the St. Francis dam demonstrated beyond argument that the location and construction of dams in settled communities are matters of public concern. Some measure of public control is therefore imperative, and expert geologic examination is an indispensable prerequisite where the failure of the dam would endanger human life and welfare.

Tunnels. Geologic study along the line of a proposed tunnel should show what rocks will be encountered and what their structure is; it should show the faults, if present, and the likelihood of inflow of water into the tunnel. All these are factors in determining the cost of con-

Fig. 276. Buried gorge exposed through operations in 1909 for the New York City water supply. Esopus Creek, 10 miles west of Kingston, New York.



struction and the length of time necessary to drive the tunnel. Inflow of gas (carbon dioxide, hydrogen sulphide, methane) and high temperature are other factors, but are not readily predictable.

A matter of great concern to engineers is the possibility of running into a buried gorge while driving a tunnel (Fig. 276). The disastrous consequences that may ensue are well illustrated by the famous example of the Lötschberg tunnel in the Swiss Alps. The tunnel had advanced 8750 feet in limestone and was under the Kander River at a depth of 600 feet. On July 24, 1908, a great mass of water-saturated stream sand and gravel suddenly broke into the tunnel, killed 26 men, and in the space of 10 or 15 minutes filled up 6000 feet of the tunnel. Unexpectedly, the tunnel had run into the old, buried valley of the Kander, now filled with sand and gravel (Fig. 277). Because of this mischance

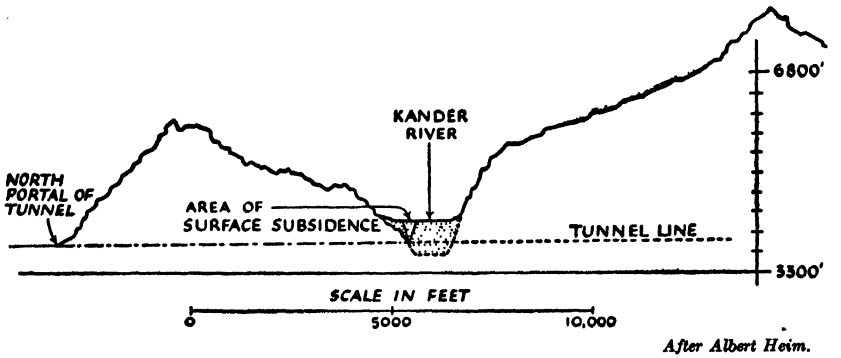


FIG. 277. Section through the Lötschberg tunnel, Switzerland, showing the great thickness of gravel and sand unexpectedly cut below the valley of the Kander River.

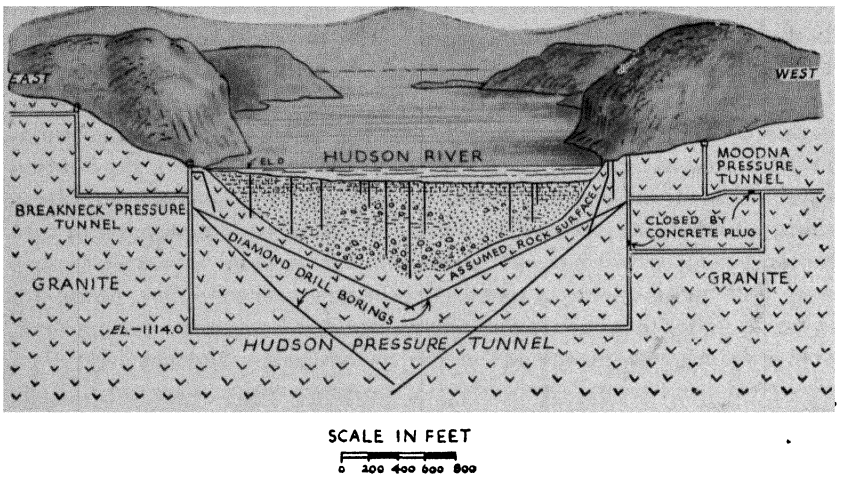
the course of the tunnel had to be changed in order to avoid driving through the water-logged mass of sand and gravel, and the length of the tunnel, instead of being 8.5 miles as originally planned, had to be increased to 9.04 miles.

In the preliminary examination of the proposed line of the tunnel it had been estimated that the loose material in the valley of the Kander had a maximum thickness of 230 feet and that the tunnel would have more than 300 feet of solid rock over it. The estimate of the thickness of the detrital filling, which could not have been more than a guess, should have been checked by borings. This example, as well as many others that might be cited, completely justify the demand of engineers for quantitative data in matters of this kind. The great thickness of the gravel filling in the upper valley of the Kander River is the result of a combination of extraordinary circumstances. At some time after the recession of the glacier that formerly flowed down the Kander, an

enormous rock slide tumbled down from the precipitous east wall of the valley and extended across the valley. Behind the great barrier thus formed, the river then deposited its sands and gravels to a thickness exceeding 600 feet.

Catskill Aqueduct of the New York City Water-Supply System. One of the great engineering projects in recent decades was the construction of the Catskill Aqueduct. The aqueduct is 105 miles long and brings water from the Catskill Mountains, on the west side of the Hudson River, to New York City on the east side of the river. Before construction was begun, the geologic conditions along the right-of-way were carefully determined and at all critical places were verified by borings and other exploratory work. The choice of a site for crossing the Hudson River gave special concern, since a tunnel under the bed of the river was necessary and the water in the tunnel would be under high pressure. Three sites were practicable from an engineering standpoint. That at Storm King at the upper end of the gorge of the Hudson was indicated as being the most satisfactory from geologic considerations. The major factor in favor of the Storm King crossing was that no large fault would have to be crossed. Additional favorable factors were that no limestone (a rock that because of its solubility, especially in water under pressure, is liable to cause leaks) would be encountered, and a strong granite extends across the Hudson. Borings were then put down from barges in the river in order to verify these conclusions and to obtain precise data on the depth to bedrock. Great difficulties were met in this work, for the gorge was found to be filled with coarse bouldery material, and at midstream, although a hole was put down to a depth of 765 feet, bedrock was not reached. Explorations were then carried on from both sides of the gorge by means of diamond-drill borings (Fig. 278), and these borings showed that, as anticipated, the granite extends continuously across the gorge. The great depth to bedrock, far below sealevel, had not been expected, however, for only 10 miles north the depth is 200 to 300 feet and at New York to the south it is only about 300 feet. The great depth of the gorge at Storm King is evidently a local effect of glacial erosion. The ice stream that formerly flowed down the Hudson became constricted on entering the narrow gorge at Storm King, its velocity therefore increased, and consequently its power to erode its floor increased, so that it deepened its channel greatly below sealevel. The bedrock configuration of the gorge having been established by the exploratory work, the tunnel, 14 feet in diameter, was driven, and was given a cover of not less than 150 feet of sound rock. As a result, the Hudson River pressure tunnel crosses under the river at a depth of 1100 feet below sealevel.

From the foregoing account of the Storm King crossing, it will be seen that the glaciated condition of the region was the cause of major geologic and engineering difficulties. In other places along the route the regional glaciation caused further difficulty. As the plan of construction of the aqueduct contemplated carrying the tunnel in solid rock in many places, the possibility of encountering old gravel-filled gorges buried beneath the soil was an ever-threatening danger. In areas covered by glacial drift borings were therefore necessary to obtain information about the bedrock floor. In the Moodna Valley west



After C. P. Berkey.

FIG. 278. Cross-section of Hudson pressure tunnel, Storm King to Breakneck Mountain, New York. Gorge of Hudson River as viewed from the north.

of the Storm King Crossing, the cover of drift was found to be as much as 300 feet thick for a considerable distance; moreover, it contained unusually large boulders, which made the exploratory work difficult and expensive. One of the borings went through a 34-foot boulder, which was imbedded in the drift 100 feet above the bedrock floor. Without an acute appreciation of the geologic conditions, most engineers would have stopped drilling long before the boring had penetrated through a boulder 34 feet in diameter.

Military Engineering.[1] During the First World War the British, German, and American armies employed geologic staffs. By the end of the war in 1918 the American Expeditionary Force in France had a

[1] Based on the able account, "The Use of Geology on the Western Front" (U. S. Geological Survey Professional Paper 128, pp. 85–124, 1920), by Lieut.-Col. Alfred H. Brooks, chief geologist of the American Expeditionary Force.

total of nine geologic officers, and the German Army had about 100 geologists engaged on military problems on the western front. The science was not utilized to its full possibilities, however, chiefly because of lack of adequate conception by most of the higher commanding officers that geology might be applied to military problems. Yet the problems encountered were many and of widely diverse kinds. Moreover, many were such that hardly more than an elementary knowledge of geology would have sufficed to solve them.

Examples are easy to cite. Troops were ordered during the battle of Verdun to intrench themselves on the high plateau of the Côtes de Meuse. As might have been seen by a glance at the geologic map, however, the plateau was underlain by hard limestone covered by less than a foot of soil. To intrench with the light tools furnished was impossible, and even with proper equipment would have been impossible in the time available. Consequently, many lives were needlessly sacrificed.

In order to obtain protection against the heaviest artillery used during the First World War (420-millimeter guns), 48 feet of compact earth or 24 feet of hard rock were required. Cave shelters had therefore to be excavated to a depth of 30 feet to give adequate overhead cover of rock. Consequently in determining where such cave shelters, or dugouts as they were called, should be excavated, the position of the water table was of paramount importance: it had to be at a depth greater than 30 feet in order that the dugout would be a shelter instead of a well. Water-bearing strata also had to be avoided. Ignorance of these facts accounted for many failures in constructing shelter caves.

Mine warfare, in which tunnels or "attack galleries" are driven under the enemy's positions, was employed on an unprecedented scale. In these operations it was vitally important to have detailed information on the underground geologic conditions — the character of the material to be excavated, the depth of ground water or of water-bearing strata — and in this field military geology rendered its greatest service.

Another field of importance was that of locating supplies of ground water. The amount of water required for a large modern army is generally far in excess of the available civilian supply. Base camps, hospitals, aviation fields, and other military establishments must have adequate supplies. To obtain these many wells were drilled, but often with cheerful disregard of underground conditions. In the British Expeditionary Force, however, no well drilling was permitted without the approval of the chief geologist.

Some of the many applications of geology to military operations have been briefly indicated in the preceding paragraphs. A skilful

commander utilizes the advantages of the terrain, but to take full advantage of the terrain requires the use of geology. To develop an understanding and appreciation of this fact should be a part of military education.

Conclusion. The application of geologic principles to some of the manifold problems arising during engineering enterprises have been outlined in this chapter. Many fields, such as highway, railroad, and canal construction, river control, and coastal protection against inroads by the sea, have for lack of space not been considered. Such matters apparently so remote from human affairs as the rate and direction of tilting of the land in the Great Lakes region have been brought before the Supreme Court of the United States, in connection with the right of the city of Chicago to divert the water of Lake Michigan through the Chicago Drainage Canal. It can not be expected that engineers, public administrators, and others be proficient in geology as well as in their own fields. It is enough that they have a conception that this knowledge exists and that they will know when it is necessary to turn to expert guidance.

CHAPTER 18

HISTORY THE CENTRAL THEME OF GEOLOGY

Against the background of information and explanation set forth in the foregoing chapters, let us imagine that someone attempts to describe geologic features merely as they appear to the eye, without any mention of clues to their origin. He begins with a section of stratified rocks, in which there are layers of cross-bedded conglomerate

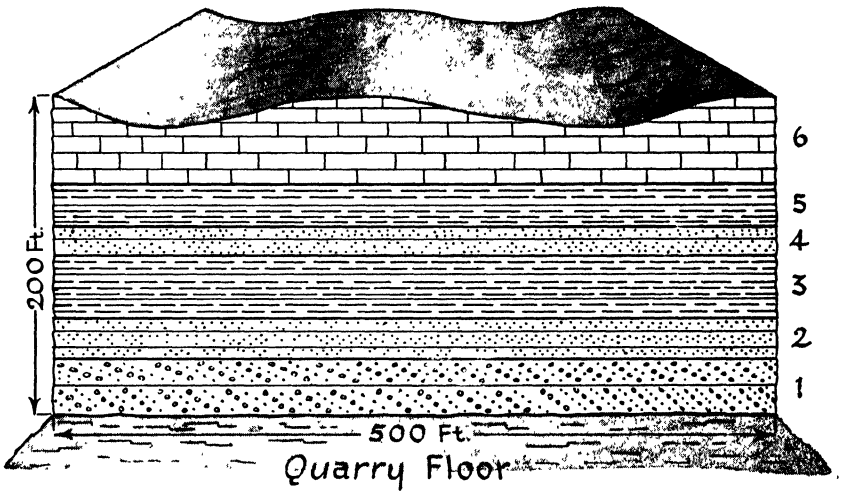


FIG. 279. Section of horizontal sedimentary strata exposed in a quarry face. From bottom to top these beds are: 1, cross-bedded conglomerate containing well-rounded pebbles; 2, sandstone, cross-bedded and ripple marked; 3, mudstone with mud cracks and animal tracks, containing fossil leaves and logs; 4, sandstone containing fossil clam shells and lobster claws; 5, shale with fossil clam shells and fishes; 6, limestone with several kinds of marine fossils.

containing well-rounded pebbles made of quartzite, granite, and other kinds of rock material (Fig. 279). Above the conglomerate lie, in successive order, layers of sandstone with cross-bedded structure (Fig. 161, p. 201) and with asymmetric ripple marks on their surfaces (Fig. 159, p. 200); mudstone marked with patterns of mud cracks (Fig. 158, p. 198) and with tracks of animals, and containing leaf impressions and petrified logs; pebbly sandstone crowded with fragments of

clam shells and lobster claws; shale inclosing fossilized entire clam shells and impressions of fishes; limestone with many kinds of marine fossils.

How is it possible to give a fully satisfactory picture of these rocks that is purely descriptive and free from interpretation? Conceivably the pebbles in the conglomerate could be described as " rounded objects of various kinds and colors "; but it must be an unobservant person indeed who would not recognize at once their striking resemblance to the smooth pebbles common in stream channels and on beaches. If the description should speak of " pebbles " and " sand grains " as the constituents of the conglomerate and sandstone strata, the inference must follow that these strata were once layers of loose gravel and sand which in some way have been converted into firm rock. Similarly, exact descriptions of the cross-bedding and the ripple marks in the sandstone could hardly fail to suggest that currents of water had a part in depositing the sand. The mudstone presents an even stronger temptation to depart from bare description, because any intelligent person realizes that leaf impressions and petrified logs represent trees that once lived, and it is an obvious inference that the fine-grained rock in which they are imbedded was once soft mud — an interpretation that is greatly strengthened by the mud-crack patterns. When the higher layers in the section are reached, it is impossible to keep an accurate description free from implications of origin; the fossils of shellfish and other marine forms fairly shout that the sea once was there and that the beds of sandstone, shale, and limestone represent deposits on the former sea floor. Even a layman unacquainted with geology would sense that the section of strata is a book of history, and that any description of the rocks is without meaning unless it points out the features that speak eloquently of significant past events.

Physical Geology in Retrospect

Our study began with a statement that the primary object of geology is to decipher the history of the Earth as it is written in the rocks (p. 10). Equipment essential for reading the geologic record is there summarized briefly as (1) knowledge of rocks and minerals; (2) acquaintance with the gradational processes at the Earth's surface, and with the upbuilding forces within the Earth; (3) appreciation of the great magnitude of geologic time; (4) understanding of the uniformitarian doctrine; (5) ability to draw sound inferences from geologic evidence. This statement preceded the study of geologic features and principles, and therefore had to be taken on faith or accepted with reservations. Now that we have surveyed the major aspects of physi-

cal geology, it is well to view the entire subject briefly in retrospect, to insure that the various parts are set in proper relation to each other and to the division of geologic study still to be considered — historical geology.

Rocks and Minerals. Introductory study of geology considers the Earth as a new and unfamiliar body. Hence the logical first question must be, "What is the Earth made of?" The part that can be seen is made of rocks, which consist of minerals in various combinations. With the beginning of an attempt to classify the common rocks, we recognize that they can be understood only in terms of their genesis. This fact appears in the names assigned to the major groups: igneous (fire-made), sedimentary (pertaining to sediments), and metamorphic (changed, or made-over). To understand what we see in any rock we must learn as much as possible about its entire history. Thus the study of geology develops into historical research at the very outset. Every rock mass bristles with suggestive features that arouse within us the sleuthing instinct — a desire to connect and amplify tantalizing clues and thus develop a consecutive story. But for the moment we repress this tendency, and focus our attention on the physical characteristics of these materials in the visible part of the Earth. What part do they play in the changes now in progress at and near the Earth's surface?

Gradational Processes. The most obvious changes are being performed by gradational agents, which tend to destroy the lands and to spread out the waste products at lower altitudes. The rocks are broken up and changed chemically by weathering; great quantities of soluble matter are carried by water into the sea; the mantle of rock debris, constantly undergoing physical and chemical change, is being moved slowly seaward by mass-wasting, by running water, and by glacier ice; the moving debris is augmented by material abraded and quarried directly from bedrock through action of the transporting agents; waves and currents erode the shores, and distribute on the sea floor the debris received from all sources. All these activities can be observed, and they can be discussed merely as processes that operate at the present time. However, it is difficult to consider the gradational processes apart from the results they have achieved in the past, and indeed the processes themselves are much better understood in connection with those results. We watch a small stream digging a gully, shift our view to a much larger but otherwise similar gully that obviously represents prolonged stream erosion, then recognize successively older products of the same process in valleys that range in size from small ravines to the Grand Canyon (Fig. 238, p. 297). From the concept that streams have cut great valleys we progress to a realization

that widespread land surfaces are in various stages of reduction to baselevel by erosion (p. 89). When our attention is turned to glaciation, we no sooner recognize the grinding and depositing activities of valley glaciers than we perceive also the clear evidence that the same glaciers once extended miles farther down their valleys, and that ice sheets covered vast areas in North America and Europe (p. 148).

Processes of deposition are an even more effective key to past events. Bodies of sediment spread out by streams on floodplains and deltas, by waves and currents along the shore, and by glaciers in mountain valleys bear unmistakable evidence of conditions under which they came to rest (pp. 194–202). Identical features are recognized in old sedimentary strata: cross-bedding in conglomerates and sandstones betray the directions in which the depositing currents flowed (Fig. 161, p. 201); mud cracks and animal tracks in mudstones indicate withdrawal of flood water and exposure of mud flats to sunshine and air (Fig. 158, p. 198); fossils of animals and plants distinguish marine deposits from those laid down above sealevel; masses of unsorted boulders, gravel, sand, and clay, lying on polished and striated bedrock and associated with peculiar stratified deposits, speak eloquently of former glaciation (p. 138).

Thus the study of any gradational process leads us back step by step to the records of happenings in the recent and the more remote past. The present activities of erosion and deposition are only links in an endless chain of events.

The Upbuilding Forces. Volcanism is active in many parts of the world, and the importance of its role in building up land surfaces is attested by the great heights and diameters of many active cones (Fig. 175, p. 221). However, the volume of volcanic matter ejected in the span of written human history is insignificant in comparison with the vast piles of lava and ash built up during the geologic past. Mount Etna, which emits frequent destructive floods of lava, is little larger than it was when Rome was founded, and its origin dates far back into prehistoric time (p. 222). Many fine volcanic mountains — for example, Shasta and Rainier — are either extinct or have been long dormant; and some of the greatest accumulations of volcanic material, such as the Absaroka and Columbia plateaus (p. 296), are in regions that no longer have any volcanic activity. Products of volcanism are unmistakable, and they are recognized among rocks formed in all geologic periods. Study of igneous activity below the Earth's surface — the formation of dikes, sills, laccoliths, and batholiths — is of course based altogether on ancient records, since it is only by prolonged erosion that any of these intrusive bodies have been exposed to view.

Large-scale movements of the crust are almost entirely a matter of history. Numerous movements on faults have occurred within historic time (p. 259), and slow regional upwarpings have been detected by long-continued observations, as in Scandinavia (p. 259). However, these comparatively small disturbances have geologic interest chiefly because they prove that the forces responsible for crustal movements are still active, and because they indicate that some of these movements go on slowly and continuously, others by recurrent abrupt displacements separated by intervals of quiet. We see the cumulative effects in great mountain systems and plateaus, which bear on their lofty summits rocks made of deposits on ancient sea floors. By analogy with the characteristic structure of existing mountains, we recognize in belts of folded, faulted, and metamorphosed rocks now lying at low altitudes the "roots" of still older mountains that have been worn down by erosion. There is little wonder that geologists of an earlier generation, impressed by the evidence of intense deformation in mountain zones and by the magnitude of crustal uplifts, sought a cause in "catastrophes" for which there has been no parallel since the beginning of recorded human history. They viewed the stupendous results of a crustal revolution, and since they believed that the time available for all geologic changes has been brief — only a few thousands of years — their assumption of catastrophic forces was logical. Now we know that the full history of a great mountain system such as the Appalachians or the Rockies covered a vast span of time (pp. 305–311), and that the uplift need not have proceeded more rapidly than the slow crustal movements of which we have historic records.

Magnitude of Geologic Time. We are so accustomed to reckoning time in terms of days and years that our minds fail to grasp the immensity of time indicated by the record of changes on the Earth. However, a brief review of some evidence already cited will emphasize the great age of geologic features. Estimates based on the volume of lava erupted by Mount Etna during the last 2500 years give the age of this mighty volcano as about 300,000 years. Yet in a geologic sense Etna is a youthful cone, its form little modified by erosion. By contrast, many volcanic mountains that originally were comparable in size to Etna are in various stages of destruction by erosion, and others have disappeared except for central plugs that fill the ancient conduits to unknown depths (Fig. 189, p. 241). Complete leveling of a great volcanic cone must require vastly more time than its upbuilding, for all available evidence indicates that the rate of erosion is extremely slow. A swift mountain stream flowing on resistant bedrock does not appreciably deepen or change the form of its

valley in several generations of men. All large river valleys must be inconceivably old by ordinary human standards, and yet the Grand Canyon, cut several thousand feet deep in the Colorado Plateau, is geologically young (p. 299). All that has been learned by study of modern sediments indicates that fine sand, mud, and ooze accumulate on sea floors at an average rate measured in inches per century. Therefore the strata totaling several miles thick that were laid down in a geosyncline and later folded into mountains must represent an immense span of time (p. 306). Perhaps the most impressive evidence of great antiquity is furnished by former mountain zones, now reduced by erosion to low altitudes, in which tremendously thick sections of sedimentary strata were intensely folded, in part metamorphosed, and invaded at depth by large igneous masses. The complete history of such a belt consists of three major parts, each of them longer than we can comprehend: the first concerns the leisurely sinking and filling of the geosyncline; the second covers the slow folding and uplift to form lofty mountains, while great bodies of rock deep in the core of the uplifted mass became molten and then crystallized to form batholiths of granite; the third and final phase, perhaps the longest of all, accounts for removal of the highland, probably in spite of repeated upwarping, and eventual exposure of coarse-grained granite and associated metamorphic rocks that came into existence thousands of feet below the original highland surface.

If we try to imagine the complete wearing-down of the Rocky Mountains and the transport of all the debris to the sea through the Mississippi, Colorado, and Columbia rivers, our minds are staggered, and yet we gain at least a rough conception of the immensely long history that has been repeated through successive generations of high mountains. Any estimates we might make of the actual life span of a mountain system, using as a basis only our limited observations in the present, would of course be sheer guesswork. Fortunately we have the radioactive clock (p. 9), according to which the Rocky Mountains were first uplifted about 60 million years ago, and the Appalachians about 150 million years earlier.

Physical Geology an Introduction to Earth History

The Uniformitarian Doctrine. Early students of the Earth encountered many features which they could not explain satisfactorily as results of familiar processes now at work. The origin of schist, marble, and other metamorphic rocks was the subject of groping speculation until it was discovered that foliation and coarsely crystalline texture can be produced in rock material artificially by application of

pressure and heat. The widespread distribution of till, erratic boulders, and polished bedrock in northern Europe baffled all observers until study of modern glacier action revealed these puzzling features as relics of vanished glaciers (p. 148). The slow realization that great valleys are the products of ordinary stream flow is discussed on earlier pages. Thus the conviction has grown that the key to an understanding of ancient Earth features is to be found in activities of the present. Mountains, valleys, masses of granite and of folded sedimentary strata are not monuments to a dead world in which strange forces were at work; they are the cumulative results of processes, for the most part not spectacular, that have operated through the ages and apparently are as effective today as ever.

This principle of uniformitarianism (p. 10) is a fundamental part of geologic science. It does not imply that conditions have remained entirely *uniform* throughout geologic time. The evidence of vanished ice sheets in lowlands of the present temperate zones proves that climates have fluctuated considerably; and probably volcanism, crustal movements, and other processes have varied somewhat in intensity through the ages. But there has been uniformity in the sense that conditions have not varied radically on either side of an average, and therefore the geologic processes have remained much the same in kind and in the rate of their operation through long ages. At first thought it appears that profound changes must have occurred to bring about the formation of great ice sheets over Canada and northern United States. Students of climate tell us, however, that lowering of our present mean annual temperature by only a few degrees would cause slow, persistent accumulation of snow and ice until the glaciers of the Ice Age would be restored to their former great extent. Such a spreading of glacier ice would not bring into operation any new geologic process; it would merely substitute, in the region affected, glacial erosion and deposition, for the present activity of streams and mass-wasting.

According to the uniformitarian doctrine, the present is a fair sample of geologic time, and all geologic features can be understood in the light of changes now in progress on and within the Earth. The doctrine is happily stated in the much-quoted epigram, " The present is the key to the past " (p. 10).

The Use of Inference. Let us return briefly to the section of sedimentary strata used as an illustration at the beginning of this chapter (Fig. 279). An attempted description led at once to inferences regarding the origin of each layer of rock; the conditions under which the bed was formed, the agents that fashioned and deposited the sediments,

and other facts are clearly indicated by features of the bed itself. Interpretation of these features uses the uniformitarian principle. Cross-bedding in the conglomerate and sandstone shows that the gravel and sand were swept in and dropped by currents, and the general direction of foresetting indicates the direction of flow (Fig. 161, p. 201). Pebbles of granite and quartzite in the conglomerate suggest the kinds of bedrock that were being eroded upstream. The mudstone containing petrified logs and leaf impressions is presumed to have been deposited on land, because we suppose that trees have always been land plants, as they are now. This interpretation is supported by mud cracks and animal tracks in the same mudstone. The sandstone, shale and limestone containing fossils of characteristic marine animals are accepted as deposits on a sea floor, because there is no evidence that such animals have ever lived in any environment other than the sea; and since these strata lie above the mudstone formed on land, they record submergence of a land mass. There was later emergence, since these strata are now above sealevel.

These interpretations illustrate the last of the items of equipment for reading the geologic record, as listed on pages 10–11: the ability to draw sound inferences from geologic evidence. Obviously this ability must have a foundation in knowledge of the Earth as it is today, and of the geologic processes now active. As explained above (p. 361), this knowledge is gained in part by observing present-day activities such as the erosive action of streams, transport and deposition of sediments, and glacier motion; and in part by studying the cumulative results of these activities — for example, valleys that are young, mature, and old. Stream valleys are in a sense historic records, but only by studying valleys in all stages of their development can we appreciate the nature and the full possibilities of fluvial erosion. Sedimentary strata are historic documents of the most useful kind; but they must be studied also as important parts of the present crust of the Earth, and many features of these rocks supplement our knowledge of modern deposition on floodplains and deltas and in the sea.

Thus the physical and the historical aspects of geology are intertwined and can not be rigidly separated. In a general way, however, physical geology provides the key to Earth history. By way of illustrating the use of this key we have already considered isolated paragraphs of geologic history — for example the most obvious facts in the development of the Grand Canyon (pp. 299–300), and a general outline of the long evolution of the Appalachians (pp. 305–311). But these are merely unrelated fragments of geologic history. The geologic processes have acted continuously, and on some parts of the Earth a

record must have been written for every part of geologic time. Our goal is the consecutive story, with all major events in the Earth's history set in proper order, along with a record of life from its earliest beginnings. This great history, known as historical geology, is set forth in a separate volume.

APPENDIX

TOPOGRAPHIC MAPS

Topography is the configuration of the land. A *topographic map* is a representation of a land area, greatly reduced, showing the positions of hills, valleys, streams, lakes, and other features, the exact shapes of hills and valleys, the differences in elevation between them (*relief*), and the steepness of their slopes. The map employs conventions to show the topographic features of the area and the positions of roads, towns, and other works of man. In order to use a topographic map intelligently it is necessary to know what the conventions signify, and to be able to form in the mind's eye a picture of the land area represented.

Orientation. Lines of latitude and longitude are usually selected as the boundaries of a topographic map. Most maps therefore represent unit areas known as *quadrangles,* and are standardized as to form and orientation. The map is oriented so that its top lies to the north. The lines of longitude (*meridians*) that limit the map on the east and west extend geographically north and south. On the other hand the lines of latitude (*parallels*) that limit the map on the north and south trend due east and west. Since meridians are not parallel but converge to a point at each pole, maps having meridians as east and west boundaries are not true rectangles.

The geographic north pole and the north magnetic pole do not coincide; therefore a line (determined by a compass needle) drawn from most points on the Earth's surface toward the magnetic pole diverges either to the right or to the left of true or geographic north. The amount of this divergence in any region is the *magnetic declination* and is usually indicated on the lower margin of the map by the angle between two converging lines.

Conventions. All water features such as streams, lakes, swamps, and the sea are represented on a topographic map in blue, the works of man (*culture*) in black, and the relief of the land in brown. Special conventions for various features on both land and water are explained in detail on the back of the map sheet.

Scale. The *scale* of a map indicates the proportion between distance on the ground and the corresponding distance on the map. For ex-

ample, a scale of 1 inch to 1 mile means that two points on the ground exactly 1 mile apart will appear on the map exactly 1 inch apart. A common scale used internationally is 1 to 1,000,000, in which one unit on the map represents one million units on the ground. This scale (expressed as the fraction $\frac{1}{1000000}$ is too small for most purposes, and therefore larger multiples of it are used. The scales $\frac{1}{125000}$ and $\frac{1}{62500}$, both extensively used for topographic maps in the United States, are respectively 8 and 16 times $\frac{1}{1000000}$.

A graphic scale in miles and kilometers and a fractional scale are placed along the lower margin of every topographic map so that distances on a horizontal plane can be readily measured on the map by reference to those scales.

Relief; Contour Lines. The vertical dimension is shown by *contour lines* (often called simply *contours*), which are printed in brown. The difference in elevation between each two successive contours on any map is known as the *contour interval,* and this is indicated on the lower margin along with the scale.

Each contour line passes through points that have the same altitude above mean sealevel. Therefore if one starts at a certain altitude on an irregular surface, and walks in such a way as to go neither uphill nor downhill, but always on a level, he will trace out a path that corresponds to a contour line. Obviously such a path will not be straight but will curve around hills, bend upstream in valleys, and swing outward around spurs. Viewed broadly, every contour must be a closed curve, just as the shoreline of an island or of a continent returns upon itself, however long it may be. Actually there are many contours that are closed curves even upon a relatively small map, such as those marking the higher elevations of isolated hills, but many more do not close within a designated area. These extend to the borders of the map and join with the contours on adjacent maps.

In order to form a more definite concept of a contour line, one may picture an island in the sea crowned by two prominent, isolated hills, with much steeper slopes on one side than on the other, and with an irregular shoreline. The shoreline is a contour line (the zero contour) because the surface of the water is horizontal. If the island is pictured as submerged until only the two isolated peaks project above the sea, and then raised above the sea 50 feet at a time, the successive new shorelines will form a series of contour lines separated by 50-foot contour intervals. At first, two small islands will appear, each with its own shoreline, and the contour marking their shorelines will have the form of two closed curves. When the main mass of the island rises above the water the remaining shorelines or contours will pass com-

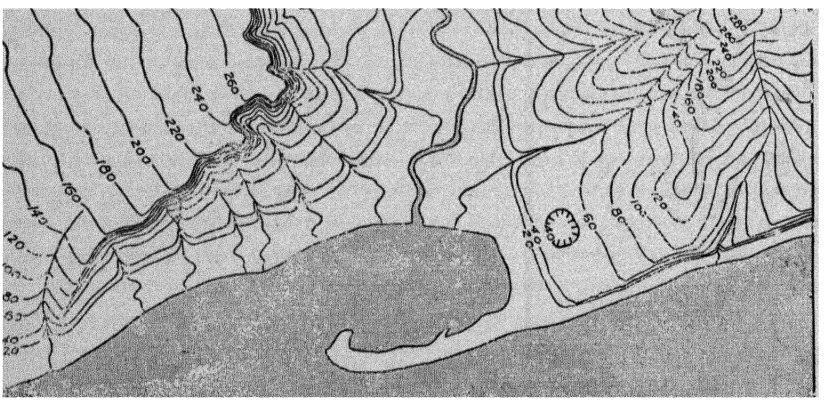
pletely around the land mass. The final shoreline is represented by the zero contour, which now forms the lowest of a series of contours separated by vertical distances of 50 feet.

As the island is raised, the successive new shorelines are not displaced through so great a horizontal distance where the slope is steep as where it is more gradual. In other words, the water retreats through a shorter



Modified after U. S. Geol. Survey.

FIG. 280. Ideal landscape sketch.



Modified after U. S. Geol. Survey.

FIG. 281. Contour map of the landscape shown in Fig. 280.

horizontal distance in falling from one level to the next along the steep slope than along the gentle slope. When these successive shorelines are projected upon the flat surface of a map they will therefore be crowded where the slope is steep and farther apart where it is moderate. In order to facilitate reading the contours on a map, certain contours (usually every fifth line) are strengthened and numbered in brown.

It is customary to print the exact elevations of certain points on a map. These are either prominent relief features, such as mountain peaks, or permanent bench marks, marked "B.M.," followed by the elevation in feet. Such figures must not be confused with the figures showing the elevations of contours. The latter are always multiples of the contour interval and are placed between broken ends of the contour they designate.

Depression Contours. Because the contours that represent a depression without an outlet resemble those of an isolated hill, it is necessary to give them a distinctive appearance. Depression contours therefore are marked on the downslope side with short transverse lines termed *hachures.* The contour interval employed is the same as in elevation contours.

Ideal Example. The illustrations (Figs. 280, 281) show the relation between the surface of the land and the topographic map representing it. Figure 280, a sketch, represents a stream valley between two hills, viewed from the south. In the foreground is the sea, with a bay sheltered by a recurved spit. Terraces in which small streams have excavated gullies flank the valley. A rounded summit and sloping spurs separated by steep narrow valleys characterize the hill on the east. The spurs are truncated at their lower ends by a wave-cut cliff, at the base of which is a beach. The hill on the west rises abruptly above the valley by a steep scarp, and descends gently westward, trenched by a few shallow gullies.

Each of the features on the map (Fig. 281) is represented by contours directly beneath its proper position in the sketch. The contour interval selected is 20 feet.

Construction and Use of Topographic Maps

Most of the governments of the world construct topographic maps for both civil and military purposes. In North America the majority of the government topographic maps are made by the United States Geological Survey and the Geological Survey of Canada, respectively. The construction of an accurate topographic map requires much time and precise work, as it is necessary to determine a large number of exact elevations and positions before the contours can be drawn and other important data entered on the map. It is not surprising, therefore, that more than half of the continent remains to be mapped topographically, although in some of the States mapping has been completed, and in each of the other States and Provinces at least some work has been done. The geological surveys aim to complete maps for the entire area of the United States and Canada.

A good topographic map serves many useful purposes. It enables the engineer engaged in the construction of roads, railroads, dam sites, power-transmission lines, pipelines, and other similar projects to outline, before he leaves his office for the field, some of the problems to be solved in an area in which he is going to work. It forms the most acceptable base for the construction of geologic maps with their manifold scientific and practical applications, and it is helpful to the prospector, the camper, and the motorist going out into areas new to them. In fact, the ability to read a topographic map quickly and accurately is a valuable asset to anyone who, for work or for pleasure, has to do with the land.

INDEX

(Asterisks refer to illustrations)

A

Abrasion, glacial, 134*, 151*
  stream, 70
  wind, 158, 159*
Absaroka Plateau, 296
Agassiz, Louis, 2, 148
Agate, 113
Alkali lakes, 119
Alluvial deposits, 74
Alluvial fan, 188*
Alluvium, 74
Amphibole, 22
Amygdaloid, 24, 35
Andesite, 34
Angular unconformity, 269*
Animas Valley, 143*
Anthracite, 321
Anticlines, 246, 247*, 251*, 324*
Aphanitic, 25
Appalachia, 308
Appalachian geosyncline, 306, 309*
Appalachians, 305, 308
Applied geology, 11
Aqueducts, 355
Aquifer, 107*
Argillites, 38
Arid climate,
  fluvial cycle, 97*
Arkose, 38
Artesian system, 107*
Artesian water, conservation, 108
Artificial levee, 82*, 83
Atmosphere, 3
Atoll, 181*
Austin Dam, Texas, 351

B

Bacteria, in soil, 55
Badlands, 95, 96*
Baltic Sea, uplift near, 244
Bar, 176*
  bay, 176
  offshore, 175*, 179*
Barrier reef, 181*
Basalt, 34, 216*
Basaltic lava, 228*
Baselevel, 71
Batholith, 240, 241, 242*
  relation to other geologic phenomena 243
Bay bar, 176
Beaches, 171*, 172*, 174*, 178*
Bed veins, 334
Bedrock, 43
  fractures in, 46*
Belknap Mountains, N. H., 151*
Bench, wave-cut, 173*, 174*
Bering Glacier, Alaska, 132
Biotite, 22
Bitter lakes, 119
Bituminous coal, 321
Black Hills, uplift, 303*
Black Rapids Glacier, Alaska, 129
Blue Ridge, 99*
Bogoslof Island, 184
Boiling springs, 231
Bombs, volcanic, 215*
Borax lakes, 119
Bottomset beds, 76
Boulder Dam, Nevada, 122, 347*
Boulders, glacial, 153
Breccia, 36, 220*
  volcanic, 219
Buried gorges, 354
Buttes, 94, 95*

C

Calcite, 20
Calderas, 222
Cape Cod, 169
Capture, of basins, 96

Carbon dioxide, 46
Carlsbad Caverns, New Mexico, 110, 111*
Carolina capes, 176*
Catskill Aqueduct, New York, 355
Caverns, 110
Cementation, 193
Centrum, of earthquake, 284
Chalcopyrite, 19
Chalk, 39
Changes of level, 100
Channel (stream), 69
Charleston, South Carolina, earthquake, 282
Cheat River valley, West Virginia, 65
Chemical decay of rocks, 47
Chert, 192
Chesapeake Bay, 100
Chitina Glacier, Alaska, 144*
Chlorite, 22
Cinder cone, 218*
Cirques, 131*, 133, 150*
Clays, 191
Claystones, 38
Cleavage, micaceous, 16
  of minerals, 15
  rhombohedral, 16
  slaty, 41
Cliff, wave-cut, 122, 171*, 172*, 173*, 174*
Climates, 2
Coal, 125, 319, 320
  chemical composition, 321
  classification, 321
  metamorphism, 322
  origin, 321
Coasts, embayed, 175*, 177, 178*
Colorado Plateau, 299
Colorado River, 68, 120
Columbia Plateau, 227, 296
Columnar structure, 238, 255, 256*
Compaction, 193
Concretions, 113, 201*
Confined flow, 106
Conglomerate, 36
Consequent streams, 85
Contact metamorphism, 264, 265*, 266
Contamination of wells, 109*
"Continental drift," 313
Continental masses, 3
Continental shelves, 4, 182
Continental-slope zone, 182
Continents, 4
Contour lines, 369
Coquina, 38
Coral reef, 180*, 181*, 244*
Corded lava, 216*
Crater Lake, Oregon, 221*, 222
Creep, 58, 65
Crevasses, 128
Cross-bedding, 165, 199, 201*
Crust, 4
  equilibrium in, 314
Crustal movements, cause, 313
Crustal revolution, 308
Cuesta, 98*
Cycle, fluvial, 90
  in dry regions, 95
  of erosion along coasts, 177

D

Dakota artesian system, 108
Dams, geology of, 348
Death Valley, 79*
Deccan trap, 227
Decomposition, 46
Deep-sea basins, 3, 182
Deep-sea zone, 182
Deflation, 156
Delaware Water Gap, 99
Deltas, 76, 77*, 118*, 121*
Depositional shore features, 174
Deposits, glacial, 138
  in caverns, 112
  in pores and cavities, 113
  iron-ore, 337
  made by wind, 162
Destructive floods, 82
Detritus, 36
Dikes, 219, 237, 238*, 239*
Diorite, 33
Diorite porphyry, 34
Dip, of beds, 250
  of fault, 257
Disconformity, 269*, 270*
Disintegration, 46, 48, 50
Dismal Swamp, 124
Distributaries, delta, 78
Divides, 87*

Dolomite, 20, 39
Doming, 302
Dredging, for gold, 340, 341*
Drift, glacial, 138
  stratified, 139*
Dripstones, 111*, 113, 115
Drowned valley systems, 100
Drumlins, 140, 141*
Dunes, 162
  migration of, 165
Durham Castle, England, 44*
"Dust Bowl," 156, 158

E

Earth, as a Planet, 2
  constitution of, 291, 292*
  core of, 292
  diameter of, 3
  interior of, 289
Earth-flowage, 63*
Earthquake vibrations, 283
Earthquakes, causes, 275
  centrum of, 284
  distribution, 281
  elastic rebound theory, 278*
  intensity, 280
  nature and origin, 275
  precautions against, 288
  volcanic, 275
Economic geology, 11
Elastic rebound theory of earthquakes, 278*
Embayed coasts, 175*, 177, 178*
End (terminal) moraine, 140, 141, 142*, 143*
Engineering geology, 346
  Catskill aqueduct, 355
  tunnels, 353
Epicenter, of earthquake, 284
Erosion, by streams, 70
  by wind, 156
  effect of vegetation on, 94
  glacial, 133
  rate, 68, 93
  soil, 59*
Erratic boulder, 151*
Erratics, glacial, 152
Eskers, 146*, 147*, 152
Etna (volcano), 222, 236
Everglades, Florida, 124
Exfoliation, 50*
Explosive pits, 223

F

Fabric, of rocks, 25
Falls, 72
Fan, 78, 79, 80*, 121*, 188*
Fanglomerates, 36, 188*
Fault scarps, 259, 260*, 261*
Fault surface, 256*
Fault-block mountains, 300, 301*
Fault-dam springs, 273*
Faults, 254, 255, 257*, 299
  magnitude, 259
  normal, 258*
  reverse, 258*
  San Andreas, 276*, 277*
  strike of, 257
  strike-slip, 258*, 259*
  thrust, 259, 312*
  types, 258*
Feldspar, 21
Felsite, 34
Ferromagnesian minerals, 30
Fiord, 131*, 137
Fissure veins, 334
Floodplain, 76, 78*
Floods, 75*, 80, 121
  destructive, 82
  stream, 69
Fluvial cycle, 90, 91*
  in a moist-temperate climate, 90
Folded strata, 248*
Folds, 246, 305
  overturned, 251
  pitch, 251
  recumbent, 251
  upright, 251
Foliated metamorphic rocks, 266
Foliates, 40
Foliation, 40
Foot wall, 257
Foreset beds, 76, 77*
Formation, 203
  areal extent, 205
Former ice sheets, 149
Fort Peck dam, Montana, 348

Fossils, 197*
  index, 203
Fracture, 25
  conchoidal, 16
  of rocks, 26, 253
Fragmental products, 214
Frank, Alberta, landslide, 61
Franz Joseph Fiord, Greenland, 137
Fringing reef, 181*
Frost wedging, 48, 49*
Fumaroles, 230, 231*
  economic utilization, 235

G

Gabbro, 33
Galena, 19
Garnet, 21
Gangue, 330
Geanticlines, 253
Geode, 113, 114*
Geologic structure, 248
  economic aspects, 271
Geologic time, 9, 363
Geomorphology, 11
Geophysical prospecting, 327
Geosynclines, 253, 307*
Geysers, 109, 232, 234
Glacial abrasion, 134*, 151*
Glacial boulders, 153
Glacial deposits, 138
Glacial drift, 138
Glacial erosion, 133
Glacial erratics, 152
Glaciated stone, 160*
Glaciated valley, 134*, 135*, 137*
Glaciation, of North America, 152*
Glaciers, 128
  fluctuations of, 128
  movement of, 128
  piedmont, 132
  quarrying and abrasion, 133
  rock, 59, 60*
  terminus, 129
  types, 130
  valley, 130, 150*
  wastage, 128
Glass, 27
Gneiss, 40
Gold, in placers, 342
Gold-bearing lode, 333*
Gold-bearing quartz, 334*
Gold deposits, 339
Gold vein, 333*
Gradational processes, 8, 361
Graded stream, 72
Grand Canyon, 6*, 68, 94, 204*, 297*, 299
  stratigraphic section at, 204
Grand Teton, Wyoming, 149
Granite, 5, 30, 32, 241
Granite porphyry, 33
Gravel, 189
Great Plains region, 95
Great Salt Lake, 122
Greenland ice sheet, 132*
Groins, 175*, 177
Gros Ventre slide, Wyoming, 62*
Ground moraine, 140, 147*
Groundmass, 28
Gullies, 81*, 85, 86*
Gusher, 327*
Gypsum, 20

H

Halite, 20
Hanging tributary valleys, 136*, 142*, 150
Hanging wall, 257
Hardness, of minerals, 17
  of rocks, 26
Harney Peak, South Dakota, 304
Helgoland, 169
Hematite, 18
Henry Mountains, Utah, 239
Hogbacks, 98*
Hornblendite, 33
Hot springs, 230, 231
Hudson pressure tunnel, 356*
Hudson River, drowned, 100
Humus, 51
Hutton, James, 10
Hydraulic action, 70
Hydraulic mining, 340, 341*
Hydrosphere, 3

I

Ice Age, 123, 148, 152*
  cause, 155

Ice sheets, 130
in Europe, 153
influence on drainage, 154
Ice-contact faces, 145
Icebergs, 131*
Igneous rocks, 5, 26
composition, 27
extrusive, 26
intrusive, 26
tabular classification, 31
texture, 27
Imperial Valley, 120
Incised meanders, 101*
Inference, use of, 365
Iron-ore deposits, 337
Islands, 178*, 180
Isoclinal folds, 252*
Isostasy, 315
Izalco (volcano), 225

J

Joint sets, 254
Joint system, 254
Joints, 254*
Jorullo, Mexico, 225

K

Kame terraces, 146*
Karst topography, 112*
Kern River Valley, 134*
Kettles, 144*, 145, 146*
Kilauea, explosive eruption, 210*
Kinetic metamorphism, 264
Kootenay River, 75*

L

Laccolith, 239*, 240*
Lagoon, 178, 179*, 180*
Lake Agassiz, 119*
Lake Bonneville, 122*, 123*, 155
Lake Erie, 118
Lake Lahontan, 123, 155
Lakes, 125*
borax, 119
erosion and deposition, 117
origin of basins, 117
playa, 119, 120*
stages in history, 118*
Laminated sediment, 196*
Landscape profiles, 96*
Landslide topography, 62*
Landslides, 60
Lassen Peak, California, 217
Lateral moraines, 142*, 145
Lava, 215
basaltic, 228*
block, 216
corded, 216*
Lava flows, 95*, 228*, 343
Lehigh River, 71*
Levee, artificial, 82*, 83
Lignites, 321
Limestone, 38, 191
Limonite, 19, 47
Lode, 332
Loess, 166, 167*, 195
Lone Star Geyser, 232*
Long waves, 289
Longshore currents, 171*
Lötschberg tunnel, Switzerland, 354*
Low-plain coasts, 178, 179*
Luster, 17

M

Magma, 26
cause of rise, 230
origin, 228
origin of gases in, 229
Magmatic differentiation, 229
Magnetite, 18
Malaspina Glacier, Alaska, 132
Mammoth Cave, Kentucky, 110
Mammoth Hot Springs, Yellowstone Park, 115
Mantle, 43*
Marble, 42
Marine depth zones, 182*
Mass eruptions, 227
Mass-wasting, 43, 57
practical aspects, 66
Matterhorn, 149
Maturity, 97*
Mauna Loa, Hawaii, 5, 216
Mayon (volcano), 221*
Meanders, 88*
incised, 101*
Medial moraine, 131*, 145
Mesas, 94, 95*

Messier Channel, 137
Metamorphic rocks, 8, 268
Metamorphism, 261, 263
  dynamic, 264
  kinetic, 264
  ranks of, 263
Meteor Crater, Arizona, 223, 224*
Military engineering, application of geology to, 356
Mineral, 13
Mineralogy, 11
Mining, hydraulic, 340, 341*
Mississippi delta, 78*
Mississippi River, 82*
Missouri River, history, 154
Monadnocks, 92*, 93
Monocline, 252*
Mont Pelée, 209, 217*, 237
Monte Somma, 212
Moraine, end, 140, 141, 142*, 143*
  ground, 140, 147*
  lateral, 142*, 145
  medial, 131*, 145
  superglacial, 145
Mount Etna, 363
Mount Rushmore, 304
Mountain structure, variations in, 311
Mountains, 295
  and plateaus, 298*
"Mountains of erosion," 296
Mud, 190
Mud cracks, 198*
Mudflows, 60, 94
Mudstones, 38
Muscovite, 22

N

Natural levees, 75*
Near earthquakes, 290
Névé, 127
New Madrid, earthquake, 282
Niagara Falls, 72, 73*, 74*, 118, 154
Nisqually Glacier, 129
Normal fault, 258*
Nunatak Glacier, Alaska, 131*

O

Obsidian, 35
Oceans, 3
Offshore bar, 179*
Ohio River, history, 154
Oil, 322, 325*
  association with salt plugs, 328
  occurrence, 323
Oil field, East Texas, 324
Oil pool, 324*
Oil wells, 326*
  life, 325
Old age, 90, 97*
Old Faithful geyser, 233*
Olivine, 22
Oozes, 185
Ore, definition, 330
Ore deposits, classification, 344
  forms, 332
  occurrence and origin, 331
  primary, 331
  replacement, 335
  secondary, 339
Ores, composition, 336
  hydrothermal, 332
Orthoclase, 21
Outwash, 143*, 145
Outwash plain, 142*, 146
Oxbow lake, 89*

P

Painted Desert, Arizona, 300*
Paleontology, 11
Paradise Glacier, Washington, 129
Peat, 125*
Pegmatite, 243
Peléan clouds, 209, 211*
Peneplane, 93, 100
Perennial snow, lower limit of, 127
Perennial stream, 85
Peridotite, 33
Permeability, of rocks, 104
Petroleum, 322
Petrology, 11
Phenocrysts, 28
Phyllite, 41
Physical geology in retrospect, 360
Piedmont glaciers, 132
Pitch, of folds, 251*
Pitchstone, 35
Pitted outwash plains, 148
Placer, definition, 339
  gold, 342

Placer, origin, 340
platinum, 343
Plagioclase, 21
Plant growth, disruption by, 51
Plateau remnants, 296
Platinum, placer, 343
Playa, 79*, 95*, 198*
Playa lake, 119, 120*
Plunge basin, 74*
Pore space, in rocks, 104
Porphyry, 27
granite, 33
Potholes, 70
Profile of equilibrium, 173, 174
Pumice, 35, 218
Pyrite, 19
Pyroclastic, 192
Pyroclastic cones, 218
Pyroxene, 22
Pyroxenite, 33

Q

Quartz, 20
Quartzite, 42

R

Rainfall, 69
Rainfall map of United States, 52*
Rainwash, 69
Rapids, 72
Recumbent folds, 251
Reef, barrier, 181*
coral, 180*, 181*, 244
Relief, 3, 368
Replacement, 113
Reservoirs, geology of, 348
leakage, 349*
Residual mantle, 44, 55, 56*
Reverse fault, 258*
Rhyolite, 34
Rills, 85
Rio Grande, 95*
Ripple marks, 163, 199, 200*
Rock composition, effects on weathering, 53
Rock flowage, effects of, 267*
Rock glaciers, 59, 60*
Rocks, chemical decay, 47
classes, 24
Rocks, contact-metamorphic, 42
fabric, 25
Running water, 68

S

St. Francis dam, California, 66, 352*
Saline lakes, 118
Salt lakes, 119
Salt plug, 328*
Salton Basin, 121*
Salton Sea, 120
San Andreas fault, 276*, 277*
San Francisco Bay, 100
San Juan River, 101*
Sand, 190
Sand dunes, 163*, 164*
migration, 164*
Sandstone, 37, 188*
Scale of hardness, 17
Scarps, fault, 259, 260*, 261*
Schist, 40
Scoriae, 218
Sea, area, 4
functions, 169
Sea floor, 182, 183
Sea-floor sediments, 183
Sea water, composition, 185
Sedimentary rocks, 8, 359*
colors, 202
Sediments, 8
calcareous, 192
sorting, 80
Seismic belts, 281
Seismogram, 286, 287*
Seismograph, 286*
Seismology, 275, 283
Serpentine, 22
Shale, 38, 188*
Shelf zone, 182
Shelves, continental, 4, 182
Shield volcanoes, 219
Shore profile, 173
Shore protection, 177
Shore zone, 183
Shorelines, 122*, 123*
evolution, 178*, 179*
Siliceous sinter, 232*
Sill, 239*
Silt, 190

Siltstone, 38
Sink, 110, 111*
Slate, 41
Slaty cleavage, 262*, 263*
Slickensides, 256*
Sliderock, 24*, 53, 57
Slumping, 64*, 65
Snickers Gap, Virginia, 99
Snow limit, 127
Snowfields, 150*
Soil, conservation, 57
  development, 55
  erosion, 80
  mature, 55
Soil-flowage, 59*
Soil mantle, 54*
Soil-protection measures, 82
Solution, 47
Solution valleys, 112
Sorting, of stream sediments, 80
Specific gravity, 18
Sphalerite, 19
Spindletop Oil Field, Texas, 328
Spits, 175*, 176, 178*
Spring deposits, 115
Springs, 105, 106*, 108
  artesian, 107
  hot, 230, 231
  thermal, 109
Stagnant ice, 148
Stalactites, 111*, 113
Stalagmites, 111*, 113
Stock, 240
Strath, 88*, 89*, 100*
Stratification, 80, 188*, 194
  origin, 195
Stratified drift, 139*
Stratigraphic traps, 324
Stratigraphy, 11, 203
Stratovolcanoes, 219, 220*
Streak, 17
Stream, consequent, 85
  definition, 69
  intermittent, 85
  load, 70
  long profile, 71*
  perennial, 85
  placer, 343*
  rejuvenated, 101*
  solution by, 70
Stream, subsequent, 98*
Stream abrasion, 70
Stream adjustment, 100
Stream braiding, 76
Stream deposition, 70, 74
Stream deposits, internal character, 80
Stream divide, 86
Stream erosion, 70
Stream floods, 69
Stream terraces, 100*, 101
Stream transport, 70
Stream-worn cobble, 160*
Strike, of beds, 250
  of fault, 257
Strike-slip fault, 258*, 259
Structural geology, 11
Structural traps, 328
Submarine topography, 184
Submergence of valleys, 100
Subsequent streams, 98*
Subsurface water, 103
  geologic work of, 110
  in fractures, 108*
  movement, 104*, 105
  pollution, 109
  recovery of, 272
  solution by, 110
  source, 103
Sun, heat, 2
Supergene enrichment, 337
Superglacial moraines, 145
Syenite, 33
Synclines, 246, 247*
Swamps, 124
  drainage of, 124

T

Taku River, 136*
Talus, 57, 58*
Tamboro (volcano), 205, 222
Temperature changes, effects of, 49
Terraces, 118*, 123*
  stream, 100*, 101
  wave-built, 174*
Thermal springs, 109
Thrust faults, 259, 305
  development of, 312*
Tidal marsh, 124, 179*, 180
Tide gage, 283*

Tides, 171
Tied island, 178*
Till, 138*, 139
Tillite, 36, 195
Topographic maps, 368
Topography, 368
Topset beds, 76, 77*
Transport by streams, 71
Transported mantle, 44
Transverse stream, 98*
Traps, stratigraphic, 324
Tree trunks, petrified, 114
Tributary streams, 85
Tributary valleys,
  hanging, 137*
Tuff, 192, 219, 220*
Twin Glaciers, Alaska, 131*

U

Unconformity, 268, 271
Undertow, 170, 171*
Uniformitarianism, 10, 364, 365
Upbuilding forces, 362

V

Valley, cross-profiles, 88*
  glaciated, 134*, 135*, 137*
  hanging tributary, 136*, 142*, 150
  Imperial, 120
  mature, 87*, 88
  old, 89
  stages of development, 87
  solution, 112
  submergence of, 100
  young, 87
Valley systems, drowned, 100
Valley floor, 75*
Valley glaciers, 130, 150*
Varve, 196*
Veins, bed, 334
  gold, 333*
Ventifact, 160*
Vesicles, 218
Vesuvius, 5, 207, 212*, 213*, 225, 236, 331
Volcanic ejecta, 214
  explosivity, 211
  gases, 214
  phases, 208, 209
Volcanic ash, 215
Volcanic blocks, 215
Volcanic bomb, 215*
Volcanic breccia, 192
Volcanic cinders, 215
Volcanic earthquakes, 275
Volcanic highlands, 295
Volcanic neck, 224, 240, 241*
Volcano, definition, 207
Volcanoes, compound, 222
  destruction by erosion, 223
  distribution of, 226*
  embryonic, 223
  geographic distribution, 225
  shield, 219
Volcanology and human affairs, 236

W

Warping, 246
Water gaps, 98*, 99*
Water supply, New York City, 346
Water table, 104*, 108*
Wave-built terrace, 122, 174*
Wave-cut bench, 173*, 174*
Wave-cut cliff, 122, 171*, 172*, 173*, 174*
Wave-worn beach cobble, 160*
Waves, 170, 171*
Weathering, 43
  agents of, 45
  chemical, 94
  mechanical, 94
  of feldspar and other minerals, 48
  of ore bodies, 336
  variations in, 51
Wells, 105, 106*, 108
  artesian, 107
  contamination of, 109*
  oil, 326*
Wind abrasion, in United States, 161
  erosion, 156
Wind-blown dust, 157*
Wind gaps, 98*, 99*

Y

Yakutat Bay, Alaska, 129
Yosemite Valley, 134*, 137
Youth, 90, 97*

Z

Zones of earthquake intensity, 281*

Outlines of Historical Geology

PHYSICAL GEOLOGY. *By* Chester R. Longwell, Adolph Knopf, *and* Richard F. Flint. Third Edition.

HISTORICAL GEOLOGY. *By* Carl O. Dunbar.

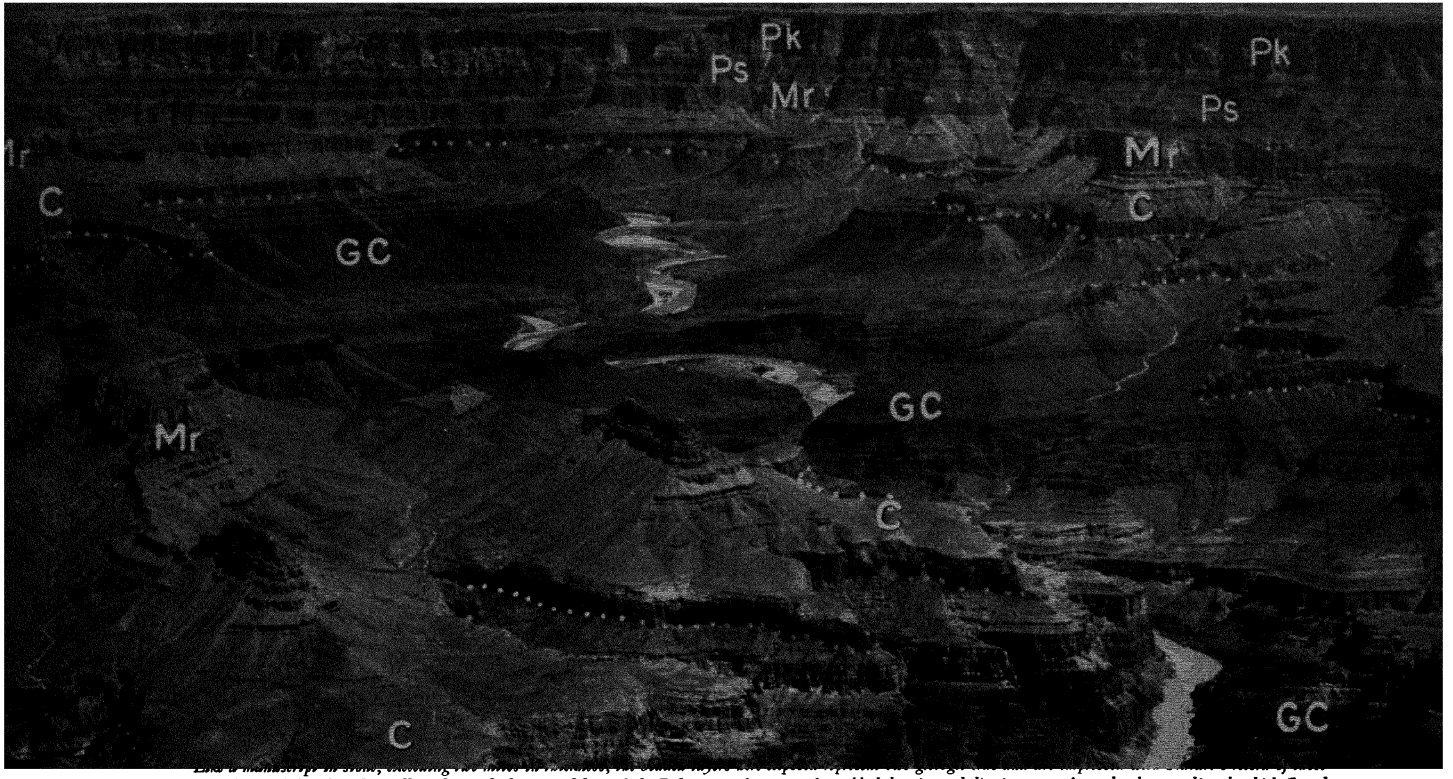
OUTLINES OF PHYSICAL GEOLOGY. *By* Chester R. Longwell, Adolph Knopf, *and* Richard F. Flint. Second Edition.

OUTLINES OF HISTORICAL GEOLOGY. *By* the late Charles Schuchert *and* Carl O. Dunbar. Fourth Edition.

OUTLINES OF GEOLOGY. OUTLINES OF PHYSICAL GEOLOGY and OUTLINES OF HISTORICAL GEOLOGY in one volume.

ROCKS AND ROCK MINERALS. *By* the late Louis V. Pirsson. *Revised by* Adolph Knopf. Third Edition.

GLACIAL GEOLOGY AND THE PLEISTOCENE EPOCH. *By* Richard F. Flint.



ancient days. The white dots follow the nearly horizontal base of the Paleozoic rocks; unconformable below it, and dipping away from the observer, lies the thick Grand Canyon system of the Pre-Cambrian; above it are formations of Cambrian, Mississippian, and Permian age. C, Cambrian beds; GC, Grand Canyon system; Mr, the cliff-forming Redwall limestone of Mississippian age; Pk, Kaibab limestone and underlying Coconino sandstone of Permian age; Ps, Supai red beds succeeded by Hermit red shale, both of Permian age. The view is northward into the Grand Canyon from a point near the mouth of Little Colorado River.

Outlines of
Historical Geology

By

Charles Schuchert

Late Professor Emeritus of Paleontology
in Yale University

and

Carl O. Dunbar

Professor of Paleontology and Stratigraphy
in Yale University

FOURTH EDITION

Seventeenth Printing

NEW YORK, JOHN WILEY & SONS, INC.
LONDON, CHAPMAN & HALL, LIMITED

COPYRIGHT, 1924, 1931
BY CHARLES SCHUCHERT

COPYRIGHT, 1937, 1941
BY CHARLES SCHUCHERT AND CARL O. DUNBAR

All Rights Reserved

This book or any part thereof must not be reproduced in any form without the written permission of the publisher.

FOURTH EDITION

Seventeenth Printing, November, 1955

PRINTED IN THE UNITED STATES OF AMERICA

PREFACE TO THE FOURTH EDITION

This brief outline of Earth history is a sequel to the *Outlines of Physical Geology,* second edition, by Longwell, Knopf, and Flint, and a junior companion of the *Textbook of Historical Geology,* fourth edition, published in February, 1941. It is written, frankly, for the student who wishes to get, in one brief course, a general survey of the past history of the Earth, and is not intended for the specialist.

Since the student is to have only a glimpse of this great panorama, he needs a telescope rather than a microscope, with which to gain, from a distance, a view that has depth and perspective rather than detail. For this reason we have presented the record of each era as a unit instead of dividing and treating it systematically by periods.

As here arranged, the physical history forms a continuous story in Part II, and the history of life a like sequence in Part III; but those who desire to associate the life record of each era more closely with its physical history may read the chapters in the following order: 1, 2, 3, 4, 5, 6, 10, 7; 11, 8, 9, 12, and 13. The chapters of Part I depart considerably from the order used in the *Textbook* and in the previous edition of the *Outlines.* The new arrangement brings the *Geologic Time Chart* into the first chapter. It is important to require the student to memorize it well before proceeding with later chapters.

Since so much of the record of life is a reflection of organic evolution we have retained a brief chapter on the subject of Evolution in the prologue of this edition. Some knowledge of the structure and relationships of the major groups of animals and plants is obviously indispensable for the appreciation of the history of evolving life. But many readers of this book will probably not have studied Zoology or Botany, and even those who have pursued such courses may have little systematic knowledge of certain groups of animals and plants that were important in the past. Such students may secure a useful orientation by studying the Appendix, An Introduction to Animals and Plants, before starting the study of Chapter 7. For several years Yale classes have been required to study this material as an outside assignment during the first few weeks of the course; the class periods are thus left free for an uninterrupted study of the geologic history.

It is hardly necessary to apologize for the increasing amount of detail in the chapters dealing with late geologic time, for all the scenery

about us and all the warm-blooded animals of our world are the products of the last geologic era, and it is here that human interest comes to focus.

As in the larger book, we have received helpful criticisms from our Yale colleagues, Professors Adolf Knopf, Chester R. Longwell, and Richard Foster Flint.

The paleogeographic maps are new and were made especially for this edition. The plates of fossils, as in the previous edition, are from the careful drawings made by Lathrop Douglass for the bigger book. Numerous photographs of specimens in Yale Peabody Museum were made by Percy A. Morris.

We are grateful once more to Clara Mae LeVene who has edited the manuscript and seen it through the press.

CHARLES SCHUCHERT
CARL O. DUNBAR

NEW HAVEN, CONN.
July, 1941

CONTENTS

PART I. PROLOGUE

CHAPTER		PAGE
1.	Records in Stone	1
2.	The Scale of Time	16
3.	The Constant Change of Living Things	24
4.	A Living Record of the Dead	34

PART II. EARTH'S CHANGING FEATURES

5.	Before the Cambrian	56
6.	Glimpses of Paleozoic Landscapes	77
7.	The Mesozoic World	105
8.	The Modern World Unfolds	125
9.	Ice Sculptures the Final Scene	147

PART III. THE PAGEANT OF LIFE

10.	Paleozoic Inhabitants of the Earth	167
11.	The Reign of Reptiles	190
12.	Mammals Inherit the Earth	210
13.	The Coming of Man	237
Appendix: An Introduction to Animals and Plants		256
Index		283

Outlines of Historical Geology

PART I. PROLOGUE

CHAPTER 1

RECORDS IN STONE

"There rolls the deep where grew the tree,
O Earth what changes hast thou seen!
There where the long street roars, hath been
The stillness of the central sea."

—TENNYSON.

PALEOGEOGRAPHY: A STUDY IN ANCIENT LANDS AND SEAS

Plotting the Ancient Seaways. If North America were depressed 600 feet (Fig. 1), the Great Lakes would become an inland sea, the St. Lawrence Valley a strait, and New England and the Maritime Provinces an island; Hudson Bay would spread widely over the heart of Canada; St. Louis would be a seaport beside the estuary of the Mississippi, and coastwise steamers could ply their trade across the expanded Gulf from Louisville to Little Rock and San Antonio; the present Coastal Plain would be shallow sea floor, and Florida a submarine bank.

Over these submerged areas sediments would accumulate, entombing the shells of marine animals such as corals, clams, and sea urchins, along with the teeth of sharks and the bones of whales. Barnacles and oyster banks, as well as beach gravels, would mark the new shoreline.

If the continent were later uplifted into land, these marine sediments would form a record of the submergence and we should need only to plot their distribution on a map to restore more or less accurately the limits of the vanished sea.

Submergences as great as the one depicted have actually occurred not once but many times (Fig. 4), whether due to a worldwide rise in sealevel or to downwarping of the continent itself; and with each one of these transgressions the outlines of land and sea have varied widely. The lands have suffered constant erosion and destruction, and their debris, transported to the shallow seas, has accumulated layer upon



FIG. 1. North America as it would appear if depressed 600 feet. The present coastal plain and the Mississippi Valley and all of Florida would then be shallow sea floor (deep shading), and the Appalachian highlands would become an island. Deep sea is represented by solid black. A little more depression would unite Hudson Bay with the Gulf embayment.

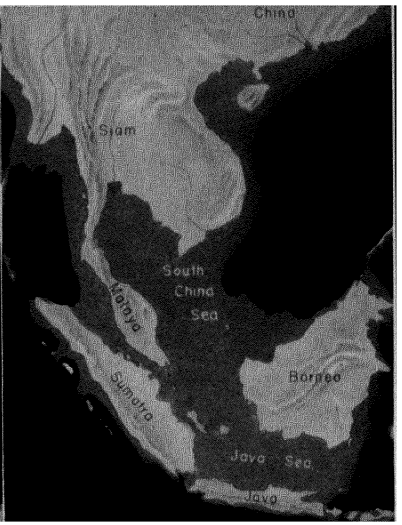


FIG. 2. Malaysia, an actual example of submergence comparable to that suggested in Fig. 1. Here the shallow shelf sea (darkly shaded), with a maximum depth of about 200 feet, has an area nearly equal to one-fourth that of the United States. It was recently a part of the mainland of Asia, and still retains evidence of drowned stream courses. Modified from Van Riel.

layer, like pages of a manuscript in stone, preserving the record of the times.

Discerning the Lost Lands. The material eroded from a land mass is deposited elsewhere to form a telltale record. The streams carry gravel and sand and mud which they spread in piedmont fans or transport to the nearest basin, dropping the coarsest material first and grading the rest into finer and finer deposits as the slope decreases. If a sea lies near, the sand and gravel are in part delivered to the waves, which grade and spread them farther from shore. The coarseness of this material and the degree of its weathering imply much about the ruggedness of the highlands and the rapidity of erosion.

Reconstructing Mountains that Have Vanished. Areas of low land supply only fine muds or dissolved material to the sluggish streams, and the deposits laid down in adjacent seas are fine muds, commonly limy. If in such a region a range of mountains should arise, the streams would be rejuvenated and erosion accelerated until maximum relief had been attained, and then, as the geomorphic cycle progressed and old age was approached, erosion would slow down, the streams would

flow more sluggishly, and again nothing but fine sediment could be transported. During this cycle the deposits formed in the bordering seas would undergo a systematic change from fine to coarse and then back to fine again; and the volume of the detrital deposits would give some measure of the size of the range destroyed by erosion.

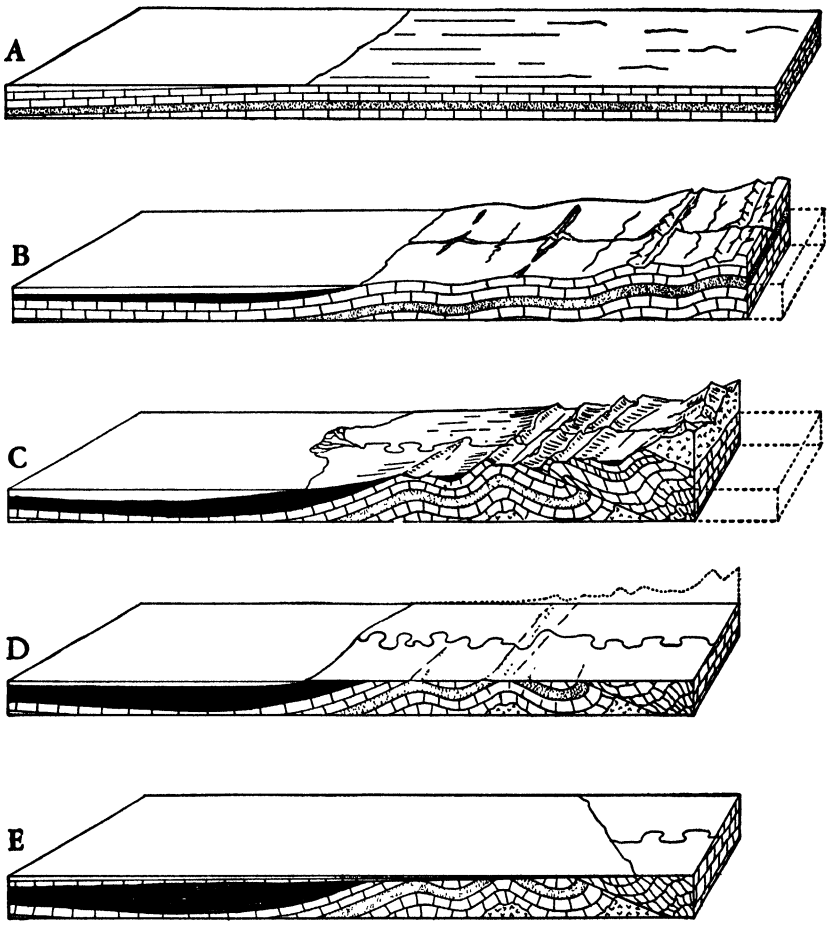


FIG. 3. Five stages in the rise and decay of a mountain range. The sediments derived from the erosion of the range are represented in black.

The history of such an event is pictured in Fig. 3. The first block shows a region of flat-lying strata just emerging from the sea; the second indicates an early stage of folding, and the third shows the mountains at their height, with rugged peaks and steep slopes. As the

mountains arose, a geosyncline formed at the left, subsiding in compensation for the uplift. At the stage represented by block *C* the loaded streams have built out an alluvial coastal plain, and deltas are pushing back the sea where major streams debouch from the highlands. A vast deposit of sand is spread over the floor of the geosyncline, grading seaward into mud but landward into beach gravel and nonmarine deposits. Block *D* represents a much later stage when the land is almost peneplaned and the geosyncline is filled with the debris. Block *E* shows eventual submergence when once more corals grow on a limy sea floor where the mountains formerly reared their proud peaks. At the surface all vestiges of the mountains are now gone, but underground a clear record remains, both where the mountains were and where their debris accumulated. The records in the two areas are entirely dissimilar and are complementary.

In the disturbed area there is a profound unconformity, beneath which lie the buried roots of the mountains whose truncated folds indicate the *nature* of the disturbance and the magnitude of deformation. The *date* of the uplift is clearly later than the youngest deformed strata and older than the first strata to overlap the truncated folds. In the area of deposition the coarseness of successive beds reflects the relief and the rapidity of erosion in the mountains, and the fossils in these strata date the uplift geologically. Even if the deformed area were permanently submerged or were repeatedly deformed until the earlier record were obscured, the sedimentary record in the adjacent region would still indicate the history of this orogeny, and the volume of the detrital deposits would give some measure of the size of the mountains destroyed.

Such criteria may be applied to the mid-Cretaceous record.* In the eastern part of the ancient Rocky Mountain geosyncline (Fig. 4) the middle Cretaceous formations are very fine shales and chalky limestones. They thicken westward and become coarser of grain and, along the western margin, grade into extensive deposits of coal-bearing sandstones evidently formed on a swampy coastal plain. Clearly, the detrital material was coming chiefly from a land that lay west of the Cretaceous geosyncline, and the great volume and the character of the detrital deposits prove that land to have been mountainous and undergoing uplift. By the further application of such principles we can restore the major features of North America as they were in Cretaceous time — a continent separated by a vast seaway into two land masses, the eastern mass mostly a low plain with monadnocks along the Appa-

*The *Geologic Time Chart* on pp. 14 and 15 shows the time relations of the Cretaceous period.

lachian axis, the western one a narrow mountainous belt. The application of such principles is the science of *Paleogeography* (Gr. *palaios*, ancient, + geography), and the inferred restorations are *paleogeographic maps*.

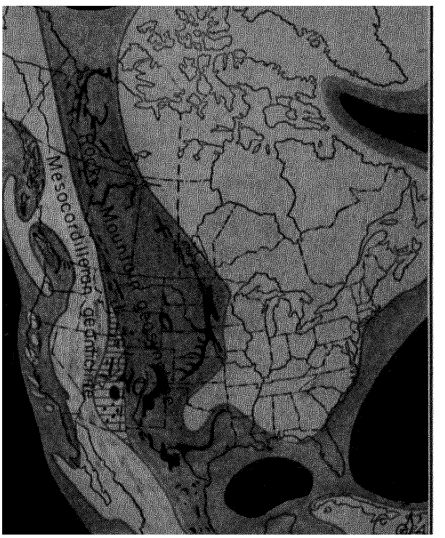


FIG. 4. Paleogeographic map of North America as it was in mid-Late Cretaceous time. Present outcrops of Cretaceous rocks of this date are shown in solid black. Inferred seaways are shown in deep shading, and an area of fluvial deposits is indicated by horizontal lines. Deep-sea basins are colored black.

BUILDING THE GEOLOGIC COLUMN

Human history was not made in a single country. For a time the most significant developments were in the Orient, or in Egypt, or Greece, or ancient Rome, before they spread to western Europe and finally to America. The historian must consult materials and manuscripts in many places before he can write an "Outline of History." Likewise, Earth history is not recorded in a single outcrop or in one continent. The records from many regions must be pieced together in their proper order until we have the composite *sequence* of events. The principles involved in reconstructing such a composite record deserve our attention.

Law of Superposition. In any particular region the sequence of geologic events is clearly shown by the order of superposition of undeformed sedimentary formations. Thus, in exposures like those of the walls of the Grand Canyon (frontispiece), it is evident that the lowest formation is the oldest, and succeeding strata successively younger. This simple and self-evident principle is *the law of superposition.*

Of course, there are many places where the succession has been locally inverted by folding or interrupted by faulting, but such exceptions will betray themselves in the evidences of disturbance and in the unnatural succession of the fossils (see next paragraph). Therefore in a general study of a region that has not been intensely deformed, the order of superposition can be readily ascertained, and the sequence of formations, as represented in that particular locality, can be deter-

mined. The succession is commonly presented diagrammatically as a *columnar section* representing the formations as they would appear in a well core.

Law of Faunal Succession. A *fauna* is a natural assemblage of animals (Lat. *Faunus*, the god of animal life); a *flora*, the corresponding assemblage of plants. Thus, all the animals that now inhabit a given region make up its particular fauna, and the fossil animals found in a rock formation constitute its fauna.

Just before 1800, William Smith discovered that in the Jurassic rocks of England, each formation has a distinct fauna, unlike that of formations above or below. He discovered also that the characteristic fauna of any one formation can be found in outcrop after outcrop as it is traced across the countryside, and so the characteristic fossils serve as a *guide* or *index* to distinct formations which he could recognize in any outcrop, without the necessity of careful tracing. Vast experience, accumulated since the days of Smith, has shown that this is a principle applicable to fossiliferous rocks generally, and one of the most important discoveries ever made in geology, since it permits us to recognize rocks of the same age in different outcrops and even in widely separated areas, and so to piece together the fragmentary record.

Smith did not know why each formation possesses a distinct fauna; his inference was based solely on experience in a region of richly fossiliferous rocks where the strata dip gently and the order of superposition is self-evident. We now know that it is due to the operation of organic evolution, whereby the animals and plants have gradually changed from age to age; naturally, each rock formation has preserved only those species that were living when it was formed.

Thus, in regions where the beds are not deformed, the succession of faunas that occupied the region from age to age can be determined from a study of the fossils in successive formations. When this succession has been verified by experience in many regions of undisturbed strata, we may depend on the fossils to indicate the true order of deposition even in areas of folding and faulting where the succession is locally reversed or broken.

Correlation of the Fragments of the Record. The matching of strata or formations from outcrop to outcrop (or from well to well underground) to determine their mutual relations and degree of equivalence in age is known as *correlation*. It is an important step in working out the geologic history, because no single area contains a record of all geologic time, and if it did the section would be so thick that its base would be hopelessly buried beyond our reach. It is fortunate that areas of deposition have shifted from time to time in

keeping with the irregular warping of the Earth's crust and although no section is complete, deposition was continuously going on somewhere, and we need only discover and correlate enough of the scattered fragments to build up a composite record of all geologic time.

For more than a hundred years the geologists of all countries have been co-operating in this endeavor to work out the full and composite geologic record, and the total thickness of the stratified rocks now recognized would exceed 500,000 feet (=95 miles) if the beds were directly superposed.

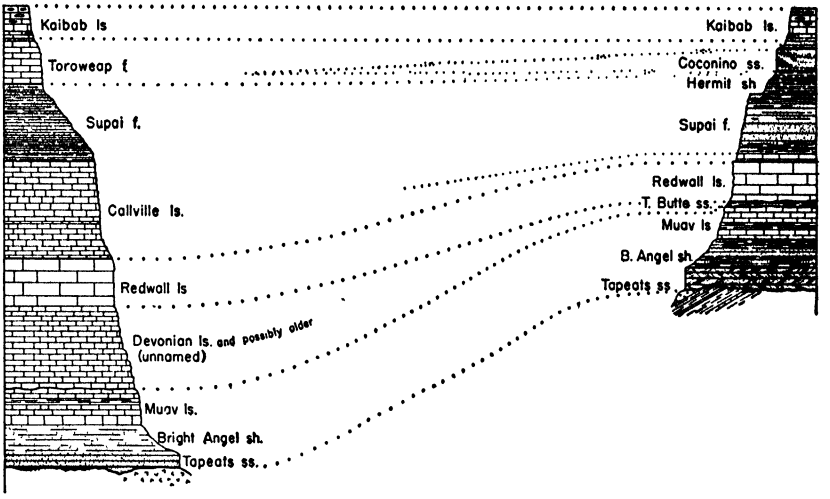


FIG. 5. Two profile sections in the Grand Canyon, illustrating the principles used in correlation. The section at the left is near the mouth of the canyon and that at the right is over 100 miles farther east, near Bass Trail.

Some of the criteria used in correlation are illustrated in Fig. 5. The left profile was measured near the mouth of the Grand Canyon and the right one at Bass Trail over 100 miles farther east. A general view of the formations represented in the section at Bass Trail may be seen in the frontispiece of this volume.

In the vicinity of Bass Trail nine major formations of sedimentary rock are recognized. At the top, rimming the canyon, is a thick formation of cherty, buff-weathering limestone (the Kaibab) rich in marine fossils of Middle Permian age.* Beneath it is a massive cliff-forming deposit of pure, well sorted, and strikingly cross-bedded sandstone (the Coconino). Below that is a soft red shale (the Hermit shale) forming

* The age relations of the periods of geologic time are shown in the *Geologic Time Chart* on p. 14.

a gentle slope down to a prominent bench that is held up by a formation of interbedded red siltstones and sandstones (the Supai) bearing footprints and fossil plants of early Permian age. The Supai in turn rests on a particularly massive light-gray limestone (the Redwall) that forms unscalable cliffs nearly 500 feet high along the canyon wall. It bears abundant marine fossils of Mississippian age. Below the Redwall is a thin sandstone (the Temple Butte) separated from the formations above and below by rather marked erosional unconformities. It has no fossils here, but not far away, along the canyon wall, it has yielded fish bones of Devonian age. Below it lies a group of three formations bearing trilobites that indicate a Cambrian age, and the lowest of these rests with profound unconformity upon ancient Pre-Cambrian rocks.

Now, if we compare with the left-hand section, the Kaibab formation is easily recognized because (1) it holds the same relative position at the rim of the canyon, (2) it has about the same thickness as at Bass Trail, and (3) it presents the same appearance as a buff-weathering, cherty limestone; moreover, (4) it yields many of the characteristic marine fossils restricted to this horizon at Bass Trail. If more proof were needed, (5) we could follow the canyon and trace the formation continuously along the rim (see frontispiece). The Redwall limestone can also be identified by the same five criteria. Over the distance of more than 100 miles it maintains about the same thickness, the same lithologic character, and the same faunas, and it can be followed in a continuous outcrop the full length of the canyon.

But the relations of the intervening formations present greater difficulties. Nothing like the Coconino sandstone is present in the western section, its position being occupied by red beds with interbedded limestone (Toroweap). The position of the Hermit shale, also, is occupied by red beds like the Supai. And in the western section there are about 2000 feet of limestone above the Redwall formation that do not appear in the section at Bass Trail. The name Callville has been given to this thick limestone formation. With the Kaibab and Redwall limestones running through as key horizons in both sections, the intervening formations are all limited to some part of the intervening time (middle Mississippian to middle Permian). But several possible relations suggest themselves. For example, the Callville limestone may thin and disappear eastward because it was never deposited there, or because it was eroded from that region before the deposition of the red beds. In this case there must be an important hiatus above the Redwall limestone at Bass Trail. On the other hand, the Callville limestone may change gradually into sandstone toward the east, and so be the equivalent of all or a part of the Supai red beds at Bass Trail.

If the latter assumption be true, it could not be established by any of the five criteria used above to identify the Kaibab and Redwall formations, for the Callville and Supai are not alike lithologically and they could hardly have the same fossils because the former is marine and the latter a nonmarine deposit. But in tracing the Callville limestone eastward along the canyon walls in continuous outcrop, we find a lateral change in lithology, as the limestone beds become sandy and reddish and finally alternate with layers of red siltstone and sandstone and *intertongue* with the red Supai. The intertonguing of the two formations, one marine and the other nonmarine, would indicate fluctuations of the shoreline back and forth across a wide belt during deposition. Such an intertonguing of two formations gives us a sixth means of correlation. Tracing along the canyon walls has actually demonstrated that the upper part of the Callville limestone does grade eastward into the lower part of the Supai red beds, as postulated. The lower part of the Callville, on the contrary, does not extend so far east and was never deposited in the region of Bass Trail. Now, if the Coconino sandstone be traced westward, it is found to grade over into regularly bedded red sandy shale, which in turn is replaced by limestone. Thus the Coconino sandstone is known to be largely equivalent to the Toroweap formation.

As for the beds below the Redwall limestone, the Temple Butte sandstone at Bass Trail is thin and probably nonmarine. It is limited below by distinctive, fossiliferous Cambrian beds. But in the western section some thousands of feet of Devonian (and possibly older) limestone intervene between the Cambrian and the Redwall limestone. These beds are marine and fossiliferous. They are still practically unstudied, but there is little chance that they will yield the same kinds of fish remains as those found near Bass Trail. It appears probable that the Temple Butte sandstone is equivalent to some small part of the Devonian limestone farther west, because (1) it occupies the same relative position between the Cambrian and the Redwall limestone, and (2) it has yielded fossil fish of Devonian age and the limestone has yielded marine fossils of Devonian age. When both faunas are fully and critically studied, each may be limited to some particular part of the Devonian system, and this may justify a more exact correlation than is possible at present.

To recapitulate, it may be noted that formations in separate outcrops may be correlated (1) because of lithologic similarity, (2) because of similar thickness, (3) because of position in a sequence of formations, (4) because of continuous tracing between outcrops, (5) because of lateral gradation and *intertonguing* when the formations are litho-

logically dissimilar, (6) because of similar fossils, and (7) because of fossils that are dissimilar (i.e., marine and nonmarine) but nevertheless indicate the same age. These are some of the chief, but not the only, means of correlation.

Subdivision and Classification of the Record

Although time flows continuously, both human and geological history are punctuated by important events that justify a recognition of distinct ages.

Crustal Disturbances Provide a Basis. Geologists have striven to find a natural basis of subdivision that would be widely applicable and thus unify the geologic study in different countries. At present the attempt is only partly successful, but there is general adherence to the belief that recurrent disturbances in the Earth's crust have broken the record and marked off the major divisions of time so clearly that they can be recognized the world over. This belief rests on the following considerations:

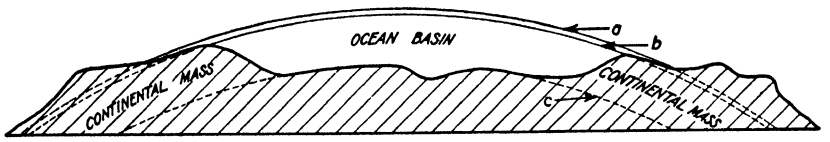


Fig. 6. Diagrammatic profile across an ocean basin and parts of two continents, vertical scale greatly exaggerated. Line *a* represents sealevel, line *b* the level of the edge of the continental shelf about 600 feet below sealevel, and line *c* the level of the average depth of the ocean floor.

1. The *deep-sea* basins lie between the continental masses (Fig. 6), generally exceed 6000 feet in depth, and average more than 12,000 feet. All sediments deposited at such depths are forever lost to us.

2. These basins are now a little more than brimful, the overflow covering the continental shelves with shallow marginal seas. A slight rise in sealevel would extend these seas far inland over the lowest parts of the continents, but a drop of not more than 600 feet would withdraw the water entirely into the deep-sea basins, leaving the continents generally exposed to erosion.

3. The sedimentary rocks that form most of the geologic record have accumulated *in shallow seas upon the continental masses* (or even upon the land areas above sealevel).

4. The great disturbances in the Earth's crust, marked by continental uplift and extensive mountain making, have repeatedly deepened the deep-sea basins and thus for a time drawn the seawater off

the continents, interrupting deposition there and forming a *break* in the sedimentary record.

5. Such an interval of crustal unrest is commonly followed by a longer one of stability, during which sealevel rises and the continents are more or less extensively covered by shallow seas in which a sedimentary record is formed. The rise in sealevel may be due to slow displacement of the water by sediments derived from the erosion of the highlands, or to slow creep of the continental masses toward the deep-sea basins, or to other factors unknown.

Since all the oceans are freely connected, a change in sealevel affects all alike, hence the *major* breaks should correspond in all quarters of the globe. In so far as this is true, we have a basis of subdivision of the record that is both *natural* and *universal.*

Confusing Effects of Local and Irregular Crustal Movements. In the above discussion we have assumed that the continental masses were stable and passive during the changes of sealevel. This, of course, is not true. There is abundant evidence in the modern coastal belts that some regions are rising while others are subsiding, and it is quite certain that similar local irregularities have characterized the movements of the past. Thus even at times of general continental emergence some regions have suffered local depression sufficient to maintain a permanent marine embayment in which transitional beds formed, bridging, more or less, even the greatest breaks. Moreover, as we shall see in later chapters, there have been numerous local disturbances, some of them involving strong mountain making, during times of general continental submergence. In a region thus affected there is a marked hiatus and marked unconformity, even though there is no corresponding break in most of the rest of the world.

Such irregularities make it difficult to evaluate the breaks in the record and have led to many controversies in the classification of geologic formations, but they do not completely invalidate the use of the greater diastrophic changes as a basis of subdivisions of geologic history.

Fossils Aid in the Classification. The evolution of life has been continuous though very slow. The resulting succession of faunas gives us a basis of chronology, although if the record of life were complete it would not necessarily form a basis for the natural *subdivision* of the record. In fact, however, the fossil record does afford our best direct means of evaluating the breaks in the record and of classifying the formations.

The progress of evolution has been greatly influenced by physical changes in the Earth. Uplift and continental emergence have radically altered the general environment, changing the course of ocean currents,

interfering with atmospheric circulation, and producing climatic changes of far-reaching effects. Moreover, the restriction of the shallow seas to the edges of the continental slopes has always produced great crowding and keen competition among the marine animals. Great crustal disturbances have thus brought on critical conditions for most plants and animals and led to a period of accelerated evolutionary change and many extinctions.

These changes take place, moreover, at the time when the seas have largely withdrawn from the continental masses and the record is effectively lost to us. The subsequent return of marine waters over the lands brings a greatly changed assemblage of animals and plants. Hence the great breaks in the physical record are also marked by major breaks in the biologic record. The fossils are therefore relied upon chiefly in the location of the physical breaks.

As implied in the foregoing discussion, the subdivision of the geologic record is based largely upon the marine sediments. The nonmarine or *continental* sediments (i.e., those deposited over the lands by streams, lakes, or wind) with their record of the land life would also serve as a basis of classification, but they are so patchy in their distribution that they are less serviceable than the marine record. Of course, the physical changes brought on by continental emergence and the elevation of lofty mountains alter the environment of land animals and land plants even more than that of marine life. When the continents are emergent, the climate is highly diversified, the land areas are expanded, and migrations are favored. Rapid evolution of the land life is thus fostered by the periods of diastrophism that interrupt the marine record.

Grouping and Naming of the Units

The natural breaks in the geologic record vary greatly in length and importance, and thus afford a basis for separating both large and small units of rocks and of geologic time.

Eras. At long intervals the Earth's crust has experienced profound disturbance and readjustment, resulting in broad continental uplifts, in the formation of great mountain systems, and in the concurrent deepening of the ocean basins. These are the crustal *revolutions*. They separate the greatest units of geologic time, which are known as *eras*. All geologic time is now divided into only a half-dozen eras, and these have been named according to the general character of the life that they record (see p. 14 for names and arrangement). Thus, the most ancient era is called *Archeozoic* (Gr. *archaios*, ancient, + *zoe*, life), and the latest, *Cenozoic*, the era of recent types of life (Gr. *kainos*, recent).

Periods and Epochs. Within each era there have been *disturbances* of the crust less profound and widespread than the revolutions but great enough to cause widespread retreats of the seawater from the continental masses, and to produce general, though not universal, breaks in the record. These episodes of disturbance separate *periods* of time. During the interval of relative stability and quiet corresponding to a period, the marine waters have flooded the continents more or less widely, producing inland and marginal seas in which sediments accumulated. The deposits corresponding to a period of time constitute a *system* of rocks. Lesser and more local breaks separate the periods into *epochs* of time and the systems into *series* of rock.

The names of systems, series, and formations are generally chosen for geographic localities where they have been first well studied, and the corresponding time units bear the same names. Thus, the *Cincinnatian series* was named for the rocks exposed in the region of Cincinnati, though equivalent formations in New York and elsewhere belong to this series and represent the Cincinnatian epoch. Likewise the Cambrian system bears the Roman name for Wales (Cambria), where its rocks were first studied, though the Cambrian period is recognized throughout the world. A few of the systems, however, were named before this custom was established and so do not have geographic connotations. Such are the Cretaceous (Lat. *creta*, chalk) and the Triassic (threefold).

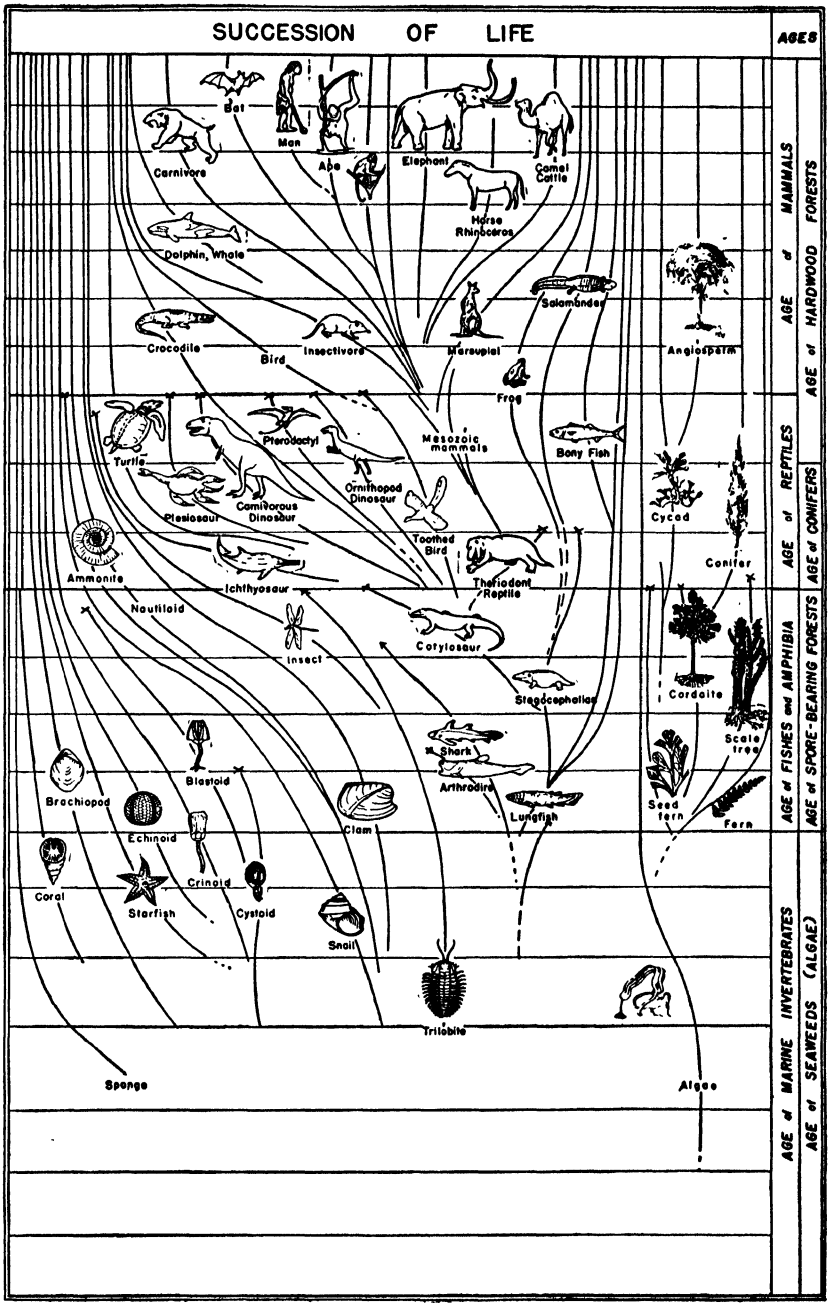
The series (of strata) and epochs (of time) generally bear geographic names, but it is also convenient to refer to them as Lower, Middle, and Upper series of a system and Early, Middle, and Late epochs of a period. In the following chapters these words are capitalized when used in this technical sense, and not capitalized when the meaning is more general or indefinite. Thus, the *Lower Cambrian* rocks were formed during *Early Cambrian* time, but the oldest known vertebrates lived in *late Devonian* time.

The Geologic Time Chart

It is essential in all historical studies to discover the order in which events have succeeded one another, for this permits an analysis of cause and effect. Moreover, such a general chronology serves as a framework about which historical data can be organized. The history of the Earth has thus been epitomized in the form of a chronologic chart known as the *Geologic Time Chart*. It is presented at this place because a knowledge of the sequence it records is indispensable in the study of the following chapters. It must be thoroughly memorized before we proceed.

TIME UNITS			DISTINCTIVE FEATURES	OROGENY	DATES
CENOZOIC ERA	CENOZOIC PERIOD	Recent epoch			
		Pleistocene epoch	The Stone Age of human history Glaciation widespread, mountains attain present heights	Cascadian Rev.	1000000
		Pliocene epoch	Climate becomes cooler and drier. Man diverges from the apes.		
		Miocene epoch	Mammals reach climax; grazing types evolve as prairies spread. Elephants reach America.		
		Oligocene epoch	Mammals evolve rapidly Great Apes arise in Eurasia		
		Eocene epoch	Modern orders of mammals appear and evolve rapidly		
		Paleocene epoch	Archaic mammals dominate. Valley glaciers appear locally.		
MESOZOIC ERA	CRETACEOUS PERIOD		Dinosaurs, pterodactyls, toothed birds reach climax and then die out Small archaic mammals appear Flowering plants and hardwood forests spread widely	Laramide Rev	60000000 To 70000000
	JURASSIC PERIOD		Dinosaurs and marine reptiles dominate Toothed birds appear Ammonites reach climax.	Nevadian Dist.	
	TRIASSIC PERIOD		Small dinosaurs and the first mammals appear Conifers and cycads dominate the forests Ammonites evolve rapidly	Palisade Dist	
PALEOZOIC ERA	PERMIAN PERIOD		Continental uplift and orogeny widespread Extremes of cold and aridity result in rapid evolution and many extinctions	Appalachian Rev	200000000
	PENNSYLVANIAN PERIOD	Carboniferous	Warm humid climate favors coal making Reptiles and insects appear Spore-bearing trees dominate swamp forests.		
	MISSISSIPPIAN PERIOD	Carboniferous	Shell-crushing sharks, crinoids, and lacy bryozoans attain climax.		
	DEVONIAN PERIOD		Lung-fishes evolve into air-breathing vertebrates (amphibians) First forests appear Brachiopods reach climax.	Acadian Dist.	290000000
	SILURIAN PERIOD		Climate warm, locally arid. Corals form widespread reefs. First meagre evidence of land life recorded.		
	ORDOVICIAN PERIOD		Seas spread widely over low continents Many groups of invertebrates make first appearance Trilobites reach greatest differentiation.	Taconian Dist	350000000
	CAMBRIAN PERIOD		Fossils abundant for the first time, representing marine life only Trilobites and brachiopods dominate Plants recorded only as lime-secreting algae		400000000
CRYPTOZOIC EON	KEWEENAWAN PERIOD		Vast lava flows and thick red sediments cover the Lake Superior region A geosyncline occupies the Rocky Mountain area	Killarney Rev	
	HURONIAN PERIOD		A geosyncline occupies the Great Lakes region. Glaciation is widespread in Canada Lake Superior iron ores are deposited		
	TIMISKAMIAN PERIOD		A long period of accumulation of sedimentary rocks is followed by great disturbances and then by profound erosion of the Canadian Shield	Algoman Rev	1050000000
	KEEWATIN PERIOD		Thick lava flows occupy the Lake Superior region, interfingering with the oldest known sedimentary rocks	Laurentian Rev	

FIG. 7. The Geologic Time Chart. In the panel at the right the ascending lines and plants illustrated. A cross at the end of a line implies extinction; an arrow indicates



show at once the geologic range and the biologic relationships of the groups of animals that the line should continue upward.

CHAPTER 2

THE SCALE OF TIME

Philosophers have speculated upon the age of the world since time immemorial, and their beliefs have ranged all the way from that of the Brahmins of India, who considered the Earth eternal, to that of Archbishop Ussher of Ireland, who in 1654 deduced from his study of the Scriptures that the Creation had taken place on the twenty-sixth of October in the year 4004 B.C. at 9 o'clock in the morning. Unfortunately, the latter date was inserted by some unknown author as a marginal reference in the King James version of the Bible, and thus became a matter of religious creed; thereafter it was heresy to assume more than 6000 years for the formation of the Earth and all its features, and, as the science of Geology grew up under the influence of this belief, supernatural explanations were at first given to many natural phenomena. The unconsolidated sediments and the glacial drift so widely spread over Europe were, for example, supposed to be the debris left by the Biblical Flood; stream valleys, especially canyons, were believed to have formed as sudden rifts during earthquakes; and mountain ranges were supposed to have arisen with sudden and tumultuous violence.

To the uprooting of such fantastic beliefs came the Scottish geologist Hutton, whose *Theory of the Earth*, presented in 1785, marked a turning point in thought on this subject. Hutton argued that *the present is the key to the past* and that, if given *time*, the processes now at work could have produced all the geologic features of the globe. This philosophy, which came to be known as the doctrine of *uniformitarianism*, is now universally accepted by learned men. It demands an immensity of time.

The growth of the physical sciences after the Renaissance provided means for a really scientific attack on the problem, and a number of ways of estimating the age of the Earth are now known. Most of them involve uncertain factors of such importance as to give the results qualitative rather than quantitative value; all of them, however, indicate great antiquity. The present belief of geologists (in which astronomers and physicists concur) is that the beginning of geologic time goes back some 2,000,000,000 years. Such figures stagger the

imagination and we hardly grasp their meaning. The astronomer Jeans framed the conception in more tangible form when he said: "If we represent the length of geologic history by the height of the Woolworth building, then we may lay a nickel on its tower to represent the span of human existence on the Earth and a thin sheet of paper upon this to represent all historic time."

The Hourglass of the Ages

The sediments carried to the sea by streams, like the sand trickling through an hourglass, give us a measure of time. This truth was foreseen by the Greek historian Herodotus about 450 B.C., when he observed the annual overflow of the Nile spreading a layer of sediment over its valley. He realized that the delta of the Nile had grown through such annual increments of river-borne muds, and concluded that its

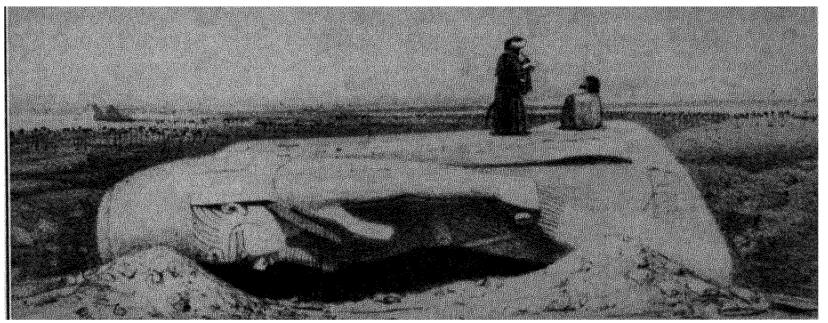


Fig. 8. Colossal statue of Rameses II at Memphis. This illustration by Bonomi in 1847 shows the statue as it lay face down, having fallen from its buried pedestal. About five years later, excavations were made to discover the thickness of the river-laid sediments about its base. The pyramids of Gizeh are seen in the distance at the left, and the Nile River is near the horizon at the right. Two observers, one standing and the other sitting, indicate the size of the statue.

building must have required many thousands of years. Concrete illustration of his deduction was made in 1854 when the foundation of the colossal statue of Rameses II at Memphis (Fig. 8) was discovered beneath 9 feet of the river-laid deposits. Since the statue is known to be more than 3000 years old, the rate of deposition at this place has averaged not over $3\frac{1}{2}$ inches per century. Excavations at Memphis showed the river deposits to have a depth of 40 feet, which, at the rate quoted above, would require about 13,500 years to form. This, moreover, is merely the surface veneer of the strata making the delta.

There are other local deposits for which the rate of deposition can be determined. Such, for example, are the postglacial varve clays in which summer and winter layers, like the growth rings in trees, record seasonal additions (Fig. 96, p. 159). Some of the older sedimentary formations appear likewise to be seasonally layered, and if so, the time involved in their deposition can be determined directly. On this basis, it is estimated to have required 6,500,000 years to accumulate the 2600 feet of banded shale in the Green River (Eocene) lake deposits of Colorado and Wyoming.

For most of the sedimentary rocks, however, no precise rate of deposition can be determined. By setting stream gages at the mouths of the major rivers we can determine the amount of sediment they now bear annually to the sea. Such data for a few of the larger rivers permit a rough estimate of the amount supplied by all the streams of the world. If we assume this to be the average rate of erosion for all geologic time, we need only divide the weight of all the sedimentary rocks by the weight of the annual increment to determine the length of time since erosion began on the Earth. But this solution is far too simple. The total mass of sedimentary rock can not be determined with any degree of accuracy because the thickness of such deposits is unknown over large areas, and because a large but uncertain part lies beneath the sea. Moreover, much of the sediment is at present derived from sedimentary rock and is returning to the sea for the second time. Probably much of the sedimentary material has been eroded and deposited again and again. Moreover, we have no assurance that the present rate of erosion is an average for all time; on the contrary, there is good reason to believe it is far too high. It is already evident, therefore, that a study of the rate of formation of sedimentary rocks can give us no exact results for the total length of geologic time. It merely indicates that the Earth is very old.

Sodium in the Sea

In the weathering of igneous rocks, the sodium is attacked to form highly soluble compounds. These salts are leached from the soil and carried in solution to the sea, whence the water returns as vapor to the clouds, leaving the sodium behind. Accordingly, the salinity of the sea must have increased steadily throughout geologic time. If all the oceanic salt has been derived thus from the weathering of primary rocks, it should form a basis for estimating the length of geologic time according to the formula

sodium in the sea ÷ annual increment of sodium = age of the sea.

The total amount of salt in the sea can be determined with a probable error of only a few per cent, since the volume of the seawater is known approximately and its salinity is almost constant. The amount of dissolved salt is tremendous; if it were precipitated it would form a mass of solid rock salt exceeding 4,500,000 cubic miles in volume. The sodium alone would weigh about 16,000,000,000,000,000 tons.

The annual increment of salt borne by the streams to the sea can also be estimated from the data gathered by stream gages at the mouths of great rivers, where the flow is recorded from day to day and the salinity measured by analysis of the water. In this way the salt derived from certain large drainage areas is measured and the total for all the lands can be estimated approximately by comparison. The sodium thus estimated is about 158,000,000 tons per year.

If we substitute the figures quoted above in our formula for a first approximation of the age of the Earth, we get about 100,000,000 years:

$$16{,}000{,}000{,}000{,}000{,}000 \div 158{,}000{,}000 = 101{,}265{,}000+.$$

For some years after the first application of this method in 1899, the figure 100,000,000 years was commonly used as the probable length of geologic time. But several considerations indicate that the figure, 158,000,000 tons, is too high to use in our calculations, for much of the present annual increment of salt is not derived from the weathering of primary rocks. Some of it is wind-blown in the form of dust from desert basins or of spray from the oceans; a part of it, some 14,500,000 tons of salt (5,700,000 tons of sodium), is mined and used by man and thus liberated into the streams; and much of it is leached from sedimentary rocks where it has been stored in the form of salt beds or disseminated salt or salt water. All this represents salt originally taken from the ocean and now being returned. Such cyclic salt makes no permanent addition to the salinity of the sea. The corrections for these and other factors would obviously be large, but we have no adequate data for a quantitative evaluation. If we should make deductions of all such cyclic salt, the annual increment would be far less than 158,000,000 tons and the calculated age would greatly exceed 100,000,000 years.

A further correction must also be made, for we have assumed that the present rate of erosion is an average for all geologic time, and a study of geologic history indicates that the present rate is far too high. We have just passed through one of the greatest of all periods of diastrophism, the continents are large and high, and erosion is greatly accelerated. In contrast, there have been long periods when the continents were low and partly submerged so that erosion was relatively

slight. We have no means of determining how much the present rate of erosion exceeds the average, but it has been thought to be three to ten times as great.

The necessary corrections for cyclic sodium and for the present accelerated rate of erosion would both tend to reduce our figure for the average annual increment of sodium contributed to the sea. This in turn would multiply our first estimate of the age of the Earth; but since so many uncertain factors are involved, the method at present offers no promise of a reliable quantitative value. It is not even certain that all oceanic salt has been produced by weathering.

The Radioactive Clock

The discovery of radioactivity at the turn of the present century brought a new and apparently precise method of measuring geologic time. The chief radioactive elements are *uranium* and *thorium;* they occur in certain types of granitic rocks (Fig. 9), and uranium occurs also in certain mineral veins, such as the pitchblende veins of Bohemia, in which Madame Curie first discovered radium.

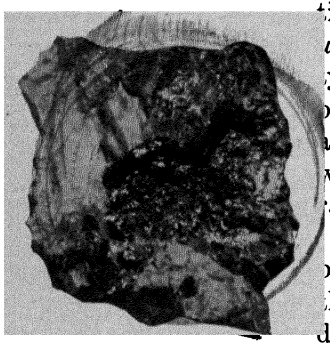


Fig. 9. A piece of uranium ore from Hybla, Ontario. The light-colored crystals are feldspar and the dark a uranium-bearing mineral, ellsworthite, which contains 15 to 18 per cent of uranium.

Regardless of chemical associations, heat, pressure, or any other known conditions, the radioactive elements undergo a slow disintegration into lead and helium. By-products of this atomic disintegration are the invisible radiations and the heat for which the radioactive substances are notable. In the disintegration of the atom of uranium (atomic weight 238.07), there are liberated eight atoms of helium gas (atomic weight 4), and the residue is an atom of lead (atomic weight 206). The reaction can be represented approximately as follows:

$$\underset{(238.07)}{U} = \underset{(206)}{Pb} + \underset{(8 \times 4 = 32)}{8He} + \text{heat}$$

We may consider the atom of uranium as a complex structure in which some of the building units are atoms of helium. The loss of an atom of helium alters the structure and changes the atom of uranium to something different. In the spontaneous disintegration, one helium atom after another is lost, and the uranium changes through a series of substances until, with the loss of the eighth atom of helium, it becomes

lead and is stable. In a mass of uranium, the disintegration is extremely slow but the rate is constant, regardless of all circumstances. After a crystal of uranium-bearing mineral has formed, the uranium must therefore gradually waste away, and lead steadily accumulate. If the rate of change be known, the ratio of lead to uranium should give the age of the mineral.

Fortunately, the rate of disintegration of uranium can be determined with great precision by counting the helium atoms emitted by a measured quantity of uranium. These may be counted automatically by a sensitive electrical device or directly by observation. For example, if a small quantity of uranium be placed on a screen of zinc sulphide, each escaping atom of helium makes a flash as it strikes the sulphide, and under a microscope these can be seen, like fireflies on a dark night, and counted. Such counts indicate that one gram of uranium yields annually 1/7,600,000,000 of a gram of lead. At this rate, U grams of uranium will produce

$$\frac{U}{7{,}600{,}000{,}000} \text{ grams of lead in one year}$$

and

$$\frac{tU}{7{,}600{,}000{,}000} \text{ grams of lead in } t \text{ years.}$$

Hence $$Pb = \frac{tU}{7{,}600{,}000{,}000}, \quad \text{or} \quad t = \frac{Pb}{U} \cdot 7{,}600{,}000{,}000.$$

Therefore, when the ratio of lead to uranium (Pb/U) in a crystal of uranium-bearing mineral has been determined, we can solve the equation for t, the age of the mineral. In precise calculations, allowance is made for the gradual decrease in the quantity of uranium, for the presence of thorium as well as uranium, and for other factors, but the principle is illustrated by the example used above.

In practice it is necessary to find an occurrence of unweathered uranium-bearing minerals, select a single fresh crystal for analysis, and determine the ratio of lead to the uranium present. Care must be taken to reject weathered specimens because uranium may be dissolved by subsurface water and either carried away or precipitated in the openings in the rocks through which it passes. If part of the uranium has been removed by solution, the lead-uranium ratio and the calculated age will be too large; and if extra lead has been added from other sources the ratio will be too great and the inferred age excessive. Fortunately, the atomic weight of the lead derived from uranium is slightly different from that of ordinary lead and so by very critical checking it is possible to determine what proportion of the lead in a mineral is of radioactive origin.

With very rare exceptions, crystals of uranium and thorium minerals have formed only in igneous rocks, and pure crystals large enough for satisfactory study occur chiefly in pegmatite dikes and other coarsely crystalline plutonic rocks (Fig. 9). Therefore radioactivity permits us to date certain igneous rocks precisely in years, but the age of sedimentary formations must generally be inferred from their associations with dated igneous rocks. Fig. 10 illustrates the problem. Assuming that uranium-bearing minerals have been found in the dike at *X* and that the lead-uranium ratio indicates an age of 60,000,000 years, we know that this is the length of time since the igneous intrusion. But the question remains, what geologic period does this represent?

The dike clearly cuts the sedimentary formation *K* and is therefore younger than *K*. It is unconformably overlapped in turn by sedimentary formation *T* and is of necessity older than that. Now, if the sedimentary formations are fossiliferous and *K* includes certain types of ammonites or dinosaurs, we know that it is of Upper Cretaceous age; and if *T* includes certain types of three-toed fossil horses we can be sure it is of Oligocene age. It is then possible to say that the intrusion is post-Cretaceous (or at most late Cretaceous) and pre-Oligocene. But in the absence of formations of intermediate age no more precise dating is possible. If, on the contrary, the overlying formation, *T*, were of Paleocene age we would know that the intrusion occurred about the end of the Mesozoic era and we would have one fixed date in our geologic time scale.

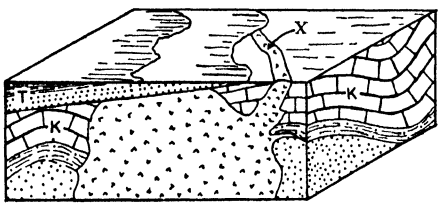


FIG. 10. Block diagram to illustrate the problem of determining the *geologic* date of formation of a radioactive mineral.

But in some cases the pegmatite dikes occur in schistose rocks that can not be directly dated. For example, the pegmatite at Branchville, Connecticut, has yielded uraninite crystals with a lead-uranium ratio indicating an age of 350,000,000 years; but it lies in a belt of deformed schists far from any fossiliferous rocks that could determine the geologic period of its intrusion.

The oldest rocks thus far determined are in Manitoba and Carelia, Russia, and their ages are around 2,000,000,000 years. Pegmatite dikes in the core of the Black Hills at Keystone, South Dakota, record an age of 1,420,000,000 years. Thus far, only a few of the uranium minerals suitable for analysis are closely dated geologically, but future work will undoubtedly greatly multiply them. The following

instances may be cited as the best-established dates in the geologic time scale:

Geologic Age	Age in Years	Locality
Late Cretaceous or Early Cenozoic	60,000,000	Gilpin County, Colo.
Early Permian	230,000,000	Oslo, Norway; Joachimstal, Bohemia
Late Cambrian	400,000,000	Güllhögen, Sweden
Late Pre-Cambrian	620,000,000	Katanga, Belgian Congo
Mid Pre-Cambrian	1,420,000,000	Keystone, South Dakota
Early Pre-Cambrian	1,800,000,000	Carelia, Russia
Early Pre-Cambrian	2,300,000,000	Winnipeg River, Manitoba

From these data it appears probable that the beginning of the Cenozoic was about 60,000,000 years ago, of the Mesozoic about 200,000,000 years, and of the Paleozoic about 500,000,000 years. Since the oldest dated rocks are intrusive into still older schists, it is probable that the Earth is at least 2,000,000,000 years old. This brings out the striking fact that nearly three-quarters of geologic time had transpired before the Cambrian period, which preserves the first adequate record of life.



WARD'S NATURAL SCIENCE ESTABLISHMENT.

Fig. 11. The Tree of Life. Simplified from a colored wall chart by Heintz and Störmer. Animals below the wavy white line are aquatic and those above are adapted to land life.

Chapter 3

THE CONSTANT CHANGE OF LIVING THINGS

The Doctrine of Evolution

A thoughtful person can hardly survey the great diversity of life about him without wondering how the many kinds of plants and animals came to be. And if he contemplates the fossil record and finds that in each geologic age the Earth was inhabited by still different types of life, that question becomes more insistent. Thus far two, and only two, answers have been suggested — the first is Special Creation, the second, Evolution.

The first theory, that of Creation, assumes that each kind of animal and plant was "molded from the dust of the Earth" by the Creator, and "given the breath of life" in its present form, each being a "special" and independent creation. To primitive people who knew but a few hundred kinds of animals and plants, and had no knowledge of Biology, this seemed the simplest and most acceptable explanation, as natural as the belief that the Earth was flat and that it formed the center of the Universe about which Sun and Moon and stars revolve.

From such early speculation it was incorporated in the ancient Hebrew scriptures and so, for centuries, exerted a profound influence on the thought of the Christian world.

The long and extensive experience of breeding domestic animals and plants suggested a different origin. It is known, for example, that all modern breeds of dog can be traced back to a single species of wild dog, that all our domestic horses have come from one or two species of wild pony, and that the many breeds of cattle have sprung from one, or at most a few, wild ancestors. If it has been possible, within a few thousand years, to change a wild dog into forms as diverse as the whippet, the bulldog, and the poodle, and if, by careful selection and breeding, it has been possible to transform the scrawny wild pony of central Asia into the sleek Arabian race horse, the toylike Shetland pony, and the ponderous Percheron, then we can only wonder if in similar fashion each kind of wild life has developed from some other, by gradual change and specialization. This line of thought led to the doctrine of Organic Evolution, which is the belief that from some geologically remote, primitive form of life all the diverse kinds of animals and plants have developed, each *evolving* from some previous form by gradual and orderly change. According to this conception, all creatures are genetically related, like the members of a great human family, and the degree of relationship of different groups of animals and plants may be represented by the branches of a family tree (Fig. 11).

Evolution is no less a *Special* Creation than that conceived in the Scriptures; it is only a *different method* of creation — one that is still taking place about us and which we can hope to understand. There is still much to learn about the ways and means by which it is brought about, but enlightened people can no longer doubt that evolution *is* the *method of creation*, and it is now universally accepted as a guiding principle in all fields of Biology.

Evidences of Evolution

The evidence of evolution is so varied and so extensive that volumes would be required to review it all, and most of it is too technical for simple presentation. Therefore, we can only hope here to suggest the *nature* of the evidence. These illustrations are chosen from three distinct lines of investigation, the first two biologic, the third geologic.

Comparative Anatomy: Homologous Structures. It is a striking fact that in related groups of animals a given organ or anatomical

structure is invariably built on the same plan. This is illustrated repeatedly in Fig. 12, for, in spite of the impressive differences between reptile, lemur, and man, the skeletons of all three are constructed on the same fundamental plan, and their elements can be matched bone for bone. The fore limb in each includes a single upper arm bone (humerus), a pair of forearm bones (ulna and radius), a series of wrist bones (metacarpals), and five digits.

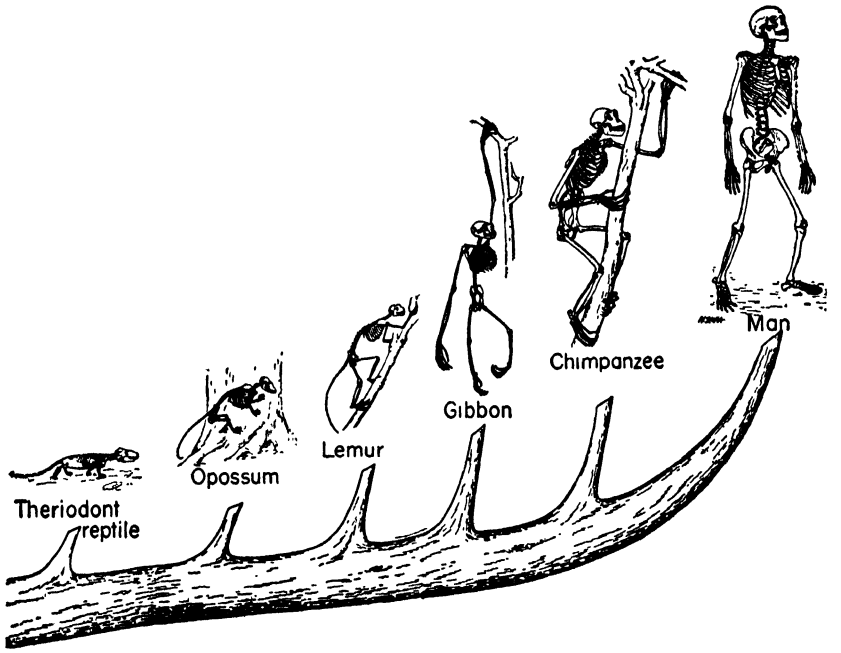


FIG. 12. Series of skeletons from reptile to man. After W. K. Gregory.

If we extend the comparison to distantly related mammals such as the bat, the seal, and the dog (Fig. 13), we find great modifications of the limbs for different habits of life; yet the arm of a man, the wing of a bat, the flipper of a seal, and the foreleg of a dog are built with the same skeletal elements, the dissimilarities being due essentially to differences in size and proportions of the individual bones. Organs that thus agree in fundamental structure are said to be *homologous* (Gr. *homos*, the same).

A study of the muscles and of the internal organs would greatly multiply the examples of homologous structures in the animals mentioned. Such likenesses indicate kinship and descent, with modifica-

tion, from a common five-toed ancestor; they are inexplicable on any other basis.

Vestigial structures — those that have lost their function — afford perhaps the most telling evidence from comparative anatomy (Fig. 16). Such, for example, are the ear muscles in man, which are homologous

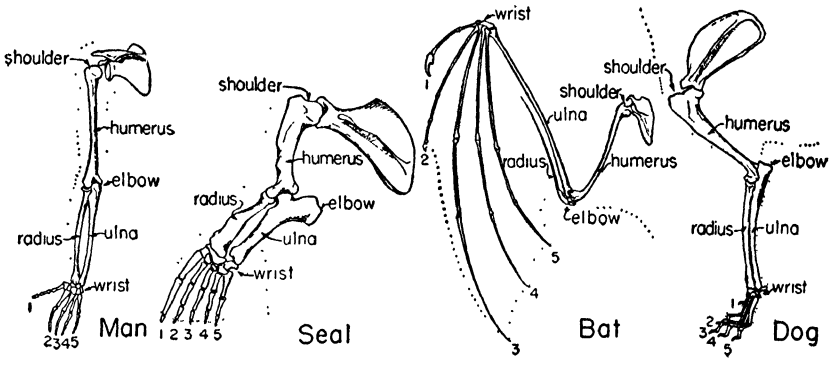


FIG. 13. Left fore limb of man, seal, bat, and dog, showing homologous structures.

with those that move the ears of the lower mammals. But in most humans they are no longer under voluntary control and serve no useful purpose. Another vestigial structure is the human appendix, which seems to be only a source of danger, although its homologue in many lower animals is an important part of the digestive system. About 180 such useless features have been recorded in the human body. One of the striking and unfortunate misfits of our anatomy is the way in which the viscera are supported in the body cavity. All the mammals, save man and the apes, walk on all fours, with the body in a horizontal position, and the delicate mesenteries that hold the various organs in place are well fitted to this posture. But in standing upright, man has brought the body into a vertical position in which the mesenteries, supporting the viscera and arranged as in the quadrupeds, are inadequate and inefficient. As a result, humans suffer from "fallen stomach," prolapse of the womb, paunchiness, and hernia. Surely, if a body were created *de novo*, it would not be endowed with useless and dangerous appendages *aping* those which are functional in other animals; and the human body would hardly have been given the most inefficient and troublesome visceral support of all the mammals, one that is efficient for the quadrupeds but not for man. Such vestigial structures admit of no other rational explanation than that man is related to other animals by common descent from ancestors in which these structures were functional.

Embryology: The Law of Recapitulation. Each individual begins as a single cell and by repeated cell division grows and passes through a remarkable series of embryological and juvenile stages before assuming its normal adult form. This orderly sequence of developmental stages constitutes its *ontogeny*.

One of the great biological discoveries of the last century is the fact that the ontogeny repeats briefly (and in many cases imperfectly) the racial history. Stated as a natural law, *ontogeny* (the developmental history of the individual) *recapitulates phylogeny* (the history of the race). The amphibians (for example, frog and salamander) provide an illustration of such recapitulation (Fig. 14). They lay their eggs in the water and these hatch into tadpoles that are in essential respects fishlike, breathing by means of gills and having no lungs or

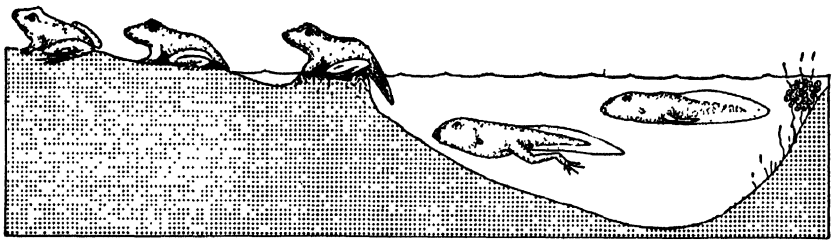


FIG. 14. Metamorphosis of the frog. From right to left: cluster of eggs; tadpoles showing two late stages in the budding of limbs; three early stages of terrestrial life showing the gradual loss of the tail in the young frog.

limbs. But during growth the gills are resorbed, lungs are formed, legs bud out from the body, and, after a transition period, the animal leaves the water to spend the rest of its days on land. This remarkable metamorphosis implies that the remote ancestors of the amphibia were fishes, from which they descended by migrating from the water to the lands, with all the modifications which that migration imposed.

Recapitulation really means that an animal has inherited from its ancestors a certain ontogeny which it repeats up to the point at which its own peculiar specialization begins. The amphibians inherited from their remote ancestors, the fishes, the capacity to lay only small eggs without much yolk and without shells. Such eggs can survive and hatch only in water, and the young, of necessity, breathe by means of gills. The amphibians were never able to improve on this habit and so, throughout the ages, have returned annually to the water to spawn.

Many fossil shells preserve a record of their own ontogeny. Consider, for example, the keyhole shell, *Pygope*, among the Jurassic brachiopods (Fig. 15). The adult shell has a hole passing through its middle, like

the hole in a doughnut. But a young one has the shape shown in *A*, a slightly older one, *B*, and a half-grown shell, *C*. The lines of growth on the adult shell, *D*, recording its margin at many stages of development, show that it passed through all the shapes preserved in the young shells. It is obvious that the very young shell was not perforated but had a shallow notch at its front margin, and during growth it became deeply bilobed and the notch became deep and rounded; eventually the lobes converged and grew together, thus transforming the notch into a hole. This ontogeny would imply that *Pygope* descended from a remote ancestor which at maturity was shaped much like the young

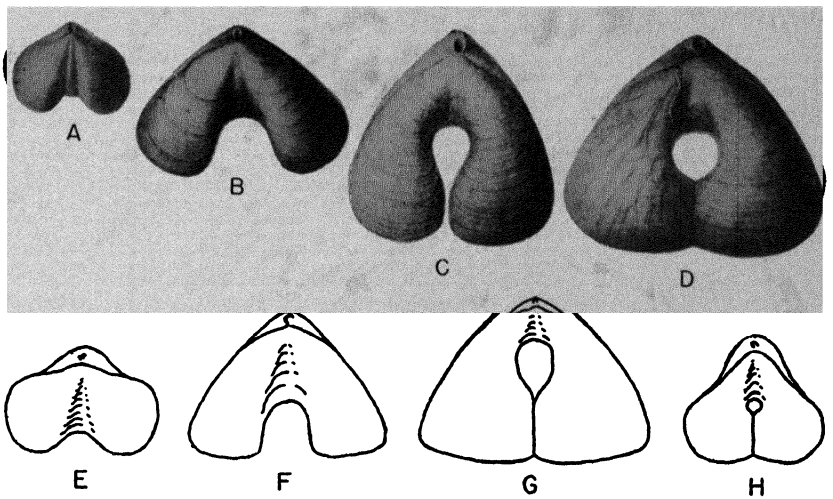
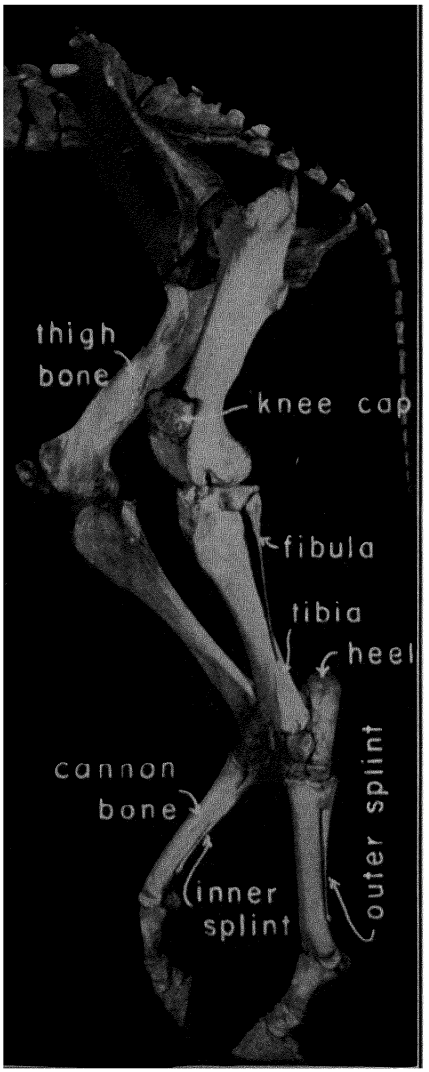


FIG. 15. Individual and racial history of the keyhole brachiopod. *A–D*, individual shells, representing four stages of growth in a single species (*Pygope diphyoides*); *E–H*, adult shells of four different geologic ages, showing the racial history; *E*, *F*, and *G* are from successive Jurassic ages and *H* from the early Cretaceous.

shell, *A*, and that, during the ages, the race underwent progressive changes of shape similar to those repeated in the ontogeny of *Pygope*. In actual fact, a series of species has been found in successive horizons in the Jurassic and Cretaceous rocks of Europe which prove that the racial development *did* follow this course (Fig. 15, *E–H*).

In so far as the early ontogenetic stages are inherited from ancestors, they clearly indicate the general nature of the ancestral stock of any animal. Thus, closely related animals should be closely alike in their early ontogeny, and, conversely, animals that are closely alike in their youth are probably genetically related even though they specialize and become dissimilar at maturity.

Paleontology: The Documentary Evidence. If life has evolved gradually since early geologic time, the fossils preserved in successive formations should record many intermediate stages between forms now widely differentiated, and should provide connecting links between even widely distinct stocks of animals and plants. In following chapters we shall have occasion to note many such cases, some of which have played a major role in establishing the doctrine of descent. In the study of embryology and comparative anatomy we have only circumstantial evidence of evolution, but in the fossil remains of evolving series we have the actual documentary evidence that the changes have occurred.



American Museum of Natural History.

FIG. 16. Skeleton of hind legs of modern horse.

The origin of the keyhole shell discussed above is an example; the ontogeny led us to infer how the perforation developed, but the discovery of fossil shells representing the inferred changes in successive Jurassic and Cretaceous formations affords the documentary proof in the case.

The skeleton of the horse's leg displays interesting vestigial structures whose significance is clearly shown by the fossil record. In the hind leg, for example, if we begin with the hip joint (Fig. 16), it is easy to identify the thigh bone and the knee cap, and below these the paired lower leg bones, the tibia and fibula. The hock is really the heel, as shown by its relations to the short metatarsals, and the elongated toe bones form the lower

leg. From this examination we may conclude that the horse walks on the *end* of one toe and that the lower part of the leg has been greatly lengthened as the heel came up off the ground (please examine Fig. 136, p. 216).

Now in primitive mammals, and even in the specialized ones that use their hands and feet for grasping or digging, the paired lower limb bones are subequal in size and provide for a rotary motion of the hands and feet. But in the horse, which can bend its leg only fore and aft at the heel, the fibula is reduced to a mere sliver and its lower end does not even make contact with the foot bones. The presence of this vestigial fibula implies, however, that the remote ancestor of the horse had a less specialized limb with freer movement of the foot. And on each side of the main toe bones (the cannon bone) there is a slender bone known as the *splint*, which can be nothing but the vestige of another toe. The splint bones clearly imply that the ancestor of the modern horse had three toes, as do the rhinoceros and the tapir.

The series of fossil horses recovered from successive Cenozoic formations in the western United States proves this inference to be true beyond any doubt. For example (Fig. 139, p. 218), all the fossil horses from the Pleistocene, and most of those from the Pliocene, are like the modern horse, but those of the Miocene *all* have three toes on each foot. In these, however, the side toes are small and in most species apparently functionless, probably dangling like the dew claws of cattle. In the underlying Oligocene beds, on the contrary, the three toes are subequal in size on each foot and all shared in bearing the animal's weight. Finally, in the still older Eocene strata, vestiges of the other two toes have been found in the front feet. No fully five-toed ancestor has yet been identified, but it is inferred that such a one existed. Illustrations of the paleontological evidence of evolution could be multiplied to any length, for they form the essence of the geological history of life.

Ways and Means of Evolution

Variation. Heredity is the principle that "like begets like," the parent passing on to its offspring all its distinctive characteristics. However, no individual is exactly like its parents, nor is it precisely like any of its brothers and sisters, even of the same brood; and commonly there is an appreciable variation among individuals of the same species. Thanks to recent progress in the science of Genetics we now understand a good deal about the way in which variations arise; but the facts are too complex and technical for brief presentation. Regardless of the

cause, experience indicates that in spite of the heredity principle, variations, mostly slight, occur in each new generation.

The Struggle for Existence. All kinds of animals and plants produce more offspring than can possibly survive. Many of the lower animals lay thousands and even millions of eggs each year — the salmon as many as 28,000,000 and the oyster more than 100,000,000 — and a plant such as the elm or maple tree produces innumerable seeds. This means that among such organisms only one out of millions lives to maturity, otherwise the population of any species would rapidly increase. Even in the higher animals, such as man, where few young are born, more die young than survive to maturity.

Thus, throughout Nature there is an intense and never-ceasing struggle on the part of all kinds of organisms to exist and to grow and to reproduce their own kind. The struggle is against the environment, against enemies that devour, or those that cause disease; commonly it is against members of the same kind, in competition for food, or even for "a place in the sun." Life's struggle is exceedingly harsh toward the young, and success is the rare exception.

Natural Selection. In a struggle so severe, any advantage, however slight, may decide between death and life. And in the many trivial variations that appear in any species, some will afford an advantage and will tend to survive, while others, less favorable, will tend to be exterminated. For example, if the species is an animal living in an environment where fleetness is necessary to escape carnivorous enemies, the slow and the underdeveloped young in the herd have little chance to reach maturity, whereas, on the average, the most precocious will survive and pass on their characteristics to new descendants. In this way Nature selects, as a breeder of stock might do, eliminating the unfit (unfit for a particular environment) and permitting only the fit to continue the race. And so, in spite of endless and random variations from generation to generation, only selected ones will survive. By this method Nature has evolved new species from old, to meet new or changed environments.

A single illustration may serve to show how such adaptations are produced. The nut-jay, which ranges over Europe from the Alps to Siberia, lives on the seeds of evergreens. In the Alps it feeds on pine cones, which are tough and hard, and require a stout, thick bill if the bird is to break them apart and extract the nut. But in Siberia, it has to feed on cedar cones instead of pine, and in these the seeds lie deeper but are not so well protected, and here a longer, more slender beak is a decided advantage. Now when the nut-jay appeared in Europe (whether by migration or evolution) those birds that varied toward

long, slender bills could not survive through a hard winter in a pine-clad region where the competition for food was keen, because their fragile beaks could not break enough pine cones. The birds with short, stout beaks fared much better. Conversely, the short-beaked birds could hardly survive in the cedar forests because they could not reach the nuts; there, the birds with longer and more slender beaks survived. Thus it has come about that, through many generations of natural selection, the nut-jay of Siberia has a slender beak with the upper jaw protruding about one-tenth of an inch beyond the lower, while the nut-jays of the Alps have short, stout beaks.

Illustrations could be multiplied ad infinitum if space permitted, for the whole complex of life is a maze of adaptations to special habits and conditions.

Many biologists believe that new species arise from old through gradual change forced by natural selection operating on random micromutations. Others believe that from time to time more profound changes in the genes may cause megamutations great enough to start a new species at one jump. There are other factors that may also play a part. As to the general doctrine of evolution by descent with modification, there is no longer any doubt, but the ways and means are still the subject of intensive research and hot debate.

Chapter 4

A LIVING RECORD OF THE DEAD

A Frozen Carcass in the Tundra. In August, 1900, a Russian hunter crossing the Beresovka River in eastern Siberia stumbled upon the carcass of an elephant, partly exposed by recent caving of the river bank but still tightly frozen in soil and ice. With mingled curiosity and fear, he knocked loose a tusk, which he later sold to a Cossack. The latter, hearing his story, relayed the news to St. Petersburg that another frozen mammoth had been found. An expedition outfitted by the Imperial Academy of Sciences made a 3000-mile journey to study and collect the beast, arriving at the spot in September, 1901, after the animal's back had been exposed to the sun of two summers and wild dogs had gnawed most of the flesh from it. Excavation soon proved that the flesh of the buried limbs and much of the body was still intact and "red."

The occurrence of this animal 80 miles within the Arctic Circle and more than 2000 miles north of the present range of the elephant is no more remarkable than the features of the animal itself. Unlike any living elephant, it bore a heavy coat of yellowish-brown wool interspersed with long black hair; it had but four instead of five toes on each foot; and its head was high-crowned and very short, giving the beast a profile quite distinct from that of any living elephant. It was, in short, a specimen of the extinct woolly mammoth, a species that ranged widely over the snowfields of Europe and North America during the last part of the Ice Age. Unmistakable pictures of such creatures were left by the prehistoric cave dwellers on the walls of some of the caverns in France (Fig. 17), but the species has been extinct so long that we find no allusions to it either in historical records or in the legends of any living people. The animal certainly died many thousands of years ago and had been preserved in nature's cold storage, the arctic tundra. In spite of its antiquity, the flesh was fresh enough to be devoured by the dogs. Clotted blood in the chest, unswallowed food, and broken bones indicated clearly an accidental death. The anatomy of the animal is almost as fully known as though it were still living.

Images in Stone. Less spectacular but no less real are the bones and shells of animals entombed in solid rock in many parts of the world. Whether it be the print of a fern leaf, the gaunt skeleton of a

dinosaur, or a mere broken shell, all are remains of creatures that lived and died and were buried in the sediments that have solidified into stone about them (Figs. 18 and 19).

The ancients observed such strange "images in stone" and speculated upon their meaning. The Romans called them *fossils*, because they were objects dug up (Lat. *fossilis*, from *fodere*, to dig).

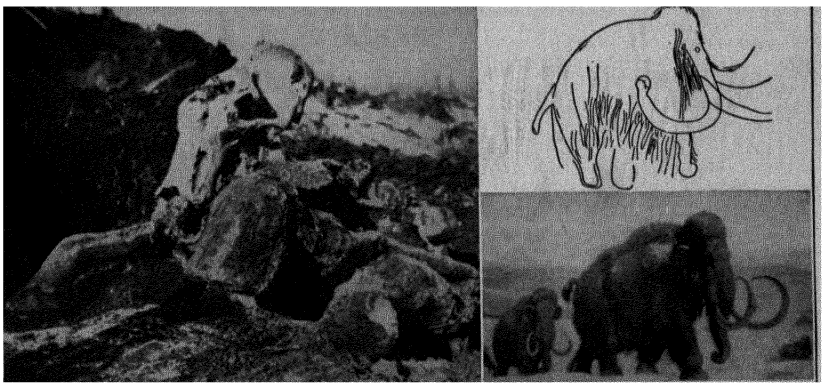


FIG. 17. The woolly mammoth. Left, the Beresovka specimen, a frozen carcass after partial excavation; lower right, a modern restoration of the species, by Charles R. Knight, based on this and other specimens; upper right, a drawing by Paleolithic man on the wall of a cave at Combarelles, France.

The Nature of Fossils. The term *fossil* was at first loosely applied to any curious object found in the rocks, but it came gradually to be restricted to those of organic nature. As now defined, it includes *any recognizable organic remains or impressions of the same, preserved from the geologic past by burial in the Earth's crust.*

Ordinary coal and petroleum are not regarded as fossil, in spite of their organic source, because they show *no recognizable structures.* However, some coals include fragments of fossil plants.

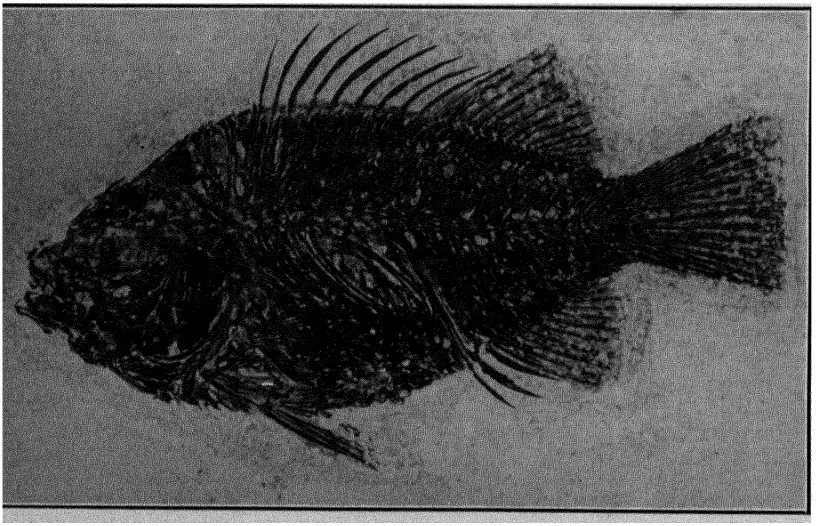
The remains of an animal or plant recently dead are not considered fossil, even though naturally buried and preserved — a considerable antiquity is implied in our definition, but since the present grades insensibly into the past we must either assign an arbitrary boundary or leave a broad indefinite zone back of which organic remains are considered fossils and after which they are not. One geological wag has proposed that "if they stink the remains belong to Zoology, but if not, to Paleontology." Commonly, the remains of organisms that died during the Recent epoch are not considered to be fossil, and yet there is a growing tendency to speak of fossil shell mounds and of fossil men, even when they are definitely of post-Pleistocene date. A more accu-

rate current definition would probably include as a fossil any naturally preserved organic remains of prehistoric times.



Field Museum of Natural History.

FIG 18. A skeleton in the rock. This complete skeleton of an extinct ground-sloth (*Scelidotherium bravardi*) was discovered in the bank of a small arroyo in the Pampas formation of Argentina by the Marshall Field Paleontological Expedition of 1927, and is now shown in the Field Museum exactly as it lay in the rock. Length of specimen as exposed, about 8 feet.



Carl O. Dunbar.

FIG. 19. Skeletal remains of a fish preserved in slabby limestone of the Green River formation (Eocene) in Wyoming. The fossil is permineralized. About ½ natural size.

Most fossils represent extinct species of animals or plants, but extinction is not a criterion by which to judge whether the remains should be

considered fossil. There are many species of marine invertebrates, for example, that have existed since Miocene time and their shells occur as fossils in Cenozoic rocks. On the other hand, the *dodo* of Mauritius was extinguished by early explorers about 1680, but its remains of historic date are not considered fossil.

The study and interpretation of fossils have become a special branch of Geology known as Paleontology (Gr. *palaios*, ancient, + *onta*, living beings, + *logos*, discourse).

Types of Preservation of Fossils

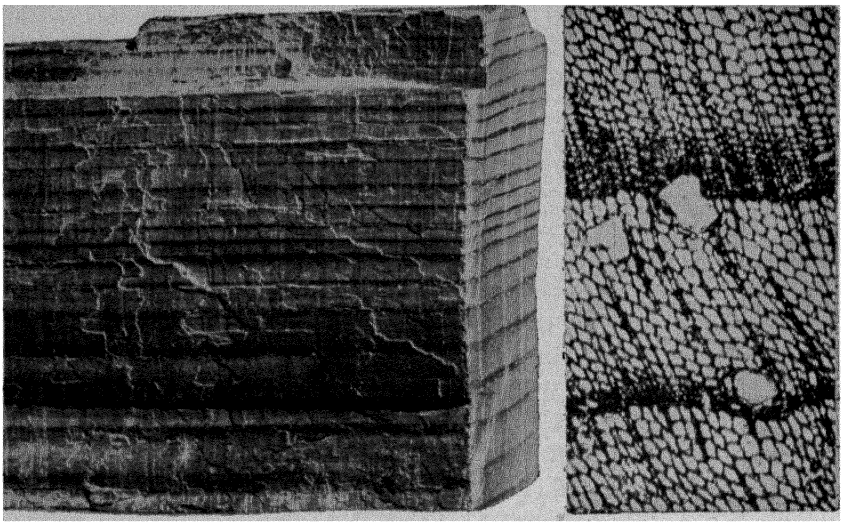
Actual Preservation. The preservation of flesh and other soft tissues is a very rare phenomenon, possible only where bacterial action and decay have been almost miraculously inhibited. Oil seeps have, in a few instances, supplied sufficiently antiseptic conditions for the preservation of flesh since Pleistocene time, and the frozen soil of the Arctic has yielded half a hundred carcasses of the woolly mammoth, but no animals older than the Ice Age have been preserved entire.

In the museum at Lemberg, Poland, there stand side by side the skeleton and the mounted skin of a woolly rhinoceros, an extinct species adapted, like its contemporary, the woolly mammoth, to life in the Pleistocene snowfields. This specimen, like several others, with parts of the skin and flesh still adhering to the bones, was found in an oil seep in Galicia. Another remarkably complete specimen was excavated in the district of Sarunia, Poland, in 1930.

The Beresovka mammoth was one of the most complete frozen fossils ever found, but the skeleton of another equally remarkable carcass was brought back to St. Petersburg from the Lena River delta in 1799, and there are records of fifty-one Siberian occurrences in which parts of the flesh and skin have been preserved. A few similar but fragmentary finds have been made in Alaska.

Although soft tissues rarely occur fossil, the hard parts, such as bone, shells, or woody tissue, have commonly been preserved since early Cenozoic time with little change. The logs embedded in Eocene lignites of Germany have suffered slight decay and discoloration, but the grain and texture of the wood are still preserved with little chemical alteration. Cenozoic shells embedded in marl or clay likewise show little change. Some of the Upper Cretaceous shells, in spite of their 60,000,000 years or more of antiquity, show scarcely any alteration, retaining faithfully the delicate details of surface sculpture, and rarely even the color pattern.

Petrifaction. In the older rocks, the hard parts alone are usually preserved, and these commonly appear to be turned to stone, as indeed they are. Such fossils are said to be petrified (Gr. *petra*, stone). The change from the original to the fossil condition is accomplished in one of several ways.



Yale Peabody Museum.

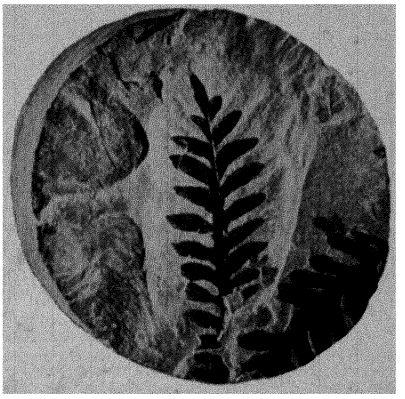
FIG. 20. Petrified wood from the fossil forests of the Yellowstone National Park. At the left, a piece of the silicified wood about natural size, showing the grain, growth rings, and medullary rays; at the right, a thin section cut from the end of this piece, enlarged about 10 times, to show the cells of the wood in parts of three growth rings. Photographs not retouched.

If the original structure is porous, as a bone or certain shells, mineral matter, usually calcium carbonate or silica, may be added from the underground water so as to fill the voids without changing the original substances. This makes the object heavier, more compact, and more stonelike, at the same time protecting it from penetration by the air or by solutions that would dissolve and destroy. Petrified bone is usually thus preserved.

Again, the original substance may be replaced, a molecule at a time, by mineral matter of a different sort. Wood is thus commonly replaced by silica, and in many instances the replacement is so delicate that even the microscopic cell structure is preserved when the wood is completely turned to stone (Fig. 20). The fossil forests of the Yellowstone provide a striking and familiar illustration.

On the other hand, the volatile elements of an organic structure may be distilled away, leaving a residue of carbon. The beautiful traces of

fern leaves so common in the roofing slates of coals are veritable "carbon copies" of the original (Fig. 21). More rarely, the presence of animal tissue is thus recorded, especially in black shales; a striking example is that of the marine reptiles known as ichthyosaurs, whose skeletons found in Lower Jurassic shales of Germany are in some instances surrounded by a film of carbon, preserving the outline of fleshy fins and tail flukes (Fig. 23). Even jellyfish and soft-tissued worms have been thus preserved in the Middle Cambrian black shales of Mount Wapta, British Columbia (Pl. 2, p. 170).



Yale Peabody Museum.

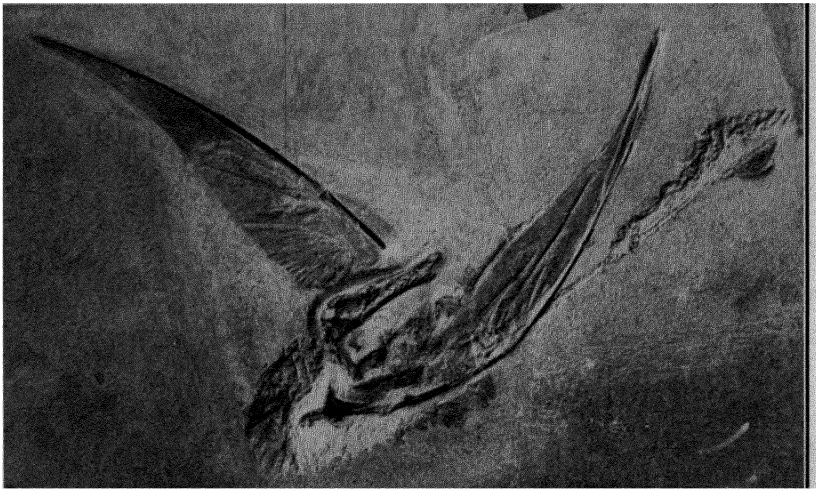
FIG. 21. Carbonized fern leaves in a deep-well core. Photograph not retouched. About ⅔ natural size.

Molds, Casts, and Imprints. After the enclosing sediment has hardened into stone, shells or other organic structures may be dissolved by percolating subsurface water, leaving a space or *natural mold*. *Artificial casts* of the original objects may then be secured by pressing dental wax or other suitable plastic material into the molds (Fig. 24). *Natural casts* are also commonly formed by the later deposition of mineral matter, commonly silica, in such spaces. Hollow objects may have, besides an external mold, an internal mold or *core*.

The terminology applied to fossils thus follows that of foundry practice, the cast being a replica of the original, and the mold, its counterpart. Molds of thin objects like leaves (Figs. 21 and 22) are commonly spoken of as *imprints*.

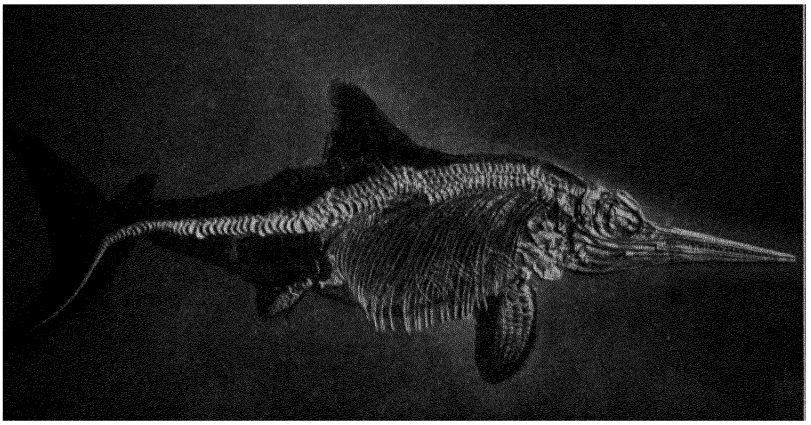
The most remarkable of all natural molds are those of the insects preserved in the Oligocene ambers. This substance is the dried and hardened resin of ancient conifers. The insects were entangled and ingulfed while the resin was still fresh and soft and thus were preserved when it hardened. In the many millions of years that have since elapsed, the delicate organic tissue has dried and practically disappeared, but the dark lifeless mold in the amber looks as real as life, and shows even the microscopic hairs and scales (Fig. 25). With the microscope it is thus possible to count the filaments on the antennæ of a gnatlike species now dead for 25,000,000 years or more!

Footprints and Trails. The tracks left by a living animal are also considered fossils when preserved in the rocks, and they supplement the



Yale Peabody Museum.

FIG. 22. A flying reptile (*Rhamphorhynchus phyllurus*), with the delicate wing membrane preserved as an imprint in a fine-grained limestone. Upper Jurassic, Eichstadt, Bavaria. About $\frac{1}{5}$ natural size.



American Museum of Natural History.

FIG. 23. A fossil ichthyosaur, a marine reptile from the Lower Jurassic shales of Holzmaden, Germany. The skeleton is permineralized, the flesh reduced to a film of carbon. This species ranges from 8 to 10 feet in length.

other remains in most interesting ways. For example, the bipedal dinosaurs were shaped much like kangaroos, with powerful hind legs and diminutive fore limbs, yet we know from their abundant tracks, as certainly as if they still lived, that they ran like an ostrich instead of leaping like a kangaroo, for their tracks are always alternating and

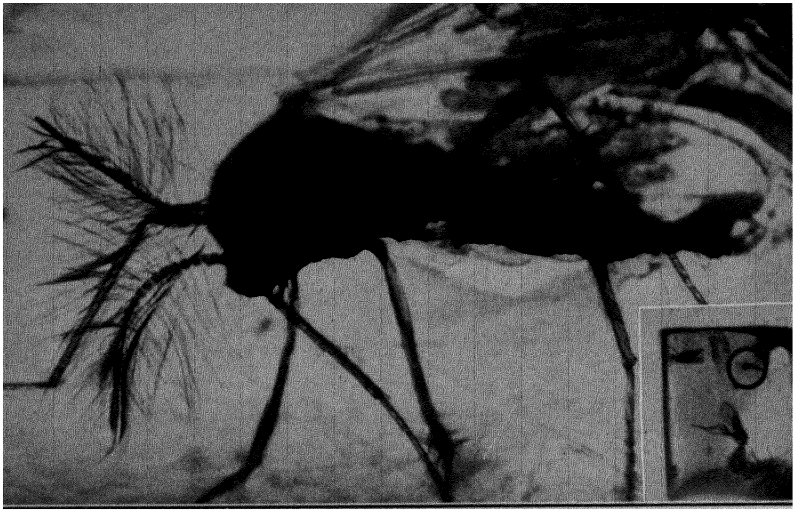


Yale Peabody Museum.

FIG. 24. Left, molds of marine shells on the surface of a chunk of Devonian sandstone; right, a cast made by coating the same surface with liquid rubber which, after hardening, was peeled loose and turned over from left to right.

never paired. From the tracks we can tell whether an animal was bipedal or quadrupedal, whether it progressed by running, leaping, or sprawling, and whether it was agile or ponderous. Tracks alone give us some of the earliest records of land vertebrates, and in several formations tracks alone record the presence of animals of which no skeletal remains have been preserved (Fig. 26).

Coprolites. Fossil excrement constitutes another class of fossils known as *coprolites*. These often contain the scales of fishes and other hard parts of animals that have been devoured. Wherever associated with skeletal remains in such a way that their source can be recognized, coprolites are of special significance for the light they throw on the food and feeding habits of the animal in question. For example, the dried dung found with fossil ground-sloths at two localities, one in South America and the other near El Paso, Texas, gives the only proof we have of the type of vegetation preferred by that race of extinct monsters.



Yale Peabody Museum.

FIG. 25. An insect in amber. The small inset at the right below shows a small piece of amber, enlarged 2 diameters, including the molds of three insects. The gnatlike specimen in the circle is here enlarged to 50 times natural size to show the microscopic filaments on its antennæ. Photographs not retouched.



Yale Peabody Museum.

FIG. 26. Slab of Triassic sandstone from Turners Falls, Massachusetts, showing imprints of raindrops and tracks of two dinosaurs. The larger tracks were made before the last rainfall; the smaller ones afterward.

Conditions Favoring Preservation

The buffalo carcasses strewn over the plains in uncounted millions a generation ago have left hardly a present trace. The flesh was devoured by wolves or vultures within hours or days after death, and even the skeletons have now largely disappeared, the bones dissolving and crumbling away into dust under the attack of the weather. This suggests that special conditions are required for the preservation of organisms as fossils. Two such conditions are paramount:

1. **The Possession of Hard Parts.** Although leaves are commonly preserved as imprints or carbonized films, animal flesh decays so rapidly that any form of preservation is rarely possible. It is not surprising, therefore, that many groups of animals, like the jellyfish and worms, have left almost no geologic record. The rare instances where soft-tissued animals are preserved, as in the Mid-Cambrian black shale of Mount Wapta (Pl. 2, p. 170), serve only to show what a wealth of animal life existed which ordinarily perished without leaving a trace in the rocks. It is evident that animals with hard parts, either external or internal, have an overwhelming preference in the chance for preservation.

2. **Immediate Burial.** A carcass left exposed after death is almost sure to be torn apart or devoured by scavengers. If it survives these larger enemies, bacteria insure the rapid decay of all but the teeth, bones, and shells. Even these hard parts are soluble and tend to crumble and fall into dust under the attack of the weather. If buried by moist sediment, however, weathering is prevented, oxygen is excluded, and bacterial action is greatly reduced. For these reasons quick burial is perhaps the most important condition favoring fossilization. Natural burial is accomplished in various ways.

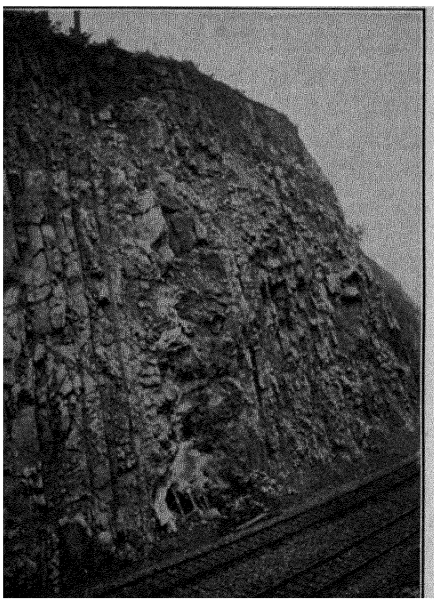
Caves provide protection against the weather not only for the living but also for the dead, and they have commonly served as the lairs of wild beasts which dragged in the carcasses of their prey and left the bones scattered over the cavern floor. In other instances, they were connected with sinks in limestone in which unwary animals were trapped. In any case, the bones were protected from weathering and commonly were covered by clay or by calcareous deposits such as the stalagmites that form on cavern floors. Man was a common inhabitant of such caves during the Ice Age, and by far the most important discoveries of early human fossils have been made in these abodes. One of these is shown in Fig. 154, p. 242.

In many caverns explorers have come upon amazing concentrations of fossil skeletons. The one shown in Fig. 27, for example, has yielded

forty-six species of vertebrate animals, including wolves, bears, mastodons, tapirs, wild horses, deer, and an antelope.

Land animals may be buried by *miring in asphalt deposits, bogs, or quicksand.*

In the summer of 1939 four boys were playing near an old gas plant at Mount Pleasant, Michigan, when they noticed a glossy area of tar that had been discharged as a waste product in the manufacture of coke and gas. One of them ventured out upon it, but when he was partly across his feet began to stick and he found himself slowly sinking. Two companions rushed to his aid and they, too, were trapped like flies on sticky paper. The fourth lad ran for help, which arrived none too soon, for the first boy, when rescued, was already submerged up to his neck and the others waist-deep. Submergence to this depth had required somewhat less than half an hour.



J. W. Gidley and C. L. Gazin, U. S. National Museum.

FIG. 27. Limestone cavern intersected by a railroad cut near Cumberland, Maryland. Traces of an ancient opening may be seen at the top of the cliff. The 46 species of vertebrate fossils recovered from this cavern are of Pleistocene age.

This incident vividly illustrates the origin of such fascinating fossil deposits as that of Rancho La Brea near Los Angeles. Here there are extensive deposits of asphalt, formed about natural oil seeps. Throughout the ages the volatile parts of the escaping oil have evaporated, leaving behind the sticky residue of asphaltum, which formed a death trap for the prehistoric animals of southern California. Animals coming to the seeps for water, or attempting to cross soil-covered patches of asphalt, were trapped like the Michigan lads. Their death cries attracted carnivores and scavengers which in turn became ingulfed. Their bones still lie beautifully preserved — although all in a jumble — in the asphalt deposits, from which they have been recovered by the hundreds of thousands (Fig. 28).

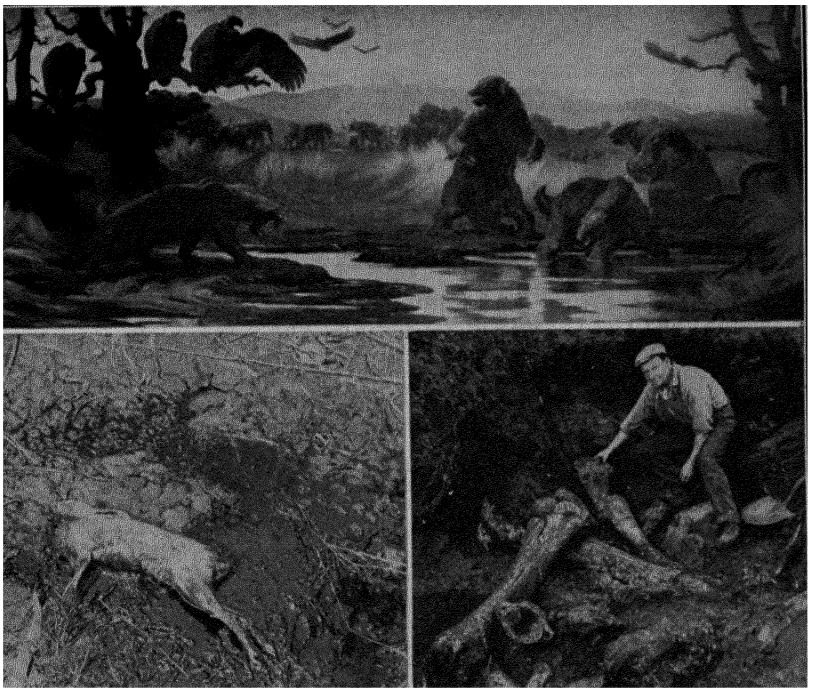


FIG. 28. An asphalt trap. Above, restoration of a scene at the Rancho La Brea asphalt pit during Pleistocene time, made by Charles R. Knight for the American Museum of Natural History; left foreground, a saber-toothed tiger, *Smilodon*, snarls at a group of giant ground-sloths while vultures wait overhead, and in the distance a herd of imperial mammoths is in view. Below, left, a jack-rabbit recently trapped in the asphalt; and, right, a mass of fossil bones in the asphalt deposits. Upper picture from the American Museum of Natural History; lower ones from the Los Angeles Museum.

The bones are marvelously preserved in such deposits because bacteria can not live in asphaltum and decay is inhibited by it. No flesh has been found at Rancho La Brea, but similar oil seeps in Poland have yielded the carcasses of the woolly rhinoceros mentioned on an earlier page.

In New England and in other eastern states another kind of death trap is recorded in the bogs now largely filled with peat and muck. These came into existence as open lakes during the closing stages of the Ice Age some 20,000 years ago, and in the ensuing millennia were gradually filled with moss and other swamp vegetation. In many instances the vegetation formed a floating mat over open water. This proved to be treacherous for some of the heavy animals of the time, notably the woolly mammoth, teeth or skeletons of which have been found in many of the bogs. In New York State alone no fewer than 217 such elephants have been discovered.

One of the most striking of all the bog deposits is that of Big Bone Lick, Kentucky, about 20 miles southwest of Cincinnati, from which more than 100 mastodons have been recovered, along with skeletons of the bison, reindeer, moose, and wild horse. This locality was known to Thomas Jefferson, who, during his presidency, reserved one room in the White House as a museum for his fossils from Big Bone Lick.

The "quicksand" in the channels of aggrading streams has also claimed its many victims, which appear in the fossil deposits of ancient channel sands.

Falls of volcanic ash commonly kill and bury, as the tragic fate of Pompeii reminds us. Many fine fossil deposits in the Cenozoic rocks of western United States are in volcanic ash, like those of the John Day



E. S. Dana.

FIG. 29. A modern forest killed and in process of being buried by alluvium on the delta of the Yahtse River, Alaska.

Basin in Oregon and Lake Florissant in Colorado. Flows of lava sometimes overwhelm timber, charring the tree trunks and then solidifying before actually burning the wood; tuff and volcanic breccia also overwhelm and cover trees. In this way the magnificent fossil forests of the Yellowstone (Fig. 87, p. 143) were buried.

In deserts and along the seashore, *wind-blown sands* may overwhelm the living or bury the dead. Dry sands, however, are not a good medium for fossilization, since oxygen can penetrate to great depths, and solution after rainfalls is very active. Hence fossils are rare in

desert deposits. Nevertheless the nests of dinosaur eggs found in Mongolia (Fig. 122, p. 198) were apparently preserved in this way by drifting sands that buried the eggs too deeply to hatch.

Water-borne sediments are so much more widely distributed than all other agents of burial that they include the great majority of all fossils. Flooded streams drown and bury their victims in the shifting channel sands or in the muds of the valley floor (Fig. 29). Whether it be drift logs or leaves or animal bodies, the result is the same; they are buried in low places where the ground is generally moist if not permanently water-covered, and where rapidly accumulating sediments give them ever deeper and more permanent burial.

The shallow sea floor is the ultimate repository of most of the sediments, and it is almost everywhere covered with such loose material in or upon which the teeming bottom life dwells. It is the inevitable fate of many shells on the sea floor to become quickly and even suddenly covered with mud or sand during storms. For this reason, the sea bottom is the greatest region for the preservation of fossils, and marine formations are usually fossiliferous.

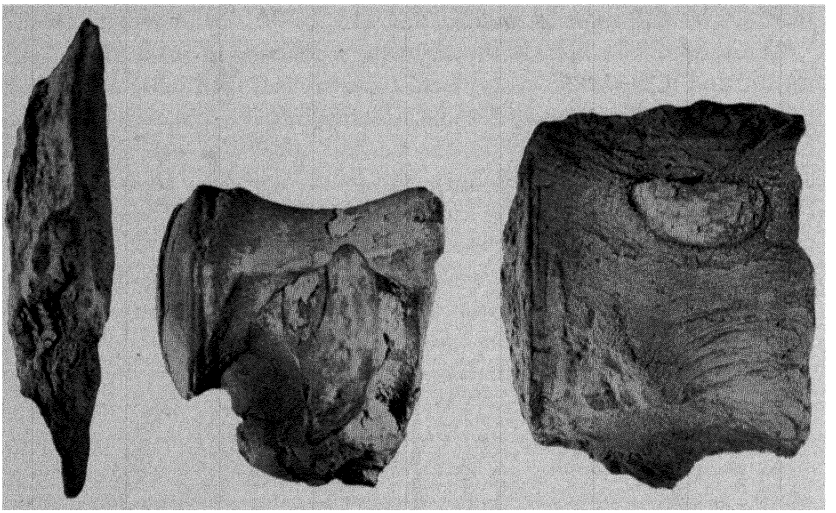
It is hardly necessary to state that fossils never occur in plutonic rocks and are not found in any other igneous rocks except where ash falls or nearly cooled lavas have overwhelmed plants and animals. They occur in all types of sedimentary rocks but are generally less common in pure sandstones and most abundant in calcareous shales and limestones. Red sandstones and shales usually have few fossils, except footprints, because the red color is due to complete oxidation, and oxidation destroys organic compounds. Even where abundant tracks prove the existence of plentiful life, as in the Triassic red beds of Connecticut, skeletal remains are rare.

After preservation, fossils may be distorted or completely destroyed during the deformation and recrystallization of rocks involved in strong folding or thrusting. Even the compaction of some types of sediment, notably black muds, may cause shells or bone to be squeezed flat (Fig. 30). The flow of weak rocks during folding commonly distorts fossils into grotesque forms. Metamorphic rocks commonly show blurred traces of fossils (as in many marbles), but where recrystallization has been complete, all traces of organic remains are destroyed.

Early Interpretations of Fossils

History does not record the first observation of fossils. A Jurassic brachiopod has been found among the amulets of Neandertal man at Saint-Léon (Dordogne), France, and there are other evidences of abo-

riginal fossil hunters. In the writings of the Greeks, there are occasional references to such objects long before the beginning of the Christian era. Some of these early observers correctly interpreted the organic remains and drew significant inferences from their presence in the rocks. Herodotus, for example, during his African travels about 450 B.C. observed fossil sea shells in Egypt and the Libyan desert, from which he correctly inferred that the Mediterranean had once spread much farther to the south than it does today. On the other hand, much fancy and mysticism were associated with fossils even by great thinkers



Yale Peabody Museum.

FIG. 30. Fossils deformed by settling and compaction of enclosing sediments. Three vertebræ of a marine reptile (*Mosasaurus*) from Cretaceous (Niobrara) chalk of Kansas. The one in the center is undeformed; that at the left was flattened by pressure against its ends; and that at the right was flattened by pressure against its sides. All were alike when buried. About ½ natural size.

like Aristotle, who, while believing them to be organic, thought they grew in the rocks. His ideas of how this came about were rather obscure, but his pupil, Theophrastus, clearly expressed the interpretation that eggs or seeds buried with accumulating sediment had germinated after burial and grown in the rocks!

The natural interpretation of fossils as organic remains of some sort seems to have been general until the beginning of the Dark Ages, when the Christian Church came to insist upon a belief in a special creation accomplished in six days, and a beginning of the Earth at a time only a few thousands of years ago. This belief left no place for extinct crea-

tures or great changes in the position of land and sea. Under this influence, interest in fossils was so subdued that few references to the matter appear in the literature of the Dark Ages. With the Renaissance, however, and the growth of natural science, fossils again claimed attention and soon became the subject of a controversy that fully equaled in fanaticism and bitterness the modern controversy over Organic Evolution.

"The Fossil Controversy." The controversy really began in Italy about 1500 A.D. when the digging of canals through Cenozoic marine formations brought to attention abundant shells so obviously like those of the present sea coast that their significance could be hardly doubted. Leonardo da Vinci, trained engineer as well as great artist, took much interest in these fossils and argued clearly that they were shells of animals once living in the places where they were found. There were many who flatly denied this, and for two centuries the controversy raged, advocates of the organic theory being frequently subjected to persecution. The most fantastic explanations were invented to avoid the biologic interpretation of fossils. Some were entirely mystical, attributing them to a "plastic force" at work in the rocks, while a few simply declared them "devices of the Devil," placed in the rocks to delude men from the true belief. One of the most remarkable illustrations of such fanaticism occurred in Germany as late as 1696 when part of the skeleton of a mammoth was dug from the Pleistocene deposits near Gotha. These fell into the hands of Ernst Tentzel, a teacher in the Gymnasium at Gotha, who declared them to be the bones of some prehistoric monster. The outraged public demanded a hearing and the evidence was examined by the medical faculty of the school, which issued the official verdict that the object was but a "freak of nature"!

When at last many devout Christians could no longer doubt the organic nature of fossils, a new idea came to the fore that made this not merely acceptable but even a powerful support for the Bible: all fossils were attributed to the Biblical Flood. The extreme to which this idea was carried is immortalized in a solemn Latin volume published in 1726 by Johann Scheuchzer, entitled "*Homo diluvii testis.*" It contained the description and figures of articulated skeletons (Fig. 31) from certain Mid-Cenozoic lake beds in Switzerland. Although in 1702 he had treated fossils as "sports of nature," Scheuchzer now declared these to be human remains preserved since the Flood. When the great paleontologist, Cuvier, later restudied one of the best of these specimens and found them to be only the remains of giant salamanders, he renamed them *Andrias Scheuchzeri!* Two reptilian vertebræ were like-

wise described and figured by Scheuchzer as "relics of that accursed race that perished with the Flood," and his figures were copied in the "Copper Bible" edition of the Scriptures in 1731.

In our own country such ideas were common even among distinguished men. On July 10, 1706, Governor Dudley of New York wrote to Cotton Mather concerning a newly discovered fossil from New York State:

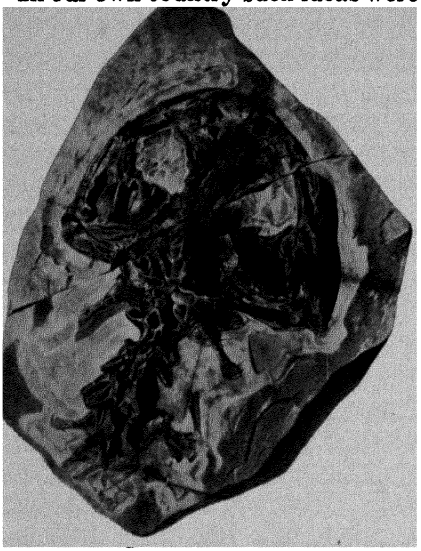


FIG. 31. *Homo diluvii testis*, a large salamander from the Oligocene lake beds at Oeningen, Switzerland, mistaken by Johann Scheuchzer for the skeleton of a human being drowned during the Noachian flood. About ¼ natural size.

"I suppose all the surgeons in town have seen it, and I am perfectly of the opinion it was a human tooth. I measured it, and as it stood upright it was six inches high lacking one eight, and round 13 inches, lacking one eight, and its weight in the scale was 2 pounds and four ounces, Troy weight.

"I am perfectly of the opinion that the tooth will agree only to a human body, for whom the flood only could prepare a funeral; and without doubt he waded as long as he could keep his head above the clouds, but must at length be confounded with all other creatures and the new sediment after the flood gave him the depth we now find."

It is difficult to realize that these words concerning a mastodon tooth were written in pious seriousness and not as a jest!

Still another illustration is needed to show that little was known of the significance of fossils before the nineteenth century. The case of Johannes Beringer will suffice. He was a teacher at Würzburg and an ardent collector of fossils who frequently took his students to a soft-shale outcrop where fossils weathered out. As a joke some student carved an image of an animal on a bit of stone and left it for the next trip. When the credulous Beringer found it and accepted it with enthusiasm, the prank was continued until a large collection was assembled, including images of insects, flowers, frogs, and astronomical objects. These were eventually described and figured in 1726 in a volume entitled *Lithographia würceburgensis*. When, shortly afterward, Beringer found Hebrew letters, and even his own name, inscribed on the stones, he realized that he had immortalized himself as the butt

of a mocking joke. In shame he attempted to buy and destroy the entire edition of his book and after spending all he had, died in poverty and sadness. Ironically adding insult to injury, his family republished the work after his death to sell it as a curiosity and so to recoup their lost fortune!

The controversy over fossils only served to kindle the interest in these objects, and by the beginning of the nineteenth century fossil collecting had become a hobby with many devotees in the church and out, one of the first large collections being made at the Vatican. By the year 1800 the organic nature of fossils was almost universally recognized, and learned men were generally agreed that they represent the life of the geologic past.

Modern Interpretations of Fossils

Geographic Significance. There are many groups of animals that live exclusively in the sea. Corals, brachiopods, crinoids, sea urchins, and cephalopods are but a few examples. Their occurrence as fossils in a rock implies the presence of the sea at some former time, even though the fossils are now far inland, or at great elevations in the mountains, as the Eocene fossils in the Himalayas at 20,000 feet. The coral reefs so common in the Silurian limestones of northern Indiana leave no doubt that a great bay or inland sea like the Baltic or Hudson Bay covered Indiana during Silurian time. If we plot the distribution of Silurian rocks that bear marine fossils, we shall determine at least the minimum extent of this ancient seaway. If in other regions we find fossil land plants with stumps or roots in place, or if we find abundant bones or shells of land animals, it is evident that the inclosing rocks were formed above sealevel. Fossils thus indicate the past distribution of lands and seas.

They may also prove the former existence of land bridges between continents now separated by oceans, or by the submergence of present land bridges. For example, the sudden appearance of the " elephants " in North America in Miocene time, long after they had developed in Eurasia, can only mean that America was then connected by a land bridge with the Old World (Bering Isthmus). By similar reasoning, it can be shown that at several times in the past North and South America have been separated or united. At present the species of marine animals on the Atlantic side of Panama and Central America are almost all different from those on the Pacific coast, and there is no way for them to mingle without an impossible migration through the cold waters by way of Cape Horn. Therefore, when certain of the older rock forma-

tions yield the same species of fossils in the Gulf region, along the northwest coast of South America, and in California, it is evident that a strait had existed somewhere across the isthmus. Here we can get a double check, for when the marine animals were free to cross from the Atlantic to the Pacific side, the land animals in North and South America were isolated and developed independently.

Climatic Implications. Most kinds of animals and plants are now restricted to definite climatic environments. Palms and crocodiles characterize the tropics and subtropics, as the reindeer and musk-ox do the Arctic. The presence of the former as common fossils in the Oligocene rocks of the Dakotas bears a very strong implication that the winters at that time were much milder than they are now in the Great Plains region. Likewise the presence of fossil musk-ox in Arkansas and of reindeer in France in sediments of the Ice Age accords with unmistakable evidence of glacial climates at that time.

In reasoning thus from the known distribution of living types, we are fairly secure for late geologic time, but less and less so as we go back to the older rocks where the species and even the genera are different and may have had different habits. Caution must be exercised even for relatively recent geologic time, since animal and plant life is highly adaptive and certain extinct species may have been adjusted to different climatic extremes than living species are. Of course the implication of a *group* of species is more trustworthy than that of one. Cumulative evidence may thus be convincing even for Mesozoic or Paleozoic faunas. For example, since all living reptiles or amphibians become torpid when the temperature drops to near freezing, the inference is justified that this was true for most, at least, of the great Mesozoic reptiles. Small reptiles and amphibians survive cold weather by crawling into holes or burrowing in the ground where they are protected during their helpless condition, but large species, unable to find such refuge, live only in regions of no frost. There is a strong implication here that dinosaurs and other great reptiles of the Mesozoic could survive only in regions of warm-temperate or tropical climates.

Documents of Evolution. Since fossils record the life from age to age, they show the course life has taken in its gradual development. The facts that the oldest rocks bear only extinct types of relatively small and simple kinds of life, and that more and more complex types appear in successive ages, show that there has been a gradual development or unfolding of life on the Earth. Moreover, series of closely allied species and genera of a single stock, from successive horizons, provide clear instances of gradual evolution. The horse series from the Cenozoic beds of western United States (Fig. 139, p. 218) is a classic

example, showing in detail the development of the modern horse from a tiny, five-toed, forest-dwelling ancestor. Although the comparative study of living animals and plants may give very convincing circumstantial evidence, fossils provide the only historical, documentary evidence that life has evolved from simpler to more and more complex forms.

Dating the Record. Since life has evolved gradually, changing from age to age, the rocks formed at any given date bear distinctive types of fossils. Conversely, each kind of fossil is an *index* or *guide* to some particular geologic age. We then need only to determine the normal succession of animal and plant life throughout the geologic past to develop a time scale or chronology within which events can be arranged in their proper sequence.

During the last hundred years, paleontologists in various parts of the world have been co-operating in this task, and so many thick rock sequences have been studied where the succession is simple and obvious, as it is in the walls of the Grand Canyon, that the general succession of types of life is now well known; and a trained paleontologist can identify the relative geologic age of any fossiliferous rock formation by a study of its fossils almost as easily and certainly as he can determine the relative place of a sheet of manuscript by looking at its pagination.

Fossils thus make it possible to correlate events in different parts of the world and so to work out the history of the Earth as a whole.

It is hardly necessary to say that where the rocks have been overturned by folding or broken by faulting the correct sequence may appear reversed or confused. Such localities will be the exceptions, proved false by comparison with many others of simple structure. Moreover, independent physical evidence of folding or faulting is generally not difficult to find in such places.

Reconstructions

The majority of fossils represent only the hard parts of creatures. Even these, moreover, are commonly incomplete. The skeleton of an animal may have been scattered by the carnivores that stripped it of its flesh, or erosion may have destroyed the exposed parts before its chance discovery. It is not enough, however, merely to describe these "vestiges of the dead," and so paleontologists are ever intent on completing the missing parts and clothing the naked bones, in imagination at least, with flesh and life. Modern museums, therefore, display many fossil skeletons with missing parts restored. In this there is no attempt to deceive, for the different luster of plaster and fossil bone makes the

artificial parts self-evident to the careful observer. Nor is the restoration a feat of the imagination. The most simple and natural principles are employed in restoring a fragmentary skeleton. For example, if part of the bones in a right limb are lacking when those of the corresponding left limb are preserved, it is obviously safe to model the missing bones as mirror images of those in the opposite limb. Thus with one entire side of a skeleton badly preserved, the whole can be reconstructed with absolute fidelity because the animal is bilaterally symmetrical. Moreover, the bones of a single skeleton fit together when naturally arranged. Even if they were disarticulated and piled in a heap, it would be as simple as solving a jigsaw puzzle to fit them together in their proper places, especially when we have articulated skeletons of similar living types for comparison. If the skeleton lacks part of its ribs, those that are preserved may be sufficient to indicate clearly the contour of the body. The missing ones, it is then evident, must be shaped to fit into this plan.

A profound knowledge of comparative anatomy will justify still other restorations that might seem to the uninitiated to be guesswork. For example, suppose but four of the neck vertebræ of a mammalian skeleton have been recovered. The specialist will know that three are missing because all mammals have seven neck vertebræ. Whether it be an elephant or a giraffe, the length of the mammalian neck is controlled by the length of the individual vertebræ, not by their number. If it were a bird or a reptile, on the contrary, no such simple decision could be made, for in those groups the number of neck vertebræ varies. Suppose it is a dinosaur, and several, but not all, of the tail vertebræ are present. The number of missing ones may be inferred from the rate of taper in those that are present. If the tail is long and slender, there is a chance here for some error, but even so, it will not lead to a great mistake.

In many instances skeletons are found alone and at least partly articulated. When two or more such skeletons are found sufficiently complete to be safely identified as belonging to the same species, the missing parts of one may be reconstructed from the other. Thus if it so happens that the front end of one has been destroyed by erosion and the tail of the other is missing, we can still restore an entire, but composite, skeleton faithfully representing the species.

However, the clothing of the bones with flesh in lifelike reconstructions does involve powers of imagination, guided by profound knowledge of comparative anatomy. We can visualize extinct creatures only by comparison with living types. If the evolution of life had been utterly haphazard, this would be futile, but few, if any, of the great groups of

animals have become wholly extinct. Many of the lesser groups have died out, but all these had gradually evolved from others, more or less closely related, which still have living descendants. This is one of the reasons why the larger paleontological research institutions are searching the far corners of the Earth for living animals of all kinds. After a careful comparison of the skeleton of an extinct reptile with all related living types, it is possible to visualize the departed with a vividness that is something more than imagination.

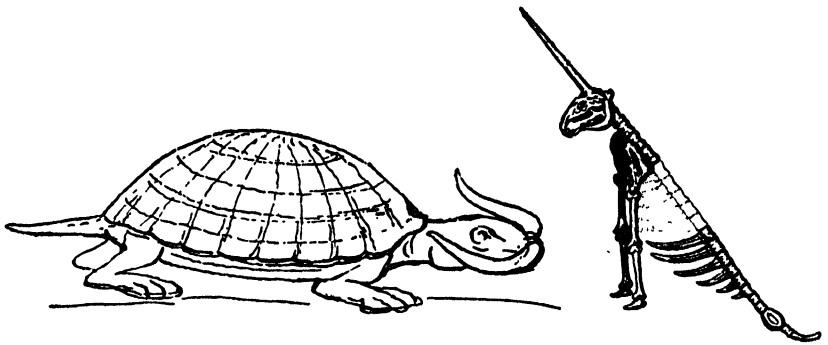


FIG. 32. Early reconstructions based on mammoth bones. Right, reconstruction as a unicorn by Otto Güricke in 1663; left, reconstruction called "The Missourium" by James Pedder in the London *Times* in 1841. The latter is after G. G. Simpson, from *Natural History*.

The first attempts at the reconstruction of extinct animals were made before anyone had a very general knowledge of anatomy or comparative morphology. It is not surprising, therefore, that these early efforts were fantastic. Two of the oldest known attempts are illustrated in Fig. 32 and were actually based on fragments of elephant skeletons. From such early reconstructions, based more on legends and myths than on knowledge of animal life, it is a far cry to the critical modern restorations in which the flesh is modeled over complete, articulated skeletons, or the models are based on careful study of skeletal material (Figs. 147, 148. DD. 226, 227).

PART II. EARTH'S CHANGING FEATURES

CHAPTER 5

BEFORE THE CAMBRIAN

AMONG THE RUINS OF TIME

The early history of the Earth presents difficulties like those met with in the study of Archeology. Back of the few centuries of written record stretch millennia of forgotten civilizations known to us only through the ruins they have left. The silent abodes of the cliff-dwellers, like the buried cities of Mesopotamia or the scattered implements of Paleolithic man, record chapters in the history of civilization no less real because they are not yet fully understood. They are still too scattered to give us a connected story of man's early history, yet search among the ruins in many parts of the world is pushing back the veil of time to give us a general view of man's rise from savagery.

It is in this spirit that we must approach the study of the Pre-Cambrian history of the Earth. For these early eras we have only the fragments of a record that we can recover from the ruin time has wrought. Enormous groups of ancient rocks, lying in tangled confusion, form an impressive record of these early times, but there are no fossils to date them, and formations once widely spread have been reduced by long erosion to scattered remnants or are largely buried by younger rocks.

Locally, these ancient formations still lie in normal superposition, and there the history is not difficult to interpret; but where they have been intensely deformed by mountain-building forces or by later igneous intrusion and then profoundly eroded, they are like sheaves of a manuscript that has been scattered and torn, leaving us only " internal evidence " as a clue to the order in which the recovered parts should be fitted together.

In this respect the beginning of the Cambrian period is a notable date in geologic history, for the abundant fossils in younger strata serve, like the pagination of a manuscript, to date the record and marshal the sequence of events. Cambrian and later geologic times may be likened to the centuries of written history; Pre-Cambrian time to those of Archeology.

Vestiges of a Beginning

Legends of Creation are among the heritages of almost every race. Many of these ideas are fantastic, but they show how strongly the mind of thinking man has been drawn to the question of the origin of this world in which we live.

Before the Renaissance there was no check upon fancy in picturing this beginning, save that of tradition and "authority." But when Galileo turned his homemade telescope toward the Heavens he opened the way for a scientific approach to the problem. Since that day in 1609, astronomers have searched the sky with telescopes of ever-

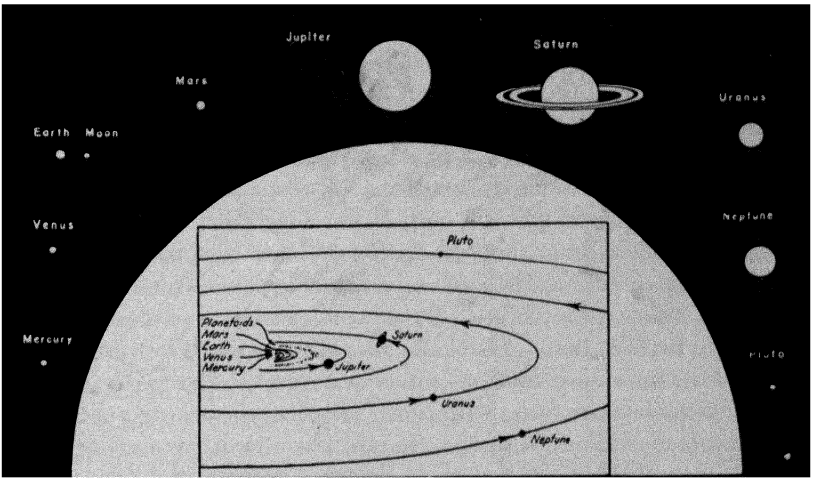


Fig. 33. The Solar System. The white semicircle represents half the surface of the Sun, and the surrounding figures show the several planets (plus the Moon), drawn to the same scale and arranged from left to right in the order of their distance from the Sun, Mercury being the nearest and Pluto the most remote. The inset superposed upon the face of the Sun represents an oblique (and incomplete) view of the system from above the common plane of the nearly circular planetary orbits (represented by solid lines). In this, the spacing of the orbits is drawn to a common scale, the size of the planets being represented on a different and greatly exaggerated scale.

increasing range. Application of the spectroscope made it possible also to analyze the light of sun or stars, however remote, and so to determine not only their chemical composition but their temperature and physical state as well. Brought thus "face to face" with the stars, we find in the ordered arrangement of the Earth and her sister planets of the Solar System (Fig. 33) some evidence of the circumstances that brought the world into being. As a background to the geologic

history, we may sketch briefly the features of this cosmic history upon which scientists now generally agree. For the sake of clarity we shall follow the story as though it were an accepted fact, not forgetting meanwhile that it is but the most reasonable theory thus far conceived of a cosmic event which no human eye has seen.

Born of the Sun. Before the birth of its planets, the Sun traveled alone through space as one of a great cluster of stars. Then came a time, probably some 2,000,000,000 years ago, when a star of a different group came near, passing at a velocity of many miles per second within a few million miles of the Sun. The tremendous pull of the passing star swung the Sun from its course and sent it whirling in a new direction, meanwhile tearing away fragments that spread like sparks from a giant pinwheel. As the star passed and the pull declined, these disrupted fragments fell back, most of them missing the Sun and so swinging into elliptical orbits about it. Out of this material the Earth and other planets of the Solar System were formed; the minute particles of solid matter which burst into luminescence as " shooting stars " when they chance to strike our atmosphere are fragments of this " star dust " which are even now being gathered up.

The condition in which this matter was torn from the Sun, whether in a few large masses or in many smaller " bolts," and the way in which it was concentrated into the planets, are problems on which there is still strong difference of opinion. Even the leading hypotheses are too complex to present here. Since the Sun is still gaseous, with a surface temperature exceeding 6000° C., it is certain that the material of the Solar System left the Sun in the form of intensely heated gas. There is some direct evidence also that Earth, like the other planets, cooled through a molten stage before solidifying. It is well known, for example, that the core of the Earth is as dense as steel, and that its outer " crust " decreases in density toward the surface, on account of a difference in composition. This density stratification of the Earth as a whole, which may be compared to the melt in a furnace, is exactly the result to be expected from a once molten condition, but would be extremely difficult to account for on any other basis. There are also astronomic considerations strongly supporting this inference.

Fireball to Planet. From its initial stage, in which the Earth was a mass of incandescent gas, the following history may be visualized. Until the temperature had fallen below 4800° C. no chemical compounds could exist. The oxygen that now forms about half the rocks of Earth's crust must then have been in a free, gaseous state, making a vast atmosphere probably a thousand miles deep and exerting a pressure of many tons per square inch at the surface of the liquid core. Metallic

carbides were the first minerals to form, but, as the temperature finally dropped below 3000° C., changes of a profound nature began, for then oxygen could unite with silica and the metals to form silicates and metallic oxides. As convection currents constantly brought fresh material to the surface of the seething Earth, oxidation proceeded on a gigantic scale until the temperature had fallen below 2000° C. and the formation of a solid crust of rock placed a protecting layer between the atmosphere and the fluid depths below. During this immensely long stage of cooling, most of the silicate rocks were formed and the atmospheric oxygen was largely depleted, its pressure dropping to a fraction of the original amount. Yet the H_2O must still have remained in a vaporous state until the Earth had cooled to 374° C. (the critical temperature above which water can not be kept in a liquid state under any pressure).

During this period of oxidation, all available hydrogen combined with oxygen to form water. As soon as the temperature fell below 374° C., the vapors began to condense (under the immense atmospheric pressure then existing), and rain fell in torrents beyond human conception, gradually lightening the atmosphere; and finally, when the temperature had fallen below 100° C., practically all the water of the primeval atmosphere had condensed, covering the Earth with seas and initiating the processes of erosion and gradation. This marks the beginning of geologic as distinct from cosmic history.

It is uncertain whether the crust formed in time to prevent the total depletion of oxygen from the primeval atmosphere. It has commonly been assumed that no oxygen survived, and that the present supply has been formed by photosynthesis of plants which feed upon carbon dioxide, using the carbon and liberating the oxygen. It seems not improbable, however, that we have inherited from the primordial atmosphere a bountiful supply of free oxygen.

Finally, solar heat began to play the principal part in warming the Earth through the now thin and broken cloud canopy. For the first time sunlight attained the surface of the lithosphere, and the origin of life was possible.

Nature of the Pre-Cambrian Record

The forming of the Earth's crust was followed by long ages whose history is still largely veiled in the shadows of antiquity. As an archeologist chooses the most fruitful "sites" to show the nature of human prehistory, so we may choose but a few typical regions to illustrate the nature of the Pre-Cambrian rocks and the problems they

present, and thus arrive at some conception of what went on in this obscure portion of Earth history.

Distribution of the Pre-Cambrian Rocks. The Pre-Cambrian rocks are presumably worldwide, but throughout four-fifths of the continents they lie deeply buried by younger formations. The exposed areas, indicated in Fig. 34, are of two sorts: (1) the cores of the mountain ranges where great uplift and profound erosion have laid them bare; and (2) the so-called *shields.** The latter are stable areas of the crust

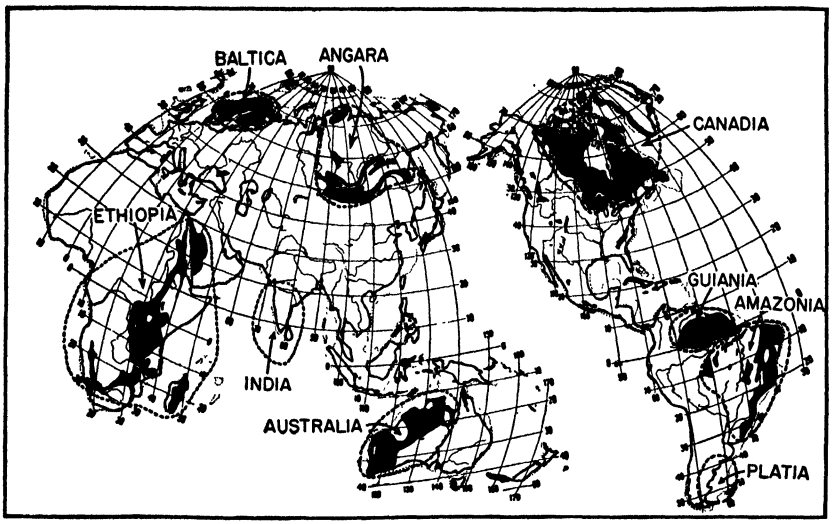


FIG. 34. Outcrop map of the Pre-Cambrian rocks (black). The several "shields" are outlined by dotted lines and are named. Base map used by courtesy of the American Museum of Natural History.

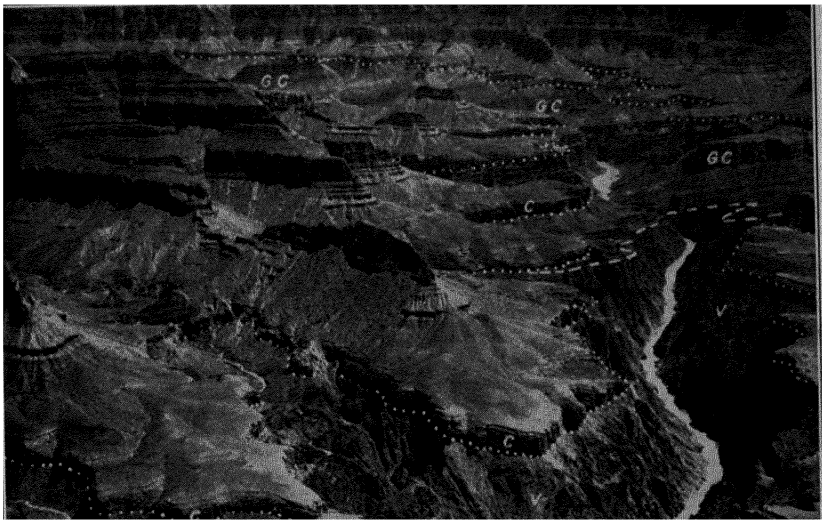
that have stood unyielding like "cornerstones of the continents." Here the ancient rocks have never been deeply buried nor profoundly eroded since the beginning of Cambrian time. The greatest of these is the *Canadian Shield*, which includes an area of nearly 2,000,000 square miles of Pre-Cambrian rocks. Centering over Hudson Bay, it stretches southward to the Great Lakes, westward to the plains of Alberta, and eastward to include Greenland, covering more than one-half of Canada. Over this vast region pink granite-gneiss predominates, but deeply infolded masses of ancient sediments and lava flows lie scattered here and there (Fig. 40).

Each of the continents has at least one of these ancient shields. Such, for example, are the Brazilian and Orinocan uplands of South

* The name *shield* was suggested by the fact that the surface of the ancient rocks arches up in gentle convexity like the surface of a medieval shield.

America, the plains of central Australia, the Baltic region of Europe, and the Angaran Shield of Siberia.

In general, the rocks of the shields were intensely deformed during the Pre-Cambrian ages by great orogenic movements and the upwelling of vast granitic batholiths, but during subsequent time they have in the main stoutly resisted deformation and, through prolonged erosion, have become great interior plains.



Spence Air Photos.

FIG. 35. View of the Grand Canyon about 10 miles east of El Tovar hotel. In the right foreground, the inner gorge exposes the Vishnu schist, *V*, overlain directly by nearly horizontal Cambrian strata, *C*. The base of the Cambrian is marked by a line of white dots. In the distance, the Grand Canyon system, *GC*, of sedimentary formations comes in between the Cambrian and the Vishnu, dipping away and to the left. The base of the Grand Canyon system is marked by a dashed white line.

THE GRAND CANYON SECTION

One of the simplest and grandest exposures of all the Pre-Cambrian rocks is that of the inner gorge of the Grand Canyon. Here Cambrian strata, still nearly horizontal, overlie, with profound unconformity, two great groups of formations, which in turn are separated by an equally great erosion interval (Fig. 35).

The older of these groups is the *Vishnu schist,* into which the Granite Gorge is carved. It includes a variety of mica-, quartz-, and hornblende-schists intruded by large granitic masses and shot through by a complex system of pegmatite dikes. The planes of foliation stand nearly vertical except where the schists are gnarled and crumpled.

Whatever the original nature of these old rocks may have been, the schists are in large part recrystallized so completely that no bedding, banding, or other primary structures remain, and it can only be inferred from their chemical natures that some of them were sediments and others volcanic rocks. It is evident that they have been greatly altered by metamorphism, probably at depths miles below the original surface. In a few places there are quartzitic members still retaining distinct bedding and even faint cross-lamination, thus betraying a definite sedimentary origin for part of the schists.

The extent or thickness of this ancient "basement complex" can not be determined because the base of these rocks is unseen, although they are gashed by the Granite Gorge which cuts more than half a mile deep into them.

Unconformable upon these old schists lies a vast thickness of sedimentary rocks aptly named the *Grand Canyon system*. In the walls of the Canyon south of the mouth of the Little Colorado there is shown a simple conformable succession of these strata exceeding 2 miles in thickness (12,000 feet), dipping gently to the northeast (frontispiece). The system begins with a basal conglomerate resting on a peneplaned surface of the Vishnu schist. Following the conglomerate comes impure limestone, then limy shale and sandy shale and quartzites of great thickness. Near the middle there are thick flows of basic lava. The limestones, and probably a large part of the shales and quartzites, were deposited in shallow marine water, but part of the sandy shale and sandstone is bright red and its bedding planes are so extensively marked by mud cracks as to imply deposition on a low floodplain or delta surface, where exposure between flood seasons allowed the muds to dry and crack. Some of the sands are cross-bedded and ripple-marked, bearing witness to current action. The region was apparently one of a great delta plain over which subaërial and submarine deposition alternated. The great thickness of such strata, obviously formed near sealevel, proves that the region subsided slowly during the period of deposition. The beds dip gently, but are no more altered than the Cambrian rocks above; yet they are for the most part destitute of fossils or other evidences of life. Some of the limy beds, however, have hemispheric or nodular structures with a fine concentric lamination that resemble closely the deposit made by modern lime-secreting algæ (Fig. 176, p. 278). These algal deposits are among the oldest of all known fossils, and it is significant that they represent one of the lowest types of life. Isolated spicules of siliceous sponges, which once lived in the sea, have also been reported from the upper part of the Grand Canyon system.

The Pre-Cambrian history of this region is summarized in Fig. 36. The first block, *A*, represents the earliest decipherable stage — one when

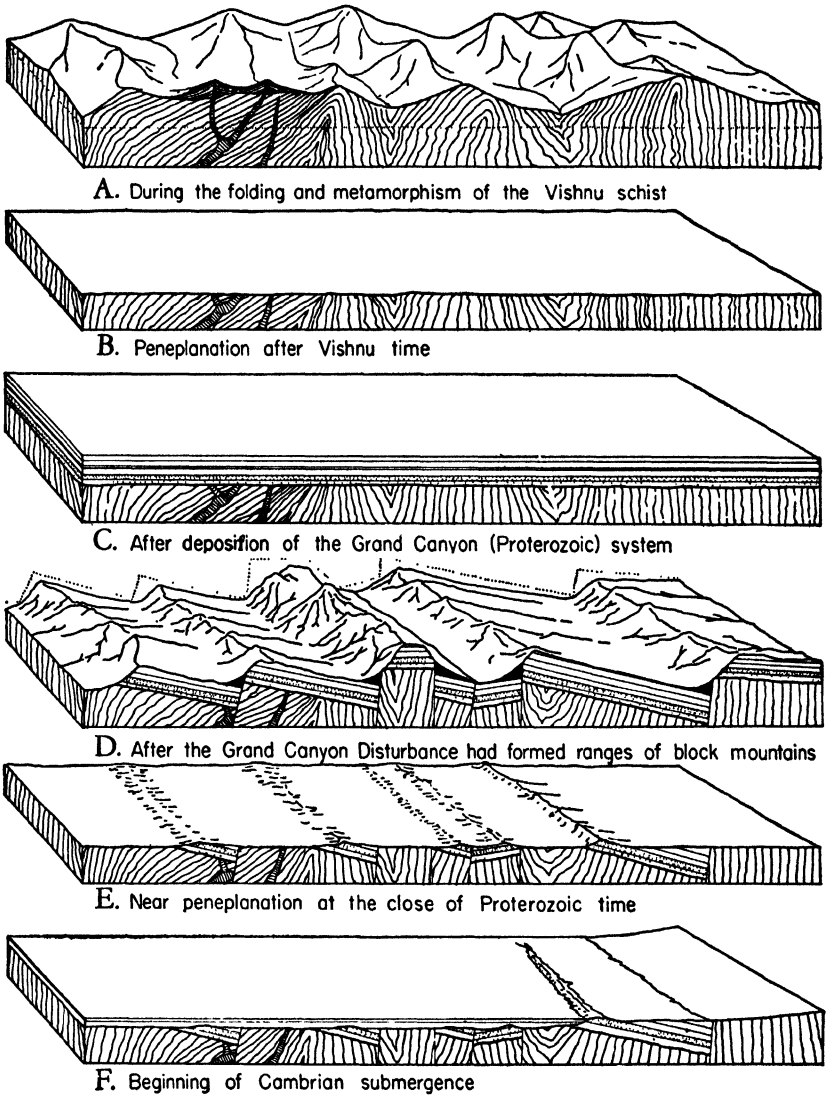


FIG. 36. Six stages in the Pre-Cambrian history of the Grand Canyon region. The view is northward and the sections represent an east-west distance of about 15 miles. The solid black shading in block *D* represents alluvium about the flanks of the Grand Canyon ranges.

the Vishnu schists were being metamorphosed into their present condition. There is really no direct evidence for the surface features of

that time; but the character of the Vishnu rocks proves that we are dealing with the "roots of mountains." Masses of bedded quartzite plunging down through the schist were once horizontal layers of sandstone; they now betray vestiges of mountain folds otherwise obliterated by the intense pressure and heat to which they were subjected while deep in the zone of flow. While thus deeply buried the rocks were mostly so recrystallized that their original nature is obscured. The granitic intrusive and pegmatite dikes were probably formed at that time.

Whatever the nature and the height of those ancient mountains, they were eventually worn down and the region reduced to a remarkably perfect peneplane (block *B*). Then the region began to subside, apparently warping down as part of a vast geosyncline that trended northward through Montana. Sediments began to accumulate, layer upon layer, as the floor slowly subsided. During subsidence the region was at times covered by an inland sea, but during part of the time its surface was kept above sealevel by streams that transformed it into an alluvial plain. With at least one minor interruption, and with some lava flows, this subsidence and deposition continued until the Grand Canyon system had attained a thickness of more than 12,000 feet (block *C*).

Eventually the region was uplifted, gently folded, and broken by great normal faults that gave rise to a system of block mountains (block *D*). This crustal movement has been named the *Grand Canyon disturbance.* Of course, these blocks suffered erosion as they arose, and their actual height at any time can not be determined; but if we project the dip of the beds in those portions of the fault blocks still preserved, the restored edges would reach elevations more than 2 miles above the present surface of these rocks.

In their turn these mountains were also destroyed and the region almost peneplaned before the beginning of Cambrian time (block *E*). Eventually the Cambrian seas spread over the region, laying down horizontal layers of sand and mud across the beveled edges of the ancient mountain blocks (block *F*).

There are in this section two profound unconformities, one between the Vishnu schist and the Grand Canyon system; the other between the Grand Canyon rocks and the Paleozoic beds. Each represents a vast hiatus during which the region was slowly reduced by erosion from a mountainous relief to a peneplane. It is probable that the hiatus above the Vishnu schist (i.e., between blocks *A* and *B* of Fig. 36) represents as much time as all the post-Cambrian rocks together.

Pre-Cambrian of the Northern Rockies

The major features so clearly shown in the Grand Canyon section are repeated with variations in several other parts of the Rocky Mountain region. Commonly, where the Pre-Cambrian rocks are exposed, two distinct groups can be recognized, an older one of intensely metamorphosed and igneous rocks, and a younger one of obviously sedimentary origin overlying the first with profound unconformity.

Portions of the Rocky Mountains in Montana, Idaho, and British Columbia display a vast system of conformable sedimentary formations. This, the *Beltian system,* so named for the Little Belt Mountains



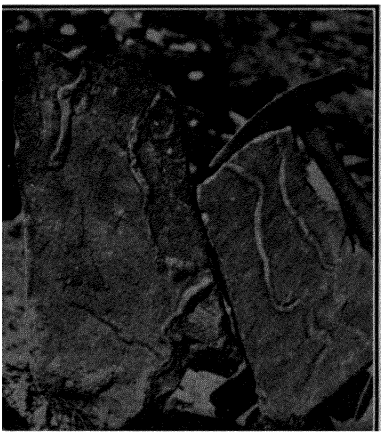
C. D. Walcott, U. S. Geological Survey.

Fig. 37. A portion of the Beltian system (Siyeh formation), exposed at the head of Nyack Creek, Flathead County, Montana.

in Montana, includes thick formations of sandstone and shale, and two widespread formations of limestone, each nearly a mile thick. The Beltian rocks are but slightly metamorphosed (Fig. 37) and, in general, resemble the Grand Canyon rocks, with which they are probably contemporaneous.

The Beltian rocks exceed 35,000 feet in thickness in the Cabinet Range of extreme western Montana and in other exposed sections commonly range between 12,000 and 25,000 feet thick. They can be traced for 300 miles or more from east to west, increasing in thickness and coarseness toward the west, where even the great limestones are replaced by detrital sediments. From these facts it is evident that

the materials were coming mainly from the west. The thick limestones were obviously formed in an extensive inland sea. Much of the shale in the eastern sections was also deposited under marine conditions, but certain thick zones of red shale and siltstone with abundant mud cracks were certainly spread over a low surface above sealevel. Evidences of nonmarine deposition increase westward, where the formations are also thicker and coarser.



C. L. and M. A. Fenton.

FIG. 38. Worm burrows (packed with sand) in the Siyeh formation of the Beltian system at Dawson Pass, Glacier National Park, Montana.

Two sorts of fossils occur in the Beltian rocks. Certain layers in the limestones and in the gray shales have deposits of calcareous algæ in individual masses up to 10 feet across and commonly so abundant as to make reef-like zones of considerable extent. The other type of fossils is rare, consisting of worm tubes and trails of crawling invertebrates (Fig. 38).

In this region, as in the Grand Canyon, there is a basement complex of ancient crystalline rocks, partly metamorphic and partly of plutonic igneous origin. These are separated from the unmetamorphosed Beltian sediments by a major unconformity. At the time of the Grand Canyon disturbance this region was not broken by great faults and was not sharply folded, but there was considerable warping and great regional uplift, following which as much as 20,000 feet of the Beltian strata was removed before the Cambrian seas crept in across their beveled edges. But since the warping is gentle, the Cambrian beds commonly appear parallel to

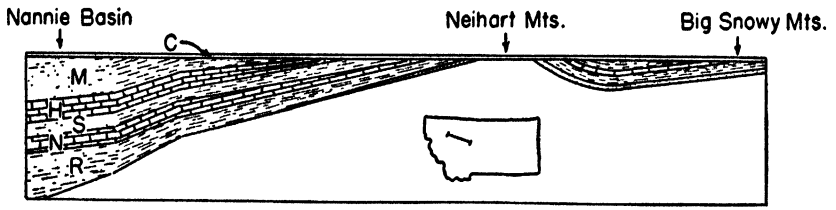


FIG. 39. Beltian system unconformably overlain by Cambrian, *C*, in Montana. The section runs from Nannie Basin in the Swan Range to the Big Snowy Mountains, a distance of 200 miles. Vertical scale is four times the horizontal. In the Nannie Basin the thickness of the Beltian rocks exceeds 10 miles. *R*, Ravalli red beds; *N*, Newland limestone; *S*, Spokane red beds; *H*, Helena limestone; *M*, Missoula sandstones and shales. After Deiss.

the Beltian, and the profound nature of the hiatus (i.e., the lost interval) is apparent only when a regional study shows that in different areas the basal Cambrian sandstone cuts across some 20,000 feet of Beltian strata (Fig. 39).

The Record in the Canadian Shield

Granite Intrusives. The Canadian Shield presents the largest area of Pre-Cambrian rocks now exposed. Its two million square miles in central and eastern Canada consist largely of granite or granite gneiss; but widely scattered over its surface there are irregular patches of volcanic and sedimentary rocks, for the most part intensely metamorphosed (Fig. 40).

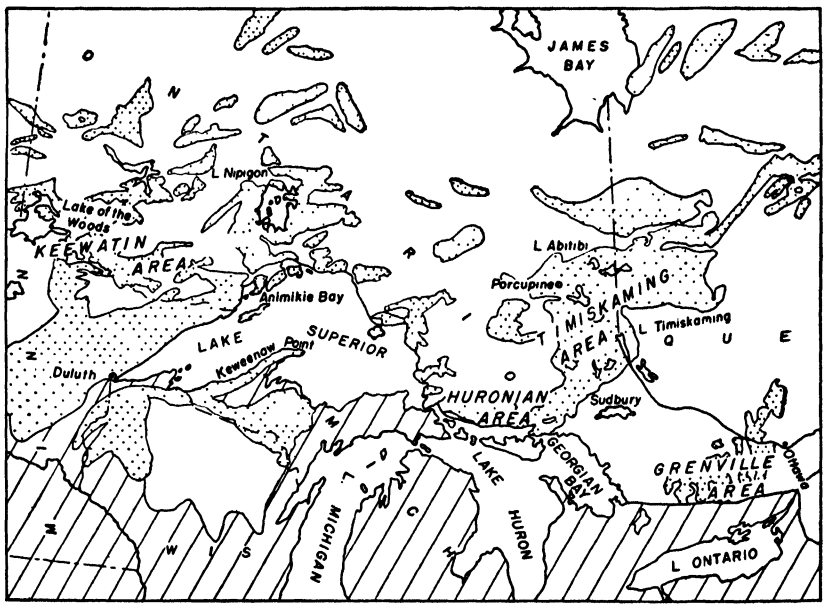
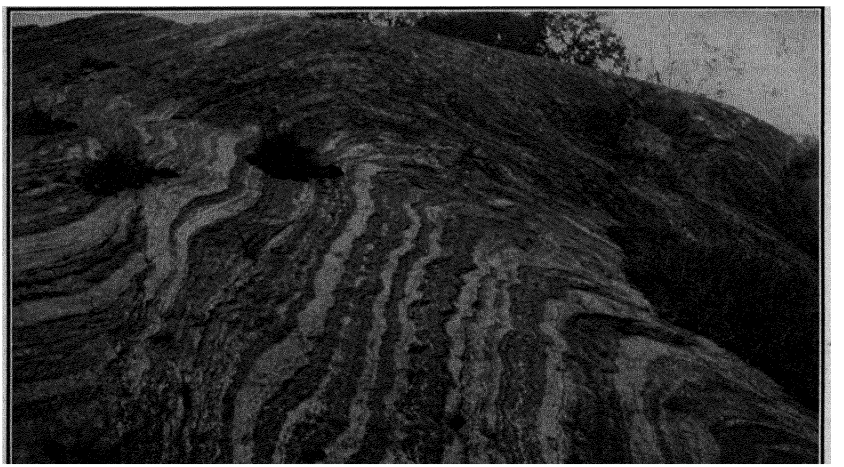


FIG. 40. Outcrop map of Pre-Cambrian rocks of the Great Lakes region, a part of the Canadian Shield. Pre-Cambrian sedimentary rocks and volcanics are stippled; granitic rocks are unshaded; overlapping Paleozoic strata are obliquely lined.

When first studied, the granite of this region was supposed to be a part of the "original crust" formed when the molten Earth solidified. But upon critical study it was found that the granite in many places cuts across and is intruded into the sedimentary rocks. Moreover, some of the latter are intensely metamorphosed near the contact with the granite. Thus it came to be realized that the granite is intrusive and not a part of the original crust. The irregular patches of sedimentary

rocks are, for the most part, downfolded remnants of thick and once widespread formations. In many places they are caught between, and more or less wrapped about, domelike masses of the granite. It thus becomes evident that the sedimentary and volcanic rocks once made a cover for the region many thousands of feet thick — a cover that was intruded and locally domed up by granite batholiths until the original floor on which they were laid down had been ingulfed or re-fused beyond recognition; then the whole region was so deeply eroded that the granite was laid bare and only the most deeply infolded and partly ingulfed remnants of the sedimentary cover have been preserved.



Geol. Survey, Canada.

FIG. 41. Crumpled limestone (Grenville), with injections of Laurentian gneiss (dark layers). Prescott County, Ontario. The break in the beds near the left margin is due to faulting.

It is a stirring thought to contemplate two million square miles of granite all coming into place molten and white hot. One can only wonder what wild scenes of confusion reigned in those primeval days, what volcanic outbursts overwhelmed the surface, and what innumerable earthquakes rocked the continent as the original crust was repeatedly broken and largely ingulfed in the rising magmas. But, of course, the intrusions were distributed over an immensely long stretch of time — probably more than a thousand million years — and possibly no vast subsurface mass was all fluid at once, for the individual batholiths are only tens or scores of miles across. Moreover, we are impressed by the extent of the granitic rocks because erosion has stripped the batholiths of their roofs and laid bare horizons that were once

several miles below the surface. Nevertheless, the regional extent of the folding and recrystallization of the older surface rocks, cradled in these vast stretches of granite, testifies to the colossal nature of the early crustal deformation and igneous activity.

Early in the study of Canadian geology the granitoid rocks were named the *Laurentian gneiss* in the area north of the St. Lawrence Valley, and that name has been extended widely to similar granites in other parts of the Shield, but it is now known that granites were intruded at three widely separated intervals during Pre-Cambrian time, and each of these is now separately named. They can not be safely distinguished by lithologic characters, however, and uncertainty exists in many places as to which of the granitic intrusions is represented. The Laurentian was originally assumed to be the oldest, but it has not been traced into contact with other formations where its relative age can be proved. Moreover, recent data from radioactive minerals indicate an age of 1,050,000,000 years, whereas similar evidence for a granite exposed northwest of Lake Superior (cutting the Rice Lake series) points to an age of about 1,900,000,000 years.

Keewatin Lava Flows. Among the remnants of surface formations scattered over the Shield, at least four great systems of rocks can be recognized. Northwest of Lake Superior, the oldest of these includes the Keewatin volcanics. Although largely altered to greenstone schists, these rocks in many places show the structures of lava flows. Amygdaloidal horizons indicate the scoriaceous surface of individual flows that welled up quietly and spread in thin sheets comparable to those of the modern Columbia Plateau. Locally, there are great thicknesses of volcanic ash, as at Michipicoten Bay, where the Wawa tuff is still 11,000 feet thick. In many localities the lavas are interbedded with sediments that accumulated between eruptions. These attain a considerable thickness in some places, as in the Vermilion Range of northeast Minnesota where the lavas interfinger with the Soudan formation of sedimentary strata that exceeds 1500 feet in thickness and bears the iron ores of the range.

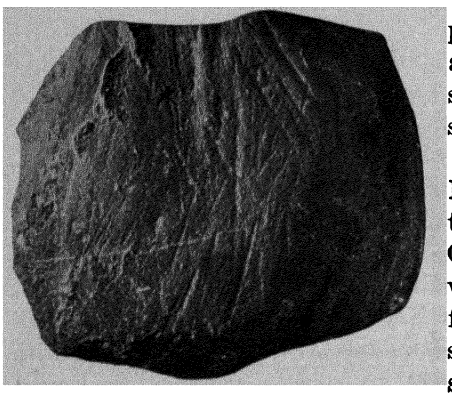
In the Keewatin rocks we have a record of an ancient basalt plateau that early in Pre-Cambrian time occupied a large area north and west of modern Lake Superior.

Timiskaming System: Roots of Ancient Mountains. Overlying the Keewatin lavas with regional unconformity is a thick and widely distributed group of altered sedimentary rocks, named the Timiskaming system for its good exposures about Lake Timiskaming. Although remnants of this once extensive system are identified over an area that stretches nearly a thousand miles eastward from the original locality of

the Keewatin lavas, these now outcrop in small areas commonly less than 20 miles long and 2 or 3 miles wide; the largest is not over 120 miles long.

Near the famous mining camp of Sudbury, Ontario, a thickness of 20,000 feet of these rocks may be measured. Their character varies from place to place, depending on the original relief and the conditions of deposition, with conglomerates and other coarse sediments predominating in the Sudbury region while shales with minor limestone members are most conspicuous farther west.

After their deposition these strata were strongly folded and intruded by batholiths of granite. The mountains then formed across the southern part of the Canadian Shield may have had the grandeur of the modern Rockies. The granite intruded at this time is the Algoman, and it is the second of the great granites of the Canadian Shield. During the long interval that followed, the mountains were eroded away and the entire region was again reduced to a peneplane, leaving only the "roots" of the mountains, comprised of the crumpled and folded and metamorphosed rocks we see today in the Timiskaming system.



Royal Ontario Museum.

FIG. 42. Striated boulder from the Gowganda tillite at Cobalt, Ontario. About ⅓ natural size.

Huronian System and the First Glacial Deposits. The third great group of Pre-Cambrian rocks in this region was named the Huronian system for its exposures along the north shore of Lake Huron. This is a system of sedimentary rocks far less disturbed than the last described. The strata stretch away to the north and east of the lake shore, and for more than 165 miles to the northwest, on a peneplaned surface that cuts across the highly deformed Timiskaming system and the granites.

The Huronian rocks also reach a thickness of 15,000 to 20,000 feet and are divisible into three well-defined series separated by important unconformities. They include all the common types of sedimentary rocks, though arkoses, sandstones, and quartzites predominate greatly over fine shales and limestone. They record the gradual filling of a geosyncline that formed along the axis of the present Great Lakes. In part they are probably floodplain and delta deposits, but in part at least

they are almost certainly marine and mark the presence of an extensive inland sea, comparable perhaps to modern Hudson Bay.

Particular interest attaches to a conglomerate (Gowganda) at the base of the Middle Huronian, which includes faceted and striated boulders as large as 10 feet across (Fig. 42). This is succeeded by a

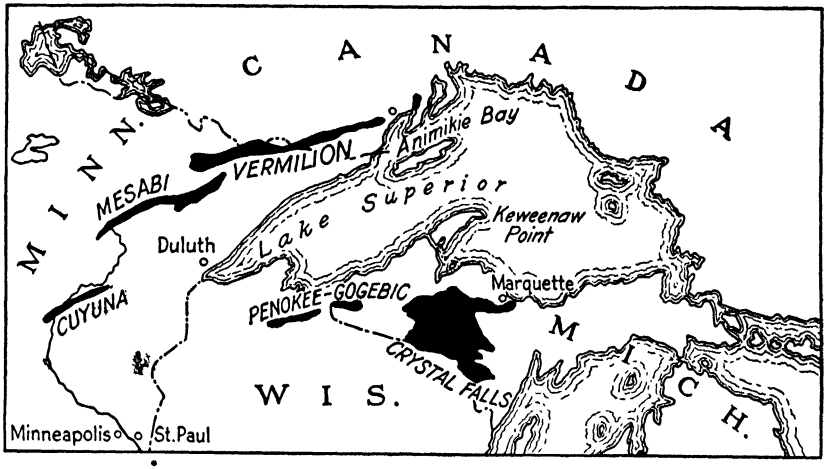


FIG. 43. Sketch map of the Lake Superior region, showing the distribution of the iron ranges (black).

massive formation strongly resembling lithified boulder clay, and that, in turn, by thinly banded slates that include scattered boulders apparently dropped from floating ice. In two localities there is evidence of a grooved and striated floor beneath the conglomerate.

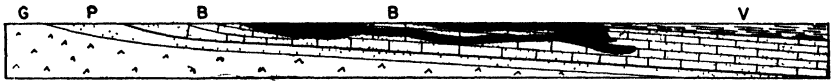
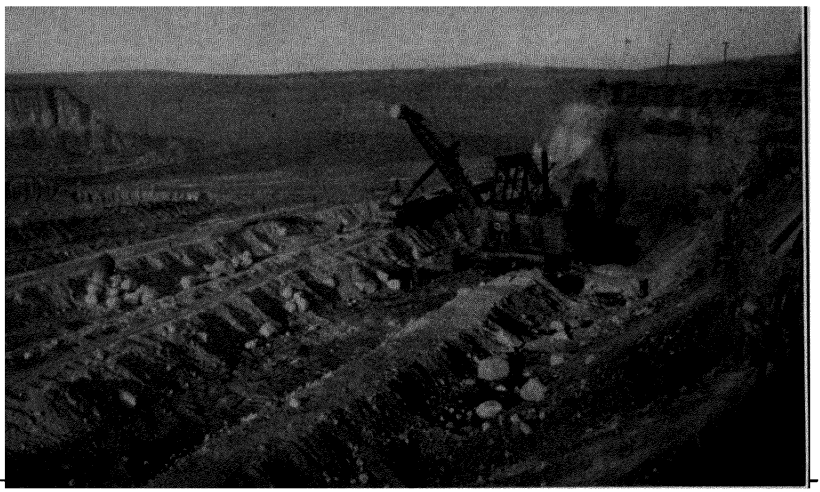


FIG. 44. Section across the Mesabi Range at Hibbing, Minnesota, showing the gentle dip of the iron formation. *P*, Pokegama quartzite; *B*, Biwabik iron formation; *V*, Virginia slate. The enriched ore bodies are shown in solid black. Length of section about 4½ miles. Vertical scale twice the horizontal. Adapted from Van Hise and Leith.

Here are all the evidences of glaciation — the earliest ice age of which we have any record. Patches of such ancient tillite, locally as much as 500 or 600 feet thick, extend across most of the southern border of the Canadian Shield a .d indicate a continental ice sheet of large dimensions, possibly comparable to that which in Pleistocene time occupied the same area.

The Huronian includes another type of deposit having exceptional interest, namely, the cherty iron carbonate beds from which the principal rich iron ores of the Lake Superior region were formed (Figs. 43–45).

About 80 per cent of the iron produced in the United States comes from the "iron ranges" of this district. The ore bodies are in linear belts following the outcrop of the Huronian rocks where, during long ages of erosion, the percolating subsurface waters have oxidized and concentrated the iron into massive deposits which, in places, can be removed by steam shovels in vast open cuts (Fig. 45).



L. P. Gallagher.

FIG. 45. Open-cut iron mine in the Mesabi Range, Minnesota.

Along the eastern border of its outcrop the Huronian system is ingulfed in granitic intrusions (Killarney) like those of the Laurentian but much younger.

Keweenawan Lavas and Red Beds. The last great group of Pre-Cambrian rocks in the Canadian Shield is the Keweenawan system of lava flows and red sandstones and shales. After the Huronian deposition, the southern part of the Canadian Shield was gently uplifted and more or less warped but not strongly deformed. After an interval of erosion, fissure eruptions began on a grand scale, as flow after flow welled out to build up an extensive basalt plateau like that of the Keewatin. These are the Keweenawan lavas. The surface of successive flows is still rough and slaggy, and much of the lava, originally highly vesicular, is now amygdaloidal. The total volume of the outflows about Lake Superior has been estimated at 24,000 cubic miles. During this time also there were very extensive intrusions of basic magma in the form of great sills, such as the one which bears the world's

greatest deposit of nickel ore at Sudbury, Ontario, or that which outcrops at Duluth and underlies much of the Lake Superior Basin.

These lavas are interbedded with, and succeeded by, red sandstones and shales that reach an aggregate thickness of 15,000 feet or more. These strata represent the material eroded from the rough surfaces of the lava fields and deposited rapidly over the lowland of a barren landscape. There is no evidence of marine deposition; on the contrary, the oxidized condition of the red sediments, the cross-bedding of the sandstone, and abundant mud cracks in the shales imply deposition on floodplains under seasonal rainfall.

The upwelling of the Keweenawan lavas gave rise to the rich copper deposits of northern Michigan. The copper was carried in hot waters emanating from deep-seated magmas and was deposited chiefly in the vesicles of the lava flows or as a cement between the pebbles of conglomerates intercalated between the lava flows.

Mountains of the Late Pre-Cambrian. As a final episode in the Pre-Cambrian history of Canada, fold mountains of considerable magnitude were formed in at least three widely separated parts of the Canadian Shield; and in each of these there were extensive intrusions of granitic batholiths. One of these ranges lay along the axis of the Great Lakes crossing Lake Huron and Georgian Bay. Here the eastern margin of the Huronian system is intensely metamorphosed and ingulfed in intruded granite. A second range lay along the east side of the present Hudson Bay, and a third occupied central Labrador.

The intrusives of this age are known as the *Killarney granite* from a locality of that name on the north shore of Georgian Bay. This was the last of the granitic intrusions in the Canadian Shield. About 300 miles east of Killarney lies the region where the Laurentian granite was named.

The Pre-Cambrian in Other Countries

Each of the continents has one or more nuclei of ancient rocks, comparable in general features to those of the Canadian Shield — a complex of granitic and metamorphic rocks in which may be read the record of colossal igneous activity and repeated crustal disturbances stretching over a vast lapse of time, punctuated by long intervals of erosion that have reduced the record to dismembered fragments.

Such an area is the Baltic Shield of Europe, comprising the Scandinavian countries and Finland. In Asia the Pre-Cambrian rocks form the Angara Shield of Siberia, in Africa they occupy much of the continent south of the Sahara, and in Australia they floor much of the desert

of the central and western parts of the continent. It goes without saying, of course, that Pre-Cambrian rocks are buried beneath the younger formations in all the continents.

Recapitulation

Like mountains seen from a distance, the Pre-Cambrian world can be seen only in its general outline through the haze of uncounted millions of years, its grander features standing out boldly while the detail is lost to view. We know but little of its long and complex history, which probably spanned much more than a thousand million years.

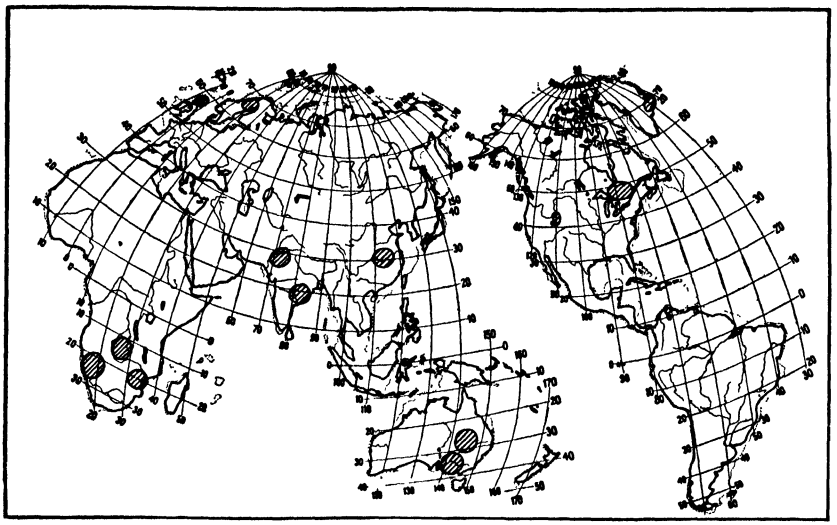


Fig. 46. Distribution of Pre-Cambrian glaciation (obliquely lined areas). Base map used by courtesy of the American Museum of Natural History.

Clearly, the crust was crumpled and broken by repeated disturbances and ingulfed by igneous invasions of unequaled extent. But these disturbances may not have been more violent than the slow growth and destruction of modern mountain systems. Erosion and deposition of sediments proceeded then as now, and the climate was obviously as varied as in later geologic periods.

The Huronian glaciation of North America was duplicated at some time in the late Pre-Cambrian in China, India, Africa, and Australia (Fig. 46). However, such ice ages were relatively short intervals — each one at most of a few million years — in the long eras during which the climate apparently was not rigorous.

Probably the greatest contrast with the modern world lay in the primitiveness of life. No forests mantled the mountain slopes, no prairies covered the plains, no animals inhabited the desolate wastes of the barren lands. Only in the seas was there a beginning of the organic host that in later geologic ages would also possess the lands. Of this primitive life we know but little; the lowly blue-green algæ are recorded in the calcareous deposits of some of the Pre-Cambrian formations, especially in the Grand Canyon and in Montana, and "worm" trails, sponge spicules, jellyfishes, and protozoans have been reported, but these fossils are seldom seen.

This is certainly not an impressive array to represent the life record of more than three-fourths of the history of the Earth! But the carbon that occurs in the black shales and slates of the Pre-Cambrian, and in its bedded graphite deposits, offers strong, though indirect, evidence that life was abundant, even though of a low order. In the later rocks, at least, such carbonaceous matter, whether it be coal beds or the disseminated carbon of black shales, can be traced with certainty to its source in animal or plant tissues that have been buried with the sediments. We know of no other way in which carbon could be disseminated through a sedimentary deposit and interbedded with shales and sandstones.

We may infer, therefore, that life was probably abundant in the Pre-Cambrian seas, but was of a low order, and in addition was small and soft-tissued so that it stood little chance of actual preservation as fossils.

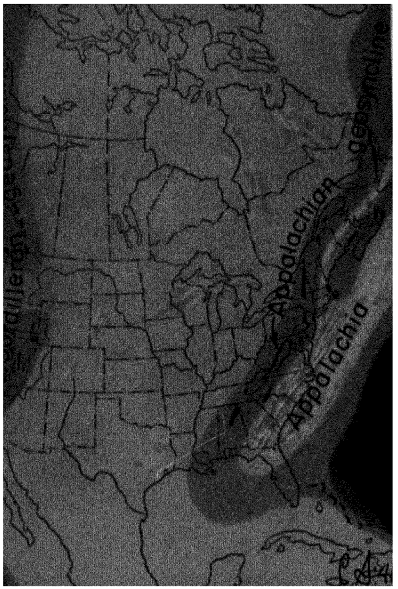


Fig. 47, A (left). Early Cambrian paleogeography of North America. Lands lightly shaded; shallow seas deeply shaded (with small black spots marking present outcrops of their marine deposits); deep sea black.

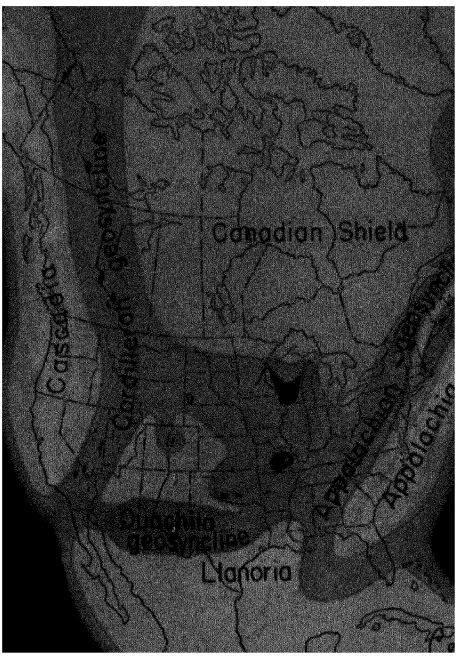


Fig. 47, B (right). Late Cambrian paleogeography. Symbols as above. Appalachia was now low.

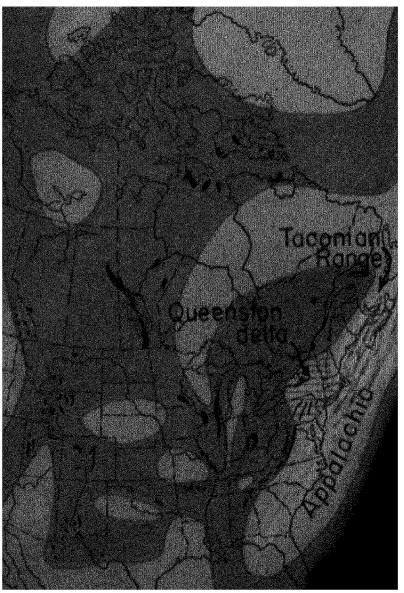


Fig. 47, C (left). Late Ordovician paleogeography. Symbols as above; nonmarine deposits of the Queenston delta horizontally lined. The Taconian Mountains were now rising in northern Appalachia but the rest of the continent was reduced to great low islands.

Chapter 6

GLIMPSES OF PALEOZOIC LANDSCAPES

The Pattern of Lands and Seas

In both outline and relief, Paleozoic North America differed greatly from the present. At the beginning of Cambrian time two great geosynclines were forming, the *Appalachian trough*, roughly parallel to the eastern margin, and the *Cordilleran trough* near the western. As slow submergence followed, each trough became a seaway two to four hundred miles across, isolating the interior of the continent from its marginal borderlands. Thus North America, like ancient Gaul, became divided into three parts (Fig 47, *A*).

Appalachia, the eastern borderland, extended out to unknown eastern limits, occupying the area of the present Piedmont and Coastal Plains and probably the continental shelf as well. *Cascadia*, the western borderland, occupied the site of the modern Coast Ranges and apparently extended some distance beyond the present continental margin.

Both these borderlands were mountainous, and their erosion supplied abundant detrital sediment to the geosynclines; the central mass of the continent, on the contrary, was generally low, although ranges of hills or monadnocks doubtless marked the sites of prominent late Pre-Cambrian mountains already worn low.

Before the close of the Cambrian (Fig. 47, *B*) another geosyncline, the *Ouachita trough*, took form across northern Mexico, Texas, and Oklahoma; and a corresponding borderland, *Llanoria*, stretched away to the south into the region which is now the Gulf of Mexico.

These seven elements persisted as the dominant features of the North American continent through all the changes of the Paleozoic era — three borderlands, three geosynclines, and a great stable interior. The borderlands were from time to time worn low, but were repeatedly uplifted; they were the mobile areas — the lands of Paleozoic mountains — while the interior of the continent remained relatively low and quiet. The geosynclines trapped most of the debris eroded from the adjacent lands and would soon have been filled if they had not continued to sink. In them we find the most complete record of the times in strata that reach an aggregate thickness of 30,000 to almost 50,000 feet. During much of the era they were occupied by shallow seas,

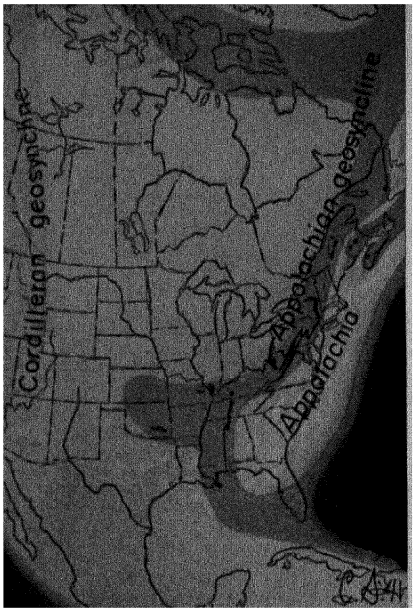
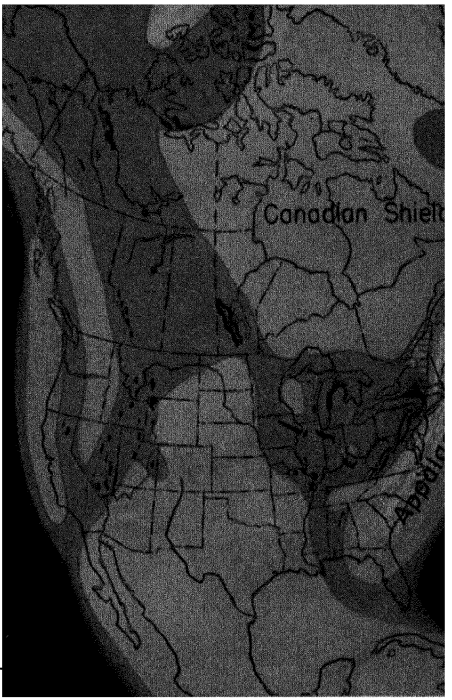


Fig. 48, A (left). Early Devonian lands and seas. Lands lightly shaded; shallow seas deeply shaded (with black spots marking present outcrops of their marine deposits); deep sea black. The Cordilleran geosyncline was completely emergent at this time.



ig. 48, B (right). Middle Devonian lands and seas. Symbols as above.

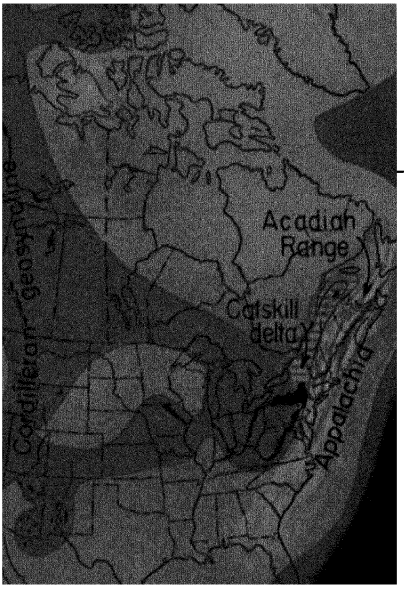


Fig. 48, C (left). Late Devonian paleogeography. Horizontal lining denotes areas of nonmarine deposition.

but at times they were drained by uplift or filled somewhat above sealevel with fluvial sediments.

Appalachia was a complex land mass during the early part of the Paleozoic, with at least two parallel mountain axes in its northern half separated by a small geosyncline, the *Acadian trough*, which paralleled

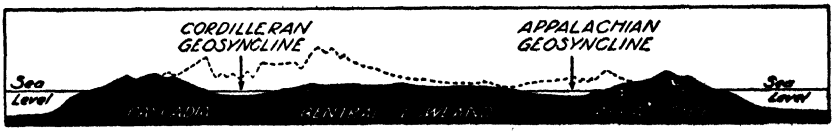


FIG. 49. Profile across the North American continent in Cambrian time (black), to show the relations of the geosynclines and borderlands to the modern continent (broken line). The section runs through San Francisco and Washington, D.C. Vertical scale greatly exaggerated.

the Appalachian trough proper in northern New England, New Brunswick, and southern Quebec. Accordingly, when most submerged, the old borderland appeared to break up into at least two peninsulas (Fig. 47, *B*), but later its elements were welded more fully together.

CYCLES OF SUBMERGENCE

As the Cambrian period progressed, the continent was more and more widely submerged, the interior seas spreading beyond the geosynclines until they covered much of the low interior of the United States (Fig. 47, *B*). Eventually, however, the inland seas gradually withdrew, leaving the continent fully exposed to erosion. Then for a time no record was formed within the present land area; the first great cycle of submergence was complete and the Cambrian period had come to a close.

It must not be supposed that these Cambrian seas spread and receded with the violence of floods, for the time involved was about 60,000,000 years, and the changes were probably slow, like the broad crustal warps now reflected in drowned or emerging coastlines. The northern part of the Baltic coast of Sweden, for example, is said to be rising now at the rate of one centimeter a year. In the course of a normal human lifetime this would amount to less than three feet, but in ten thousand years it would suffice to tilt all the water out of the Baltic Sea and turn it into dry land, or, if continued for a million years, would uplift the region as high as Mount Everest (according to Shand).

The history of the Paleozoic era is the record of seven great cycles of submergence comparable to that of Cambrian time, one for each of the periods. Each cycle began with small seas, generally confined to

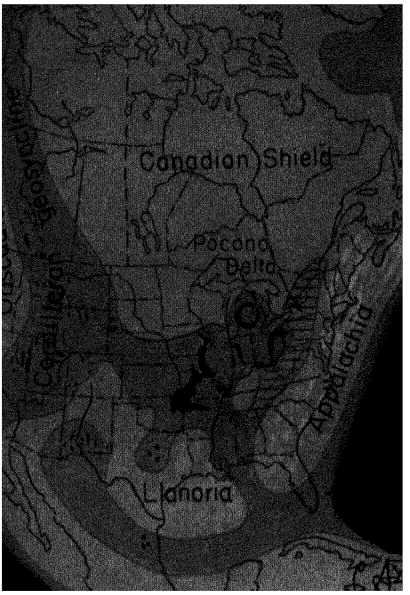


Fig. 50, A (left). North America in early Mid-Mississippian time. Lands lightly shaded; shallow seas deeply shaded (with black spots marking present outcrops of their marine deposits); areas of nonmarine deposits horizontally lined; deep sea black.

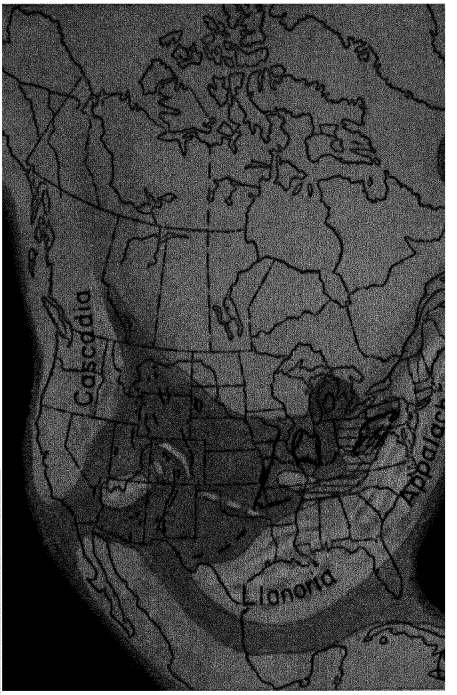


Fig. 50, B (right). North America in Mid-Pennsylvanian time. Symbols as above. Coal-forming swamps alternated with shallow sea over the eastern part of the vast interior basin.

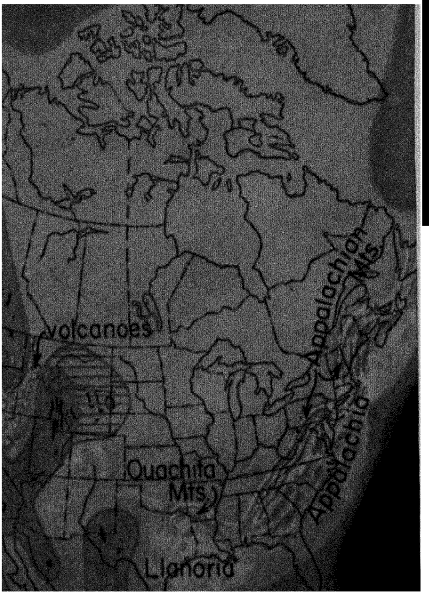


Fig. 50, C (left). North America in Mid-Permian time. Symbols as above. The Appalachian trough was now being uplifted, but the folding probably came mostly in the latter part of this period.

the geosynclines, and culminated in a vast inundation of the interior of the continent, ending again in a gradual but complete emergence. In general, mountain building coincided with times of emergence, and thus further emphasized the breaks between periods.

The Ordovician began like the Cambrian, with narrow seaways creeping along the axes of the great geosynclines; but the submergence spread rapidly in the Middle Ordovician, since the continent was already worn low and a slight rise in sealevel sufficed to bring invasions from east, west, north, and south. These eventually covered approximately half of the present continent and reduced the land to a group of great, low islands (Fig. 47, *C*). Marine deposits formed in these Ordovician seas preserve a record of the period.

The best modern counterpart of such a submerged land may be seen in Malaysia, which includes the greatest submarine shelf in the world (Fig. 2, p. 2). Here the Sunda shelf sea now has an area nearly one-fourth that of the United States, with a maximum depth of about 200 feet. It is clear that the whole area was recently a part of the mainland of Asia, for the islands harbor large mammals, both ı ɔent and fossil, that could only have reached them by dry land; and the sea floor bears a pattern of drowned stream courses.

Local warping greatly altered the outlines of the shallow Ordovician seas, slight depressions causing advances of considerable extent over the lowlands, slight uplifts transforming great areas of sea floor into land. Thus the shorelines shifted back and forth over the low interior of the continent. Many maps would be required to present in detail the ebb and flow of the Ordovician seas.

Finally the waters withdrew and the continent again stood completely emergent, and thus a second period was brought to a close.

Similar submergence, not quite so great, marked the Silurian and the Devonian periods. Three stages in the latter cycle are illustrated in Fig. 48. During the early part of the period the sea was limited to the Appalachian and Ouachita geosynclines; it began to spread early in the Middle Devonian (Fig. 48, *B*) and later widely flooded the Cordilleran geosyncline as in the previous periods; finally, toward the close of the Devonian, nearly all of the continent was emergent and the Acadian Mountains were rising in the northern part of Appalachia.

In general features, this cycle was repeated during Mississippian time, when both Appalachian and Cordilleran geosynclines were submerged and a vast shallow sea stretched across the central states (Fig. 50, *A*). For a time almost the entire Rocky Mountain region was under water and pure and widespread limestones were forming which now outcrop in the mountain flanks.

About the close of this period, however, Appalachia and Llanoria were notably uplifted and joined together to form a mountainous rim to the continent extending unbroken from Newfoundland to Mexico. At the same time mountains began to rise locally in Oklahoma, Colorado, and New Mexico, and in Idaho and eastern Oregon. This marked the beginning of disturbances that continued intermittently to the end of the Paleozoic era. Although marine waters returned to cover a large part of the United States early in Pennsylvanian time, the scene had largely changed. Vast quantities of sand and mud, derived from the rising mountains, spread over the sea floor to form the Coal Measures. Great areas were filled with such sediments and transformed into swampy lowland over which the coal-forming vegetation accumulated.

The Permian submergence was less extensive, being limited to basins in western and southwestern United States and Mexico, and extreme western Canada and Alaska.

Coal Swamps of the Pennsylvanian

During the Pennsylvanian period the interior of the United States was a vast structural basin, not unlike that of the modern Amazon Valley. To the north of this lay the low Canadian Shield and in the far west a borderland as yet very imperfectly known. While the sea crept into the basin from the southwest, the streams from Appalachia and Llanoria, converging toward its eastern side, struggled to hold back the sea and build out a vast alluvial plain. Slow rise of sealevel or depression of the basin prolonged the struggle between rivers and sea, turning the scales in favor of first one and then the other, as the shoreline crept back and forth, transforming the eastern interior of the United States alternately into shallow sea and vast swampy lowland (Fig. 50, *B*).

Under a warm, humid climate, lush forests of primitive trees covered the lowlands, and in the swamps such vegetation settled into standing water, where it escaped the destructive action of the air and accumulated as peat, later to be transformed into coal.

The largest swamps were mostly marginal to the sea and at times contained brackish water, but, in part, they were formed by irregular warping far from the shore. In Illinois and Indiana each coal is commonly followed by a " caprock " of marine limestone, indicating eventual drowning of the swamp by the sea. Certain of these thin marine beds are remarkably persistent and a few can be traced as far east as Pennsylvania, an indication that at times the interior basin was flooded

almost to the foothills of Appalachia; but from Illinois eastward the marine zones are thin and form but a small percentage of the rock section, whereas west of the Mississippi River they thicken at the expense of the nonmarine beds, and in Nebraska and Kansas they comprise more than half of the Pennsylvanian rocks. In many parts of the West the entire system is marine and predominantly limestone, but Oklahoma, Texas, and Colorado have thick deposits of shale, sandstone, and conglomerate, derived from local highlands such as the Colorado Mountains that made their appearance at the end of the Mississippian and formed mountainous islands in the Pennsylvanian seas. Nearly all the coal is east of the one-hundredth meridian.

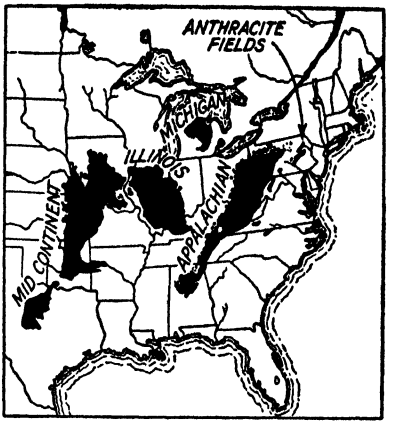
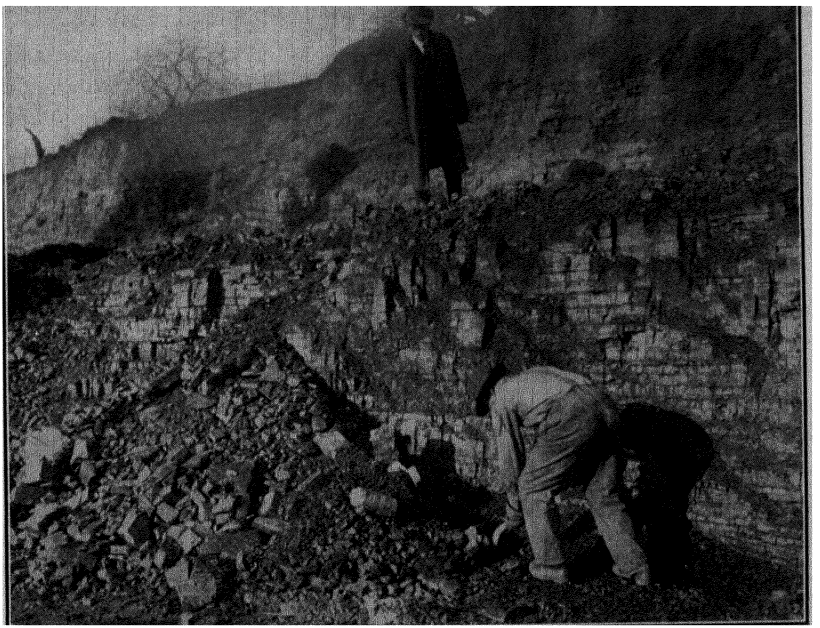


FIG. 51. Pennsylvanian coal fields of the United States.



U. S. Bureau of Mines, Pittsburgh.

FIG. 52. Outcrop of the Pittsburgh coal seam at Pittsburgh.

Crustal Unrest in Appalachia and Filling of the Appalachian Geosyncline

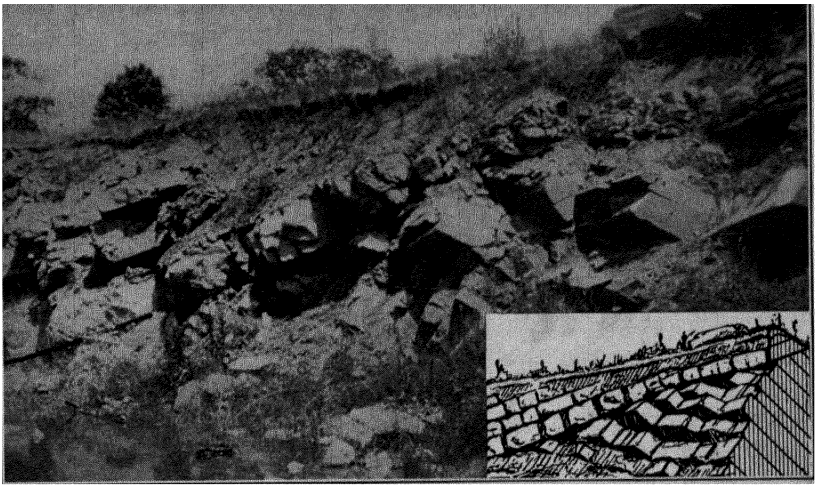
During the Paleozoic era, the North Atlantic was surrounded by a belt of disturbance like that which now girdles the Pacific Ocean. Appalachia, being part of this mobile belt, was repeatedly uplifted into mountains, and at times bristled with volcanoes. Although periods of disturbance were separated by long intervals of stability and erosion, so that each generation of mountains was largely destroyed before the next was uplifted, these mountains are so related in time and space that we may think of them as successive generations of Appalachians.

The Taconian Disturbance. During the Cambrian period, North America appears to have been stable and quiet, and before its close the borderlands were worn so low that the streams carried but little sediment, and limestone or dolomite formed over the geosynclines even close to shore. But during the Ordovician period Appalachia began to rise, at first slowly and then with acceleration, and late in the period its northern part was thrust into a range of mountains that followed an old axis through Nova Scotia, New Brunswick, and New England, reaching at least as far south as New Jersey (Fig. 47, *C*). This crustal movement has been called the *Taconian disturbance.* Although the mountains lay mostly to the east of the geosyncline, the pressure from that direction folded and crumpled the Ordovician and Cambrian deposits as far west as the present Hudson Valley. These folds were later eroded down to sealevel and overlapped with profound unconformity by the Silurian (Fig. 53).

The Taconian disturbance was accompanied by much volcanic activity in eastern Quebec and Newfoundland, where lava flows and volcanic ash falls are interbedded with Ordovician strata. During the early stages of the uplift, several volcanoes were active also in the central and southern parts of Appalachia and from them ash falls spread westward into the geosyncline. In central Pennsylvania, for example, at least ten distinct ash beds lie interstratified in the Middle Ordovician rocks, and two have been found as far south as Alabama. A local lava flow has been noted in the Upper Ordovician at Bunker Hill near Harrisburg, Pennsylvania.

As the Taconian uplift progressed, erosion supplied the streams with increasing amounts of mud and finally of sand and gravel to carry into the geosyncline. The detrital Ordovician formations thus laid down preserve a telltale record of the uplift. Fig. 54 will illustrate the nature of this evidence.

Early in the period the Adirondack arch formed a low threshold in this vicinity between the geosyncline and the very shallow sea farther



C. R. Longwell.

FIG. 53. Unconformable contact of Upper Silurian (Manlius) limestone on Middle Ordovician (Hudson River) shale at Austin quarry, near Catskill, New York. The Silurian beds strike N. 35° E. and dip 20° N.W., whereas the Ordovician beds strike N. 5° E. and dip 55° E.

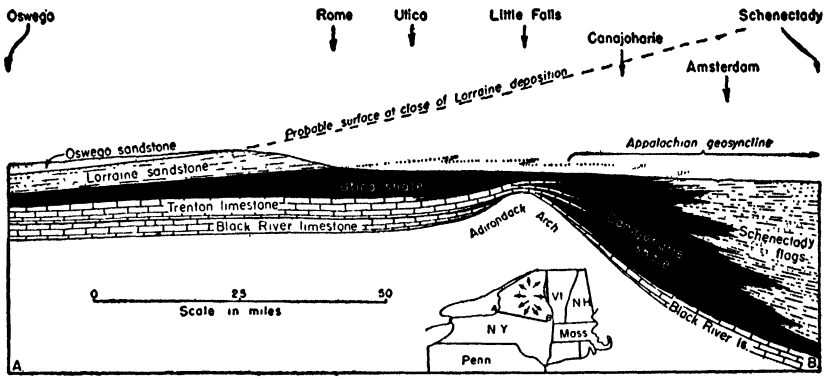


FIG. 54. Idealized section of the Middle and Upper Ordovician formations across central New York. At this latitude a now buried extension of the Adirondack arch formed a threshold for a time between the Appalachian geosyncline and the shallow sea floor farther west, but it was later submerged and muds and, finally, sands spread farther and farther west as the Taconian uplift in Appalachia proceeded. Vertical scale greatly exaggerated.

west. For a time the sea was free of mud, and the Black River limestone accumulated across the floor of the geosyncline just as it did else-

where. Later, mud spread across the geosyncline and was followed, on the east, by sand, while the Trenton limestone accumulated upon the arch and to the west of it. Clearly the mud and sand were coming from the east, that is, from Appalachia. In Late Ordovician time the sands reached westward beyond Watertown, increasing in coarseness upward. Moreover, the highest Ordovician rocks present in central New York (the Oswego sandstone) are coarse, red, nonmarine deposits representing a coastal plain that stretched westward across this region from Appalachia as the sea was retreating from the uplifted area.

Other sections across the geosyncline farther south agree in general features with the one described. Thus the stratigraphic record indicates clearly that uplift began in Appalachia as early as Middle Ordovician time and increased to a climax at the close of the period.

Silurian Volcanoes. Of course, the early Silurian formations in the Appalachian trough are detrital, because they represent the debris provided by the degradation of the Taconian highlands. In fact, they constitute a vast sheet of sandstone several hundreds of feet thick in southeastern New York and eastern Pennsylvania. It passes under different names locally (Medina, Shawangunk, Tuscarora, etc.) and is the chief ridge-maker in the folded Appalachians.

By Middle Silurian time, however, the highlands had been worn low, and late in this period the sea came back as far east as the Hudson Valley, depositing limestone (Manlius) across the truncated folds of the Taconian uplift (Fig. 53).

Meanwhile volcanoes were still active in Maine, New Brunswick, and Quebec. About Eastport, Maine, volcanic ash and lava flows exceeding 10,000 feet in thickness are interstratified with marine beds carrying Silurian fossils. Black Cape on the north shore of Chaleur Bay, Quebec, is another imposing monument to the volcanic activity of this time; it displays more than 4000 feet of dark lava flows at the top of a thick section of Middle Silurian limestones. These were largely submarine flows, and the first of them, spreading over a limy sea floor, ingulfed corals and other shells, thus providing us with one of the exceptional instances of fossils in igneous rocks.

The Acadian Disturbance. Early in the Middle Devonian, northern Appalachia began to rise again under the stress of a new orogeny. This, the Acadian disturbance, culminated near the end of the period in the folding and uplift of a second generation of Appalachian Mountains similar to the Taconian Ranges but more extensive. As suggested in Fig. 49, *C*, the Acadian highlands were partly east of the present shoreline and extended from Newfoundland through Nova Scotia and

New England, and may have continued as far south as Cape Hatteras. The southern end of the uplift lay entirely east of the geosyncline, but the northern part involved the folding of the geosynclinal deposits and the virtual destruction of the northern end of both the Acadian and Appalachian troughs, which were only once thereafter extensively occupied by the sea (during late Mississippian time).

As in the Taconian disturbance, the structural evidence in the deformed area was to a large extent obscured by the Appalachian revolution, a later and more extensive movement, but there is a clear record in the deposits of the adjacent geosyncline, showing both the geologic date and the extent of the uplift. This is well illustrated by a cross-section of the Devonian formations in New York (Fig. 55). Here the early Devonian strata are chiefly limestone or calcareous shale, even close to the old shoreline of Appalachia (a thin but widespread sand was introduced late in the Early Devonian epoch). The lower part of the Middle Devonian (Onondaga limestone) also is represented by a pure limestone, remarkably widespread and abounding in corals. Obviously, the adjacent land was low and this inland sea warm and clear. But a striking change appears in the succeeding formations. At first, black mud (Marcellus shale) spread like a pall over the geosyncline, killing most of the corals and driving many of the other marine animals westward before it. Sands in ever greater volume followed along the eastern margin of the geosyncline and gradually spread westward. Higher in the section red beds appear in the east, gradually replacing the gray sandstones and crowding them farther west. Abundant mud cracks in the red beds, as well as fossil stumps and roots, ferns, and fresh-water fishes in associated gray layers, show that this part of the deposit was being formed above sealevel.

It is evident that we are dealing with a section through a vast delta, formed during Middle and Late Devonian times along the western side of Appalachia. The red beds and the associated plant-bearing gray sandstones represent the subaërial part of the delta, and the dark shales, its deeper, seaward fringe. The increasing extent of the red beds in the upper part shows that the delta was growing as the period progressed, and deep interfingering of the red and gray members implies extensive fluctuations of the shoreline back and forth over its surface.

At the close of the period the shoreline was near the western edge of New York and Pennsylvania, and gravel was being carried across a wide coastal plain where, earlier in the period, corals had made reefs in a clear shallow sea. This striking change was due to the steady rise of Appalachia and the increasingly active erosion which produced an ever-growing volume of coarser and coarser debris.

When completed, the surface of the delta probably followed the profile of the upper dashed line in Fig. 55; later uplift and erosion have left fine exposures in the northern part of the Allegheny Plateau and in the Catskill Mountains, both of which are carved from these nearly horizontal Devonian strata. For the latter exposures, the whole deposit has been called the *Catskill delta.* The material exposed in the Catskill

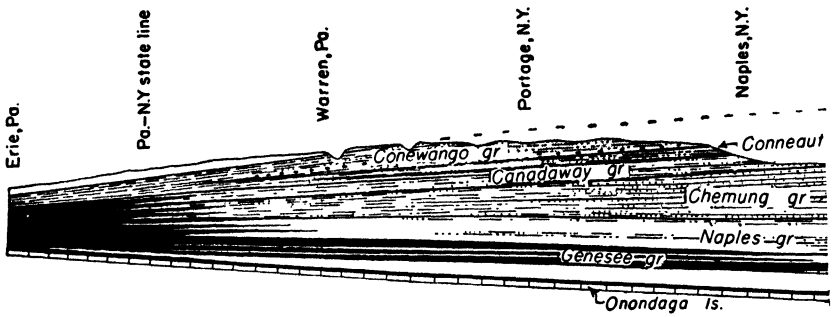


FIG. 55. Cross section of the Catskill delta, from Erie, Pennsylvania, to the Catskill dashed lines indicate the inferred original extent of the beds which have since been partially carcous shales in white. This section is fully exposed along the northern edge of the

Mountains is, however, but part of a great compound delta that extended into southern Virginia, thinning rapidly south of Maryland, where its deposits are 8000 feet or more thick. North of New York

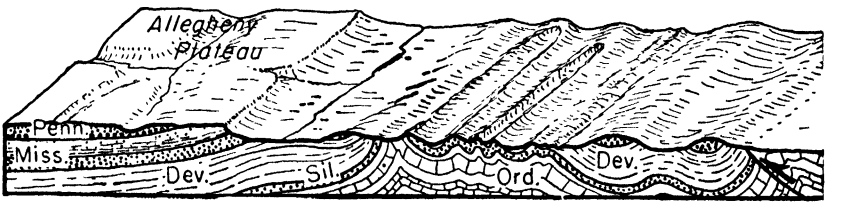
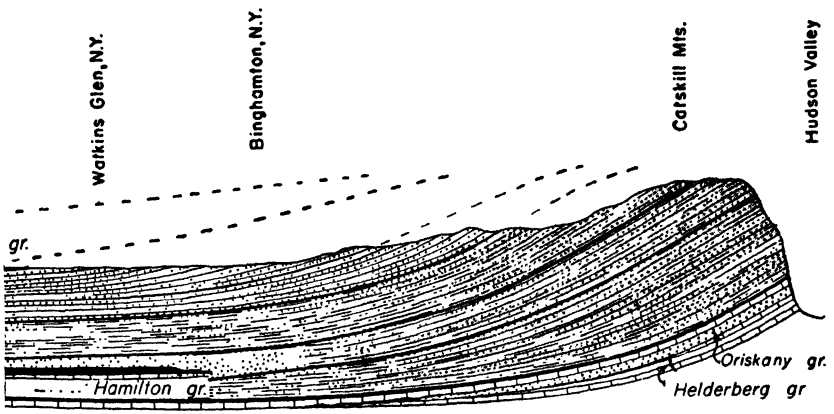


FIG. 56. Section across Appalachian structures in central Virginia, from the edge of section about 100 miles; vertical scale about 2½ times the horizontal. The position of

these deposits have been largely destroyed by subsequent uplift and erosion. (Fig. 49, *B.*)

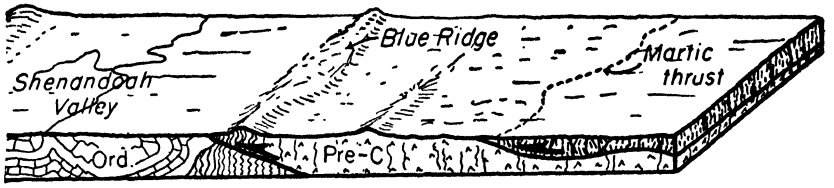
Another delta, with sediments as thick as those of the Catskills but of smaller extent, was forming at the same time in Quebec, in the northeastern part of the St. Lawrence geosyncline (Gaspé delta). There, however, the uplift began earlier than in New York, for the Lower Devonian limestones are succeeded directly by the Gaspé sandstone and conglomerate, which is not less than 10,000 feet in thickness. (Fig. 49, *C.*)

The volume of this detrital material gives some measure of the uplift involved in the Acadian disturbance. It has been estimated that the deposits represented in that portion of the geosyncline which extends



Mountains. Section about 250 miles long; vertical scale greatly exaggerated. The eroded away. Red beds are shaded, black shales are shown in solid black, and gray cal- Allegheny Plateau. Data from Chadwick and Cooper.

from the Catskills southward had a volume of 63,000 cubic miles, an amount about equal to that which would be supplied by the complete degradation to sealevel of the modern Sierra Nevada.



the Allegheny Plateau (left) to the piedmont slope near Richmond (right). Length of the section is indicated by the line *AB* in Fig. 57.

The Appalachian Revolution. During the Permian period the old borderland, Appalachia, was thrust westward, crushing and folding the Paleozoic formations of the geosyncline into a mountain chain that extended from at least western Nova Scotia to Alabama, and possibly into Llanoria (Fig. 50, *C*). This is the movement that produced the familiar mountain structures seen in the modern Appalachians (Figs. 56 and 58). In the folding south of New York, all the Paleozoic formations share alike, hence all were folded together and the disturbance was later than the youngest strata involved. Farther north

in extreme eastern New York, New England, and the Maritime Provinces, angular unconformities are found above the Ordovician and again above the Devonian rocks, for here the Taconian and Acadian disturbances both affected the geosynclinal deposits, and the later Paleozoic folding was superimposed upon the older (except in Quebec and northern New Brunswick, which were northwest of the disturbed belt in the late Paleozoic).

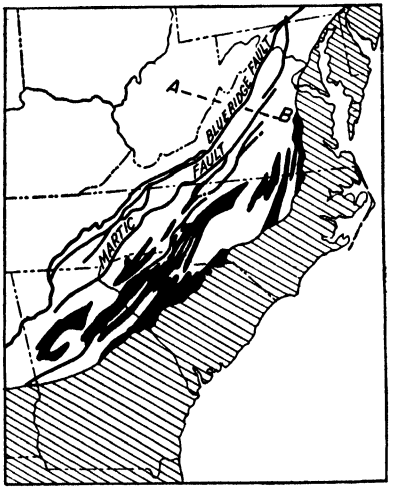


FIG. 57. Sketch map showing distribution of late Paleozoic batholiths (solid black) and major thrust faults of the southern Appalachians (heavy lines). The overlapping coastal-plain deposits are marked by oblique shading. Line *AB* indicates the position of the section shown in Fig. 56. Adapted from Jonas.

The disturbance was most intense along the eastern side of the geosyncline from New Jersey southward, where it is recorded by great thrust faults, some of which carried Cambrian rocks westward until they rested upon the Coal Measures. Fig. 57 shows the present trace of some of these faults, the Martic thrust extending for about 500 miles and the Blue Ridge fault for more than 700 miles. In this belt of thrusting, the weaker rocks are crumpled and the folds generally overturned, but the intensity of deformation dies out toward the west and the folds are more open and lower, giving way to nearly horizontal structures in the Allegheny Plateau. Thus it is evident that the forces of deformation were applied from the east or southeast.

For reasons easily understood, the date of the Appalachian folding can not be precisely determined. It obviously followed the deposition of the youngest strata involved (Early Permian) and preceded the oldest formations that unconformably overlap on the eroded folds (Late Triassic), but, in the absence of later Permian strata from the folded belt, this leaves a wide interval. Since the Early Permian strata preserved a short distance farther west (Dunkard series of West Virginia and Ohio) resemble the late Pennsylvanian formations in character, it appears that no marked change had yet occurred in Appalachia; and since the region was practically peneplaned before the Triassic rocks began to accumulate, it is clear that the folding occurred long before that date. This places the movement beyond reasonable doubt in the Permian, and it is inferred, but not proved, that it culminated at the

end of that period. In any event, it was but the final paroxysm of the crustal movement that had been growing in Appalachia and Llanoria during the late Paleozoic.

Before the close of the Mississippian period, Appalachia was strongly uplifted, as we know from the great volume of detrital sediments carried into the geosyncline, beginning in the latest Mississippian and early Pennsylvanian, since Lower Pennsylvanian deposits are about 10,000

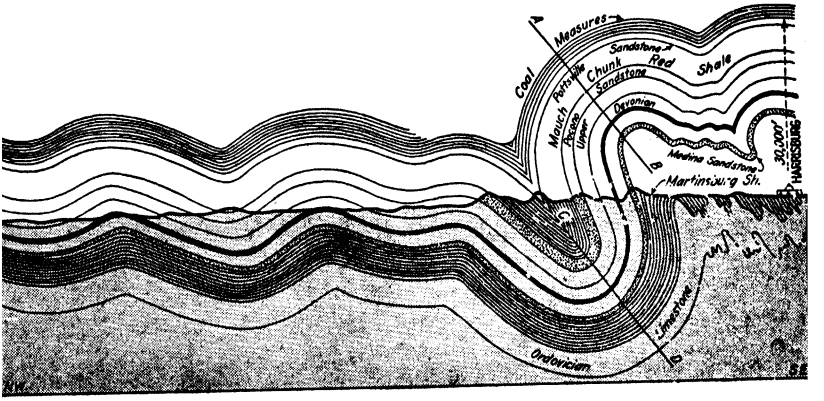


FIG. 58. Reconstruction of Appalachian folds near Harrisburg, Pennsylvania. Length of section about 30 miles; vertical scale not exaggerated. The portion now extant is shaded; that already removed by erosion is unshaded. Adapted from the Topographic and Geologic Survey of Pennsylvania.

feet thick in Alabama. The entire borderland, including Llanoria, remained high throughout the Pennsylvanian, and this, of course, implies continuous or repeated uplifts. The crushing of the geosyncline was the final episode in this long series of movements.

While eastern North America was thus in the throes of late Paleozoic orogeny, disturbances were in progress in various parts of southwestern and western United States, which had been free of mountain making since the Pre-Cambrian. In Oklahoma and Arkansas the orogenic history is complex (Fig. 59). Strong movements in Llanoria at the close of the Mississippian were matched by rapid subsidence of the Ouachita geosyncline, where the exceptional thickness of more than 20,000 feet of Pennsylvanian (and late Mississippian?) sandstones shales, and conglomerates accumulated. The Arbuckle, Wichita, and Amarillo mountains arose as chains of islands in the Pennsylvanian seas shedding abundant detrital sediments about them. And after the final deposition of Pennsylvanian and Permian formations, this geosyncline like the Appalachian, was crushed and all the Paleozoic formations folded and thrust northward, the Ouachita Mountains overriding the

eastern end of the Arbuckles. This movement was presumably contemporaneous with the folding of the Appalachian geosyncline.

Farther west, the "Ancestral Rocky Mountains" appeared in Colorado and northwestern New Mexico about the close of the Mississippian and persisted, with repeated uplift, to the end of the Paleozoic, giving rise to thick and locally coarse detrital formations, of Pennsylvanian and Permian age, accumulating where marine limestones had formed in earlier periods.

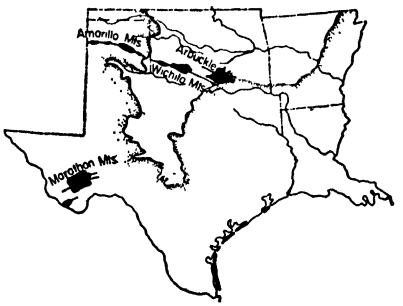


FIG. 59. Sketch map showing (in black) the location of mountains formed in Oklahoma and Texas during Pennsylvanian time. The stippled belt marks the margin of younger formations now overlapping on the late Paleozoic formations. Adapted from Van der Gracht.

Western Idaho was the scene of another Permian uplift, and there the disturbance was accompanied by extensive volcanic activity, recorded in formations of volcanic agglomerate as much as 10,000 feet thick. In northern California, the Nosoni formation, with abundant Mid-Permian marine fossils, bears the record of volcanic activity, inasmuch as it is largely made of volcanic ash and tuff, which reach a thickness of 2000 feet. Central Mexico also suffered volcanism, and in southern Coahuila (Las Delicias) the marine Permian section includes more than 8000 feet of interbedded lavas.

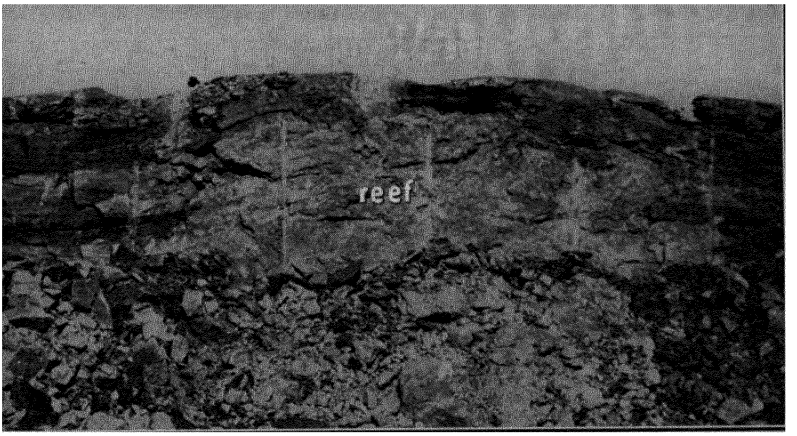
It is evident, therefore, that the late Paleozoic was a time of exceptional crustal unrest in North America.

RECORDS OF CHANGING CLIMATE

Coral Seas of the Mid-Paleozoic. The Ordovician, Silurian, and Devonian periods witnessed the spread of arctic water across the western part of the Canadian Shield in a vast seaway as much as a thousand miles wide. The formations deposited over these sea floors are chiefly limestones, abounding in corals and coral reefs. Remnants of these formations are still preserved in widely scattered outliers such as that which forms the western shore of Hudson Bay.

The aggregate thickness here is only a few hundred feet and the section is quite incomplete, with Middle Devonian beds resting directly on Mid-Silurian and these on Lower Silurian, which in turn covers Upper and Lower Ordovician. In spite of the long breaks, however, the strata lie parallel and show little evidence of the interruptions. Each

formation holds its lithologic character over surprisingly great distances, and the species of fossils characteristic of each are also widely distributed. For example, the Middle Silurian limestones include coral reefs, mostly of small size, in outcrops west of Hudson Bay, in Ontario, New York, Indiana, and Kentucky, all containing many of the same species. Even in extreme northern Greenland, where bare rocks now project beyond the margins of a perpetual ice cap, no fewer than thirty-seven species of corals have been recovered from a single Silurian formation.



Preston E. Cloud.

FIG. 60. A small coral reef (lighter rock) in the Alpena limestone exposed in a quarry face at Alpena, Michigan. Larger reefs in the same formation exceed 50 feet in thickness.

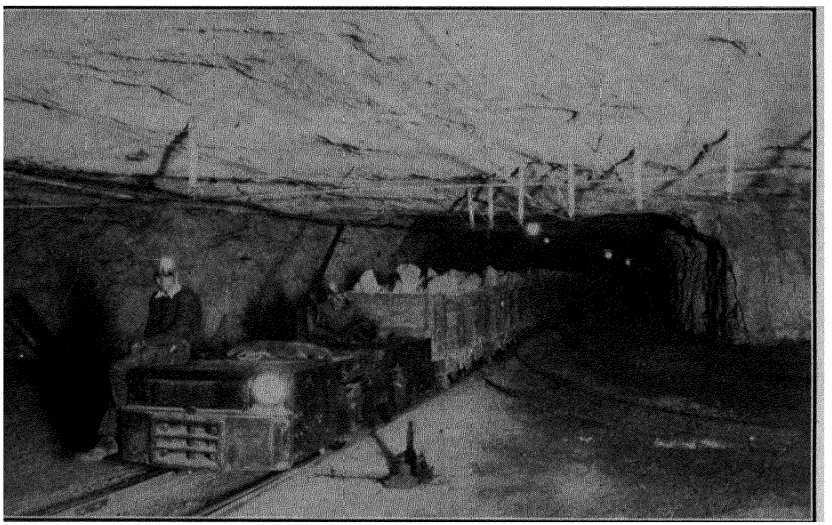
From these characters it is clear that the arctic seas were shallow, clear, and warm, and that the region was practically free of disturbance even during the times of emergence. Warmth is indicated not merely by the presence of coral reefs and widespread limestones and dolomites, but particularly by the fact that so many species of all groups of invertebrate animals — corals, brachiopods, bryozoans, cephalopods, etc. — ranged far to the north with no apparent regard to latitude. Climatic zones were certainly less marked during the middle Paleozoic than they are now, and arctic America could not have been ice-bound at that time.

It is not necessary to conclude that the Mid-Paleozoic climate was uniformly warm, however, for the formations with corals represent the times of great submergence when ocean currents may have spread the tropical warmth to high latitudes more effectively than now. Also, the configuration of the land may have diverted a warm current northward through the Cordilleran geosyncline. It is well known, for example,

that northern Europe now owes its mild climate to the "Gulf Current," whereas Greenland, in the same latitude, is perpetually ice-covered and almost uninhabited.

There is some evidence, indeed, that at times in the Paleozoic, parts of the arctic region were actually frigid. A Silurian conglomerate in southeastern Alaska has been interpreted as a tillite, and arctic Norway has two such conglomerates of less certain date but clearly of Ordovician or Silurian age.

The Silurian Desert of New York. As the continent emerged during Late Silurian time, arid conditions spread over the eastern United



Retsof Mining Company.

FIG. 61. A salt mine in the Upper Silurian at Retsof, central New York. The tunnel is cut in solid rock salt and the cars are loaded with salt on their way to the shaft.

States, and a large area including Michigan, Ontario, New York, and Pennsylvania took on the characters of a desert basin. In the midst of this region a lingering arm of the Appalachian geosyncline became a "dead sea" in which vast quantities of salt and gypsum were precipitated. In central New York, for example, the coral-bearing limestone of the Middle Silurian is succeeded by more than a thousand feet of shales known as the *Salina formation* because of its salt deposits. The lower half is mostly red and the upper half gray, with interbedded salt and gypsum. The salt underlies an area about 150 miles from east to west and extending southward under southern New York, northern Pennsylvania. and Ohio. Several distinct salt beds are interstratified

in the shales, reaching individual thicknesses as great as 80 feet. At Ithaca, New York, where the Salina shales are between 2000 and 3000 feet below the surface, deep wells have revealed seven beds of salt with an aggregate thickness of 250 feet. Syracuse is the center of an important salt-mining industry (Fig. 61). When traced southeastward toward Appalachia, the entire series passes into nonmarine red beds; but toward the southwest, in central Pennsylvania, the Salina shales grade laterally into marine shales and limestones (Tonoloway group).

The salt and gypsum represent precipitates from seawater during its evaporation, and since the formation of 1 cubic foot of salt would require the evaporation of about 80 cubic feet of normal seawater, it is clear that the deposition of the Silurian salt beds over an area of nearly 100,000 square miles indicates long and severe aridity. The water was not deep, however, the great quantity of salt being introduced by intermittent inflow from the outer ocean as evaporation proceeded.

Farther to the west, in northwestern Ohio and southern Michigan, dune sands for a time spread widely and accumulated to a thickness of 150 feet, forming the *Sylvania sandstone*. The even sorting and the roundness of these sand grains show the effect of long shifting by the wind. The remarkable display of mud cracks in the waterlimes which succeed the salt-bearing shales shows the effects of strong desiccation as the marine mud flats were temporarily laid bare.

The cause for the aridity may lie in the flatness of the extended land mass, which offered no elevations to chill the westerly winds after they had crossed the interior of the continent.

The " Old Red " Sandstone and Seasonal Rainfall. The Devonian system includes extensive nonmarine red beds in eastern North America, in East Greenland, and in the British Isles. They have exceptional interest as the repository of the oldest adequate record of land life. Even before the geologic systems were named, these rocks were well known to European geologists as the " Old Red," a term used to distinguish them from the much younger red beds of the Triassic. In America the corresponding red beds were called the *Catskill formation* because of their prominent exposures in the Catskill Mountains of New York.

The Old Red sandstone of the British Isles lies in a series of five structural basins which were formed between the ranges of the old Caledonian Mountains. During Devonian time these basins received the sediments from the rugged mountains just as the Great Valley of California is now being aggraded by the streams from the Sierra Nevada. The several narrow basins subsided as they were filled, so that vast thicknesses (up to 37,000 feet) of sands and muds accumu-

lated without allowing the surface of the intermont basins to sink below sealevel.

The conditions of deposition and the nature of the climate may be inferred from the study of these rocks and their fossils. The sediments were commonly poorly sorted; they vary greatly from place to place, these features suggesting the work of streams rather than of the sea. Conglomerates locally of great thickness and in places including coarse blocks several feet in diameter represent alluvial fans where torrential streams debouched into the basins. The purer sandstones are commonly cross-bedded, like the channel sands of streams. The siltstones and shales are marked with mud cracks at many horizons, and in places bear the imprints of Devonian raindrops. Obviously these beds are the deposits of vast floodplains where the mud, spread during the flood season, lay exposed during months of drought which followed.

Although red is the dominant color, there are also thick members of greenish gray sandstone and siltstone and gray shales. The red sediments are completely oxidized; hence they must have come to rest where the drainage permitted good aëration of the soil during the dry seasons. The gray beds, on the contrary, were formed where the ground water stood near the surface, or at times when rainfall was distributed throughout the year so as to prevent deep drying and oxidation. The widely distributed mud cracks bear witness to seasons of drought, but there are no bedded salt or gypsum deposits in the series and dune sands are lacking or unimportant. Moreover, the abundant fossils show that *the region was not a desert.* Instead, it must have been a region of marked seasonal rainfall, in which months of plentiful rain alternated with seasons of drought. This would cause the frequent wetting and drying of the soil so conducive to the formation of red sediments, and would account for the mud cracks on the wide floodplains.

The dominant animals of the "Old Red" are fresh-water fishes, of which there are many kinds known in Scotland, East Greenland, New York, and Pennsylvania. Fossil land plants are locally abundant. In East Greenland, the "Old Red" has recently yielded lungfishes and the oldest known land vertebrates (Stegocephalia).

In New York State, the red Catskill beds grade westward into gray sandstone which at Gilboa is filled with the stumps of large trees (seed-bearing fernlike forms), a record of the earliest known forest. The beds at this locality are of late Middle Devonian age.

Tropical Humidity of the Pennsylvanian Coal Swamps. Fossil plants speak eloquently of warm, moist climate during the chief coal-

producing ages of the Pennsylvanian in many parts of the world. The vegetation of the coal beds clearly grew in swamps (Fig. 62), where it accumulated under standing water, as evidenced by the spreading root systems still preserved in the fire clays that underlie the coals in many places. Moreover, the structural types of the foliage so well preserved in the roofing shales indicate marked humidity. Swamp waters are required to protect the fallen vegetation from the air and thus save it from decay. The wide distribution and the repeated occurrence of coals therefore assure us that there was a persistently moist climate over vast regions of the Pennsylvanian landscape.

This does not prove, of course, that no parts of the Earth were arid. It is well to remember that at present the dripping jungles of the Amazon Valley are separated only by the narrow Andean chain from the desert coast of western Peru. Similar extremes probably existed on the continents during Pennsylvanian time, for lofty mountains must have been accompanied, then as now, by a leeward rain shadow of deficient rainfall. The salt deposits of the Paradox formation in eastern Utah and western Colorado may indicate such local aridity about the Colorado Mountains. On the contrary, the coal swamps of the eastern interior were formed where the warm, moist winds were rising up the long western slope of Appalachia. In general, it appears that humid climatic conditions were exceptionally widespread during Pennsylvanian time.

There is also much evidence that the climate was warm, even to high latitudes, during much of the period. The mere presence of abundant vegetation is no evidence, for it is well known that the most extensive modern accumulation of peat is in subarctic regions where slow growth is more than counterbalanced by slow decay; but the *character* of the Carboniferous vegetation indicates a lack of freezing winters, at least in the lowlands where the plants are preserved. The trees, whether tree ferns, seed ferns, cordaites, or the great scale trees, bore succulent foliage of almost unequaled luxuriance. The leaves were not merely large but their texture indicates rapid growth under warm, humid conditions. For example, the very large size of the individual cells, the arrangement of the stomata (breathing pores), the smoothness and thickness of the bark, the presence of aërial roots, and the absence of growth rings in the woody trunks are all features of significance. One of the foremost paleobotanists of our times concluded that "the climate of the principal coal-forming intervals of the Pennsylvanian was mild, probably nearly tropical or subtropical, generally humid, and equable."

The animal life of the time also seems to support this view. At



DEUTSCHES MUSEUM, MUNICH.

Fig. 62. Pennsylvanian swamp forest, as restored by H. Potonié: a, scale tree, Lepidodendron; b, seed fern; c, Calamites.

certain times during the period corals were able to thrive in great abundance and to form reefs as far north as the arctic islands of Spitzbergen (lat. 78° N.). The presence of these ancient reefs in the sea cliffs of a land now treeless and ice-covered speaks eloquently of the climatic contrast between the present and the Pennsylvanian age in this region (Fig. 63).

Nevertheless, we must not assume that there were no exceptions to the picture we have drawn of widespread warmth. Great changes have occurred in the temperature of most of the lands in the few tens of thousands of years since the Ice Age. During a period like the Pennsylvanian, of millions of years' duration, there may have been important fluctuations in the world climate.

The extensive continental glaciation of India, South Africa, South America, and Australia, which some geologists attribute to Late Pennsylvanian time, we regard as of Permian age. It is discussed later in this chapter.

Without a doubt the polar regions were cooler than those of low latitudes and it may well be that the mild climate of Spitzbergen was due



O. Holtedahl.

FIG. 63. Coral reef in the early Pennsylvanian (Moscovian) strata of western Spitsbergen. Both tetracorals (*Campophyllum*) and tabulates (*Chætetes*) are present. The present arctic climate is indicated by the snowbank at the left.

to the local influence of a warm ocean current which then streamed into the Arctic. Nevertheless, the evidence for mild climate is so widespread that we can not avoid the belief that in general the Pennsylvanian was an exceptional period in the climatic history of the Earth.

Permian Deserts. During the Permian period, as the Paleozoic era drew to a close, Appalachia was rising boldly and the interior sea retreated toward the Southwest. At this time climatic extremes were marked in many parts of the world, and the central and southwestern parts of the United States took on a truly desert character.

At the beginning of the period an extensive inland sea occupied the region of the western Great Plains. It doubtless spread far east of the present outcrops and at one time reached temporarily to Ohio. Its outlet to the south across Oklahoma was restricted by the growth of a great delta from Llanoria which surrounded the Arbuckle and Wichita mountains as the modern delta of the Hwang Ho surrounds the Shantung peninsula in China. Deltas were also growing eastward from the Colorado Mountains in New Mexico. The climate gradually became so arid that evaporation exceeded precipitation, and eventually a vast dead sea occupied the middle of the basin which centered over Kansas and Oklahoma, and another one developed in west Texas. One group of the marine animals after another died out, and the water finally

became a brine from which salt precipitated. Across Mexico and the Gulf a connection with the ocean was maintained through which more salt water was supplied as evaporation proceeded. Eventually the saline waters disappeared, either because the basin was filled to sealevel, or, more likely, because of regional warping. Then, streams converging into the basin spread over its desert floor hundreds of feet of red mud and sands. For a time, extensive sand dunes covered parts of Oklahoma, where they are preserved in the Whitehorse sandstone. In the red beds there are occasional zones of gypsum which seem to indicate a temporary return of seawater and partial evaporation, though not enough to precipitate salt. There is far more gypsum in Oklahoma than in Kansas and Nebraska; in fact, Oklahoma is known as the "Gypsum State" because of these extensive Permian deposits. In westernmost Texas a deep well has gone through 1200 feet of anhydrite in which banded layers, supposed to mark seasonal deposition, suggest that from 150,000 to 300,000 years was required for its deposition.

The dune sands, the striking red beds, and the widespread deposits of salt and gypsum in the central and western United States indicate a vast interior more arid than the present Great Basin. The salt beds that stretch from Kansas to New Mexico have been estimated to include 30,000 billion tons of salt and would require the evaporation of more than 22,000 cubic miles of seawater with a salinity like that of the modern oceans. This precipitation, it must be remembered, occurred while only a part of the Permian formations were being deposited. It produced the largest salt deposits known.

Severe aridity also spread over central and western Europe at this time. Red beds are of wide extent in England and Germany, reaching northeastward into the Urals of Russia. Upon these in Germany lie the great salt deposits of the Stassfurt region, where potash salts occur with the sodium chloride, indicating complete desiccation.

In South Africa the Permian deposits are largely nonmarine red beds, though here they are not associated with salts or dune sand, and, on the contrary, include a wonderful assemblage of fossil reptiles. This region was probably one of plentiful though markedly seasonal rainfall.

Glaciers of the Late Paleozoic. At times during the Permian period great areas in the southern continents were covered with ice sheets. *South Africa* has the most spectacular evidence of glaciation, for here the ancient Dwyka tillite at the base of the Permian sequence includes large faceted boulders and rests upon the heavily scored and polished floor over which the ice moved (Fig. 64). The ice cap covered practically all of Africa south of the Equator, and also spread to Madagascar (which was then part of the continent). There were at least three

or four centers of movement, but the greatest seems to have been in the Transvaal, which then was a plateau from which the ice moved southwestward for a distance of at least 700 miles. The tillite reaches a thickness of less than 100 feet in the northeast but increases to 2000 feet in southern Karroo. *Australia* was likewise the scene of extensive and repeated glaciations, the ice apparently moving northward across Tasmania, Victoria, and New South Wales. A series of sheets of tillite are interbedded in some 2000 feet of Permian sediments which have at



A. P. Coleman.

FIG. 64. Glacial floor under the Dwyka tillite near Kimberley, South Africa.

least one horizon of commercial coal. *South America* bears evidence of glaciation in Argentina and southeastern Brazil, even within 10° of the Equator. In the northern hemisphere, peninsular *India* within 20° of the Equator was the chief scene of glaciation, with the ice flowing north; in the Salt Range on the southern flank of the Himalayas the thick Talchir tillite underlies the marine Permian formations (Fig. 65).

In the northern land masses, on the other hand, evidences of glaciation are very restricted. The only certain evidence in North America is a small deposit near Boston, the Squantum tillite, which may be the result of a valley glacier from the rising Appalachians. Striated boulders in conglomerates have been found in the Permian beds of Alaska, but the proof of their glacial origin is not conclusive. The same may be said of doubtful occurrences in England, Germany, south Russia, and central Africa.

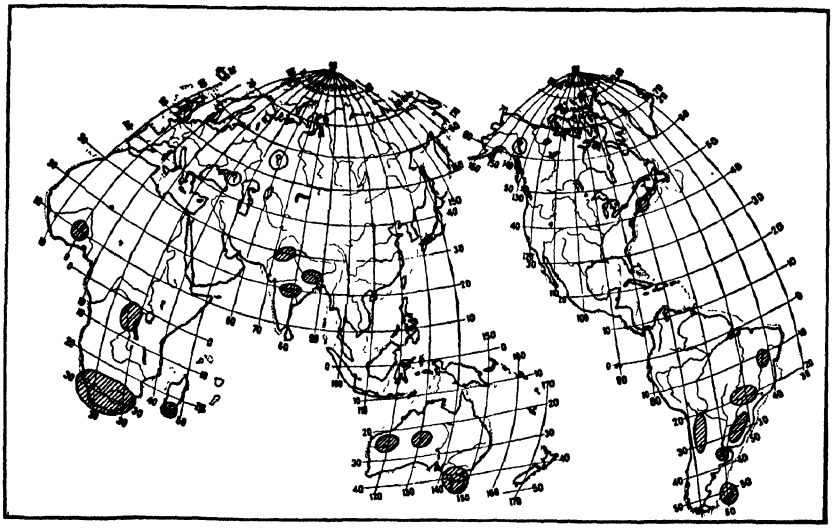


FIG. 65. Distribution of Permian glaciation (shaded areas). Base map used by courtesy of the American Museum of Natural History.

It is almost certain that the Permian ice age, like the recent one of Pleistocene time, was a relatively short age — something like one or two million years — in the duration of the long geologic period. The three widely spaced repetitions of glacial beds in the thick Australian sequence may indicate recurring glacial ages restricted to that continent. In any event, the main glacial deposits are in each region confined to a limited horizon of the older Permian rocks. The presence of large reptiles in the higher Permian red beds of South Africa would suggest a mild-temperate climate without freezing winters at the time when they lived.

The *exact time of the ice age* is difficult to prove in any of the glaciated regions. Possibly it was not the same in all the continents, though it would seem more probable that such extensive refrigeration must have affected the temperature of the whole world at once. It now appears that the best-dated glaciation occurred before the middle of Permian time.

The most remarkable feature of the Permian glaciation is the *distribution* of the ice sheets. They were chiefly in the southern land masses and in regions which now lie within a few degrees of the Equator. This circumstance more than any other has lent attractiveness to the belief in "continental drift." If the southern continents were united to Antarctica until after Permian time, the glaciation may not have spread into low latitudes. A later "drift" of these continents

toward the north would account, far more easily than any other means yet postulated, for the present distribution of the glacial deposits. But this premise itself is still in the realm of speculation!

The Permian Crisis and the Close of an Era

Momentous changes ushered the Paleozoic era to its close. As the mobile borderlands continued to rise and were thrust against the emerging continents, several of the great geosynclines were uplifted into mountains. While the Appalachian system was being folded in America, the Urals were forming in Russia, and other, transverse chains crossed central Europe and southern Asia, extending southeastward through the East Indian arc. Climatic changes of extreme severity coincided with this crustal unrest. The widespread glaciation and the long-continued aridity that swept over large parts of a world previously adjusted to the warm and moist climates of the Pennsylvanian caused organic changes of the most drastic sort. Land animals, and land plants as well, struggling against a new and harsh environment, either made effective adaptations or became extinct. Judged by the changes that occurred, the Permian must be reckoned as one of the great crises in the history of life.



Fig. 66, A (left). North America in Early Triassic time. A shallow sea occupied parts of California and the Cordilleran trough; and east of this, nonmarine red beds accumulated over a vast lowland (horizontally lined).

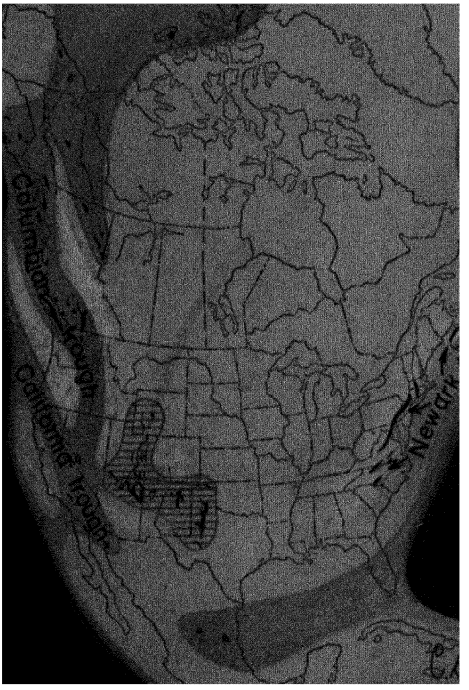


Fig. 66, B (right). North America in Late Triassic time. While seas occupied three troughs in the Far West, red beds accumulated over a great area in Wyoming, Utah, New Mexico, and Texas. The Newark fault troughs were forming in the Appalachian

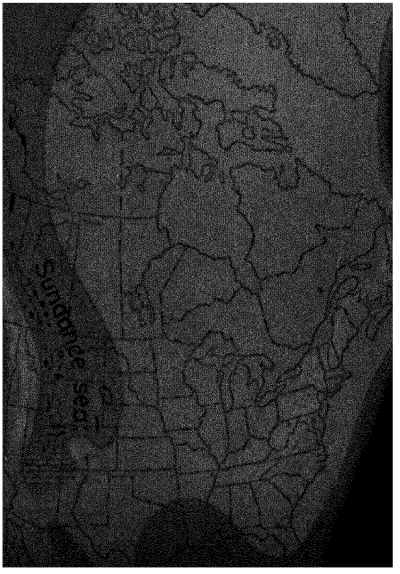


Fig. 66, C (left). North America in Late Jurassic time. The Rocky Mountain geosyncline, now taking form, was flooded from the north by the Sundance sea and from the south by a Mexican embayment. The Gulf Coastal Plain was submerged for the first time.

Chapter 7

THE MESOZOIC WORLD

Shifting Scenes

While dinosaurs held sway over the Mesozoic world, physical changes of a profound nature shaped and reshaped the North American lands (Fig. 66, *A-F*). The eastern half of the continent remained almost wholly emergent and suffered long and persistent erosion. At first, the Appalachian Mountains were probably bold and rugged, but before the middle of the Triassic period they were reduced to low relief. The *Palisade disturbance* at the end of this period renewed the relief along the axis of the Appalachian system; but as this final disturbance died away, a stable condition was attained that contrasts strangely with the Paleozoic history. The whole region was probably reduced to a peneplane during the Jurassic, and it remained low and flat throughout the Cretaceous period.

No marine deposits of Triassic or Jurassic date exist in the Atlantic Coastal Plain, and it appears that the shore was then farther east than at present; but slow submergence in Cretaceous time brought a shallow shelf sea over most of the present Atlantic and Gulf Coastal Plains (Fig. 66, *D, E*); clearly, the ancient borderland, Appalachia, had by then subsided below the Atlantic, and for the first time the waves were breaking against the present margin of the co ıtinent.

In contrast to this eastern stability, changes of ᵖ profound nature were in progress over the western half of the continent. Early in the era three distinct geosynclines were forming in the far west, one in California, another in British Columbia, and ᵃ third following the axis of the modern Rockies. Adjacent geanticlines were rising as the troughs subsided, forming mountainous islandˢ or peninsulas as suggested in Fig. 66, *B*. Volcanoes were active in northern California, Oregon, and westernmost Canada during parts of Middle and Late Triassic time and again in the Jurassic.

The Rocky Mountain geosyncline waᵓ slowest of the three to develop but eventually became the greatest. It was ill defined in the Triassic period, forming an extensive low belt to which the sea gained limited access. Early in the period marine waters reached it via California and Nevada and spread northward into Canada (Fig. 66, *A*); before the

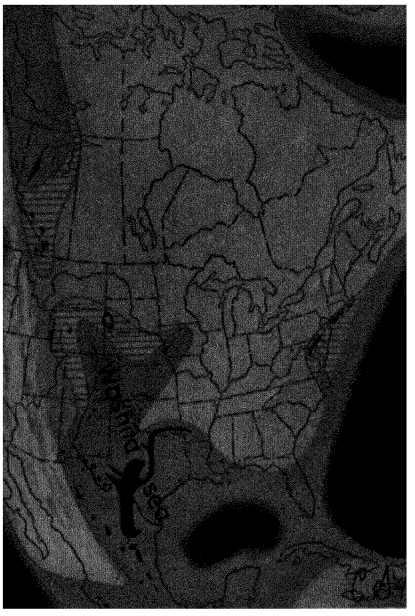


Fig. 66, D (left). North America late in Early Cretaceous time. The Rocky Mountain geosyncline was again invaded by seas from both north and south. Nonmarine coastal-plains deposits were accumulating in the Chesapeake region.

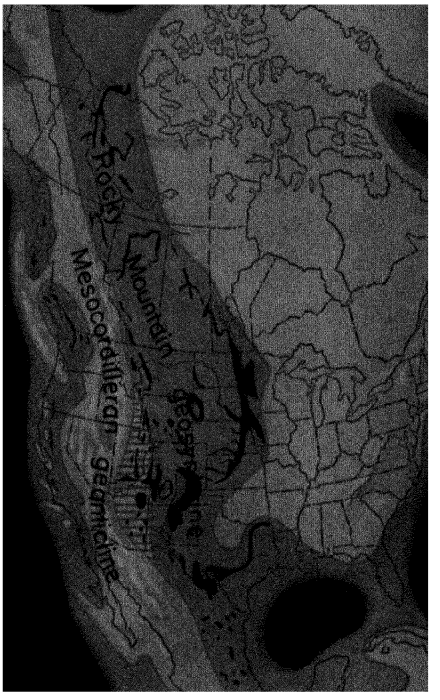


Fig. 66, E (right). North America at the climax of the Cretaceous submergence, early in Late Cretaceous time. The Mesocordilleran geanticline was rising into a mountainous axis west of the Rocky Mountain geosyncline.

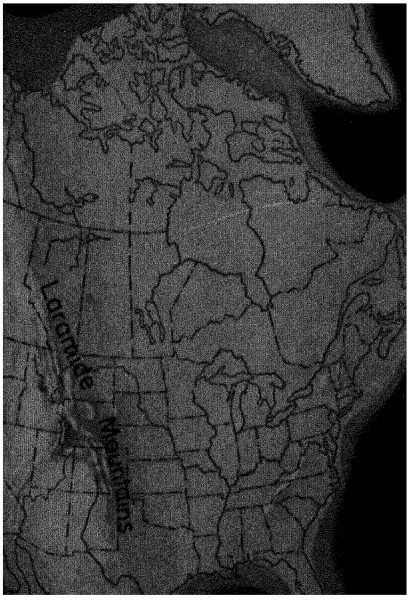


Fig. 66, F (left). North America near the close of Cretaceous time. The seas had withdrawn beyond the present shoreline, and the Laramide Mountains, first generation of the Rockies, were buckling up out of the floor of the preceding geosyncline.

middle of the period this connection was broken and the sea invaded the geosyncline for some distance from the north; meanwhile, non-marine red beds were spread over a large area now embraced in Arizona, Utah, Wyoming, Colorado, and New Mexico. Late in Jurassic time a pronounced submergence brought the Sundance sea southward as far as Utah and Wyoming, while a smaller embayment from the south covered the central part of Mexico. At the same time, the waters of the Gulf region spread northward to Oklahoma and Arkansas, as shown in Fig. 66, *C*. Meanwhile, a considerable area in Utah, lying in the rain shadow of the rising Mesocordilleran geanticline, was an arid basin in which accumulated thick deposits of dune sand.

The withdrawal of the Sundance sea was followed, during the closing stages of the Jurassic, by the deposition of the Morrison formation, well known as the source of the greatest of all dinosaurs.

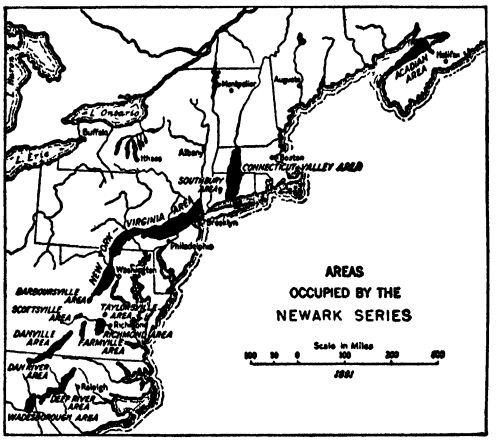
The succeeding Cretaceous period (Fig. 66, *D*, *F*) witnessed the widest and final development, and then the destruction, of the Rocky Mountain geosyncline. Although drained of seawater at the close of the Jurassic, this trough persisted as a major structural feature and was slowly subsiding during nearly all of Cretaceous time. Early in the period it was invaded by shallow seas from both the north and the south (Fig. 66, *D*); but the southern invasion was limited to Mexico and Texas until near the middle of the Cretaceous, and there limestones and marls of considerable thickness were formed. Meanwhile, fluvial sands and muds were spread over the middle part of the trough in Colorado, Wyoming, South Dakota, Nebraska, and Kansas (Dakota sandstone, etc.).

Submergence then became more rapid, and soon the geosyncline was transformed into a vast seaway (Fig. 66, *E*) from 500 to more than 1000 miles wide, extending from the Gulf of Mexico to the Arctic Ocean, and separating North America into two land masses, the eastern one very wide and low, the western narrow and mountainous. Meanwhile, parts of the Atlantic and Gulf border states and small areas along the Pacific Coast were submerged. This was one of the most extensive marine floods of all time and, at its climax, covered approximately 50 per cent of North America.

The sea slowly withdrew during the latter part of the period, and was displaced by rapid filling as uplift was renewed in the geanticline to the west of it. Over the swampy lowlands thus produced, the coal-bearing Laramie series was laid down during the closing stages of the Mesozoic. Then came compression from the west which folded and thrust the deposits of the geosyncline into the grand Laramide system of mountains — the first generation of the Rockies (Fig. 66, *F*).

Growth and Decay of the Mountains

Newark Fault Troughs, Red Beds, and Volcanics. After the Appalachian Mountains had been formed by the folding of the crust, the compressive stresses from the east died out, uplift ceased, and the mountains were slowly worn down. All this had been accomplished before the middle of Triassic time, and then normal faults began to appear along the axis of the chain, bringing about the subsidence of a series of long narrow fault troughs or graben. As these sank they were filled to great depth with coarse sediments derived, in part, from adjacent uplifted blocks. The strata preserved in these troughs have been named the *Newark group* for their exposures about Newark, New Jersey, and the basins are known as the Newark troughs. Their position is indicated in Fig. 67.



After I. C. Russell, U. S. Geol. Survey.

Fig. 67. Areas occupied by the Newark group.

The Connecticut trough is near the middle of the group and, being the best known, will serve as a type. It extends north from New Haven across Connecticut and Massachusetts, having a length of about 100 and a width of 25 miles. Its history is suggested by Fig. 68.

The Triassic rocks of the basin are conglomerates, arkosic sandstones, siltstones, and shales, with interbedded flows of dark lava (trap). Perhaps half the sedimentary beds are gray, but the most prominently exposed parts are red, and these commonly give the impression that the whole series is one of red beds. These strata have an estimated thickness of 10,000 to 13,000 feet, and show a regional dip of 15° to 30° toward a great fault that forms the eastern boundary of the trough. Their arrangement indicates that the trough subsided more than two miles during deposition.

No marine fossils have been found in these beds, but dinosaur tracks are more abundant here than anywhere else now known, occurring in profusion on the bedding planes at many horizons in the series. Ripple marks and mud cracks are also common, and the imprints of raindrops are not rare (Fig. 26, p. 42). Certain lenses of dark shale, associated

with the traps, and presumably swamp and lake deposits, are filled with fish and plant remains.

Interbedded with the sedimentary strata are three great lava flows, each separated from the next by several hundred feet of sandstone and shale. Dikes of the same basic lava cut the beds in many places, and there are sills in the older part of the series.

With these characters in mind it is not difficult to visualize the Late Triassic history of this region. Central Connecticut was then a trough like the Great Valley of California. A range of block mountains bordered it on the east, with a fault scarp facing the valley (Fig. 68). Repeated movements along the fault depressed the basin and uplifted the mountains. Meanwhile, the streams from the uplands dropped most of their load as they reached the basin, building alluvial fans along its eastern border and spreading the finer material as floodplain deposits to aggrade its floor. Rainfall was apparently torrential, and recent studies suggest that it may have been great, but concentrated into a wet season alternating with dry months. The climate was doubtless warm and probably subtropical. Dinosaurs thrived in the timbered uplands and crossed and recrossed the basin during the dry season, leaving their footprints on its muddy floor. Repeated movements along the great fault were doubtless accompanied by earthquakes of great violence as the floor of the basin settled with an eastward tilt. About the middle of the period of this deposition, lava reached the surface

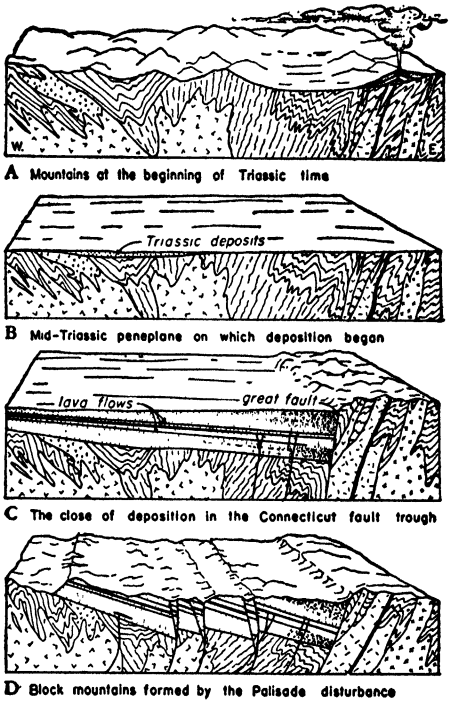


FIG. 68. Four stages in the development of the Triassic basin of central Connecticut. View northward. Length of sections about 30 miles. Modified from Joseph Barrell.

The first block shows the complex structure and rugged topography inherited from the Appalachian revolution; block *B* shows the beginning of Newark deposition after the region was largely peneplaned; block *C* shows the Newark fault trough fully developed through subsidence along the great fault; block *D* shows the final stage, with the Newark deposits complexly faulted during the Palisade disturbance. The modern structure of the region dates from this time. Triassic strata stippled.

by way of a fissure and spread widely while in a highly fluid state, filling the basin practically from side to side, and even overflowing its eastern border in places. At such times, the basin was a lake of fire, smoking by day and lurid at night as its red-hot lava slowly cooled. Eventually the flows ceased, the basin was further depressed, and the slow deposition of sediments continued. Two later flows duplicated this history, and then the igneous activity came to an end.

By the close of the Triassic the basin had the structure suggested in Fig. 68, *C*. Then came uplift, with normal faulting, which profoundly dislocated the strata of the Newark basins and produced the present structure, leaving the surface mountainous again as suggested in Fig. 68, *D*. This movement has been called the *Palisade disturbance*. It affected the axial belt of the old Appalachian system from Nova Scotia to the Carolinas.

With this final movement the forces of disturbance were relieved and the Appalachian region lapsed into a state of quiet stability that lasted throughout the rest of the Mesozoic era.

The Nevadian Disturbance. In the Far West, the first pronounced Mesozoic disturbance came at the end of the Jurassic period. The Triassic and Jurassic deposits of that region show that the Californian and Columbian troughs had subsided several thousands of feet and were filled meanwhile by sediments derived from the surrounding lands. In part these sediments are coarse enough to imply strong erosion in uplands of considerable relief, but in part they are fine-grained dark shale or even limestone. Interbedded lavas and volcanic ash prove that volcanoes were active over considerable areas in northern California, parts of Oregon, and western British Columbia, but the lack of pronounced or regional unconformities within the Triassic and Jurassic record seems to indicate that the movements throughout this western region were due to gentle warping and did not disturb the deposits of the geosynclines. Late in the Jurassic, however, regional compression from the west crumpled and folded the Triassic and Jurassic and all older rocks, and uplifted them into a great chain of fold mountains that occupied much of California and the western half of Nevada and extended far to the north through British Columbia. This was the *Nevadian disturbance*. It produced the most intense deformation the Far West had experienced since Pre-Cambrian time.

The folding was preceded and accompanied by much volcanic activity and was accompanied by deep-seated intrusions on a gigantic scale. Volcanoes were active during Late Jurassic time in a chain that extended from Cook Inlet, Alaska, to California and Nevada. The volcanoes

were largely submarine, piling up deposits as much as 3000 feet thick associated with marine strata.

During the disturbance a series of granitic batholiths was injected into the heart of the range (Fig. 69). These are now extensively exposed as a result of later erosion. The *Sierra Batholith* of California has a length of nearly 400 miles and a maximum width of 80 miles; and the *Coast Range Batholith* is still larger, extending from the Canadian border for a distance of 1100 miles and reaching as far as Alaska. Each of these is a composite formed by many related intrusives.

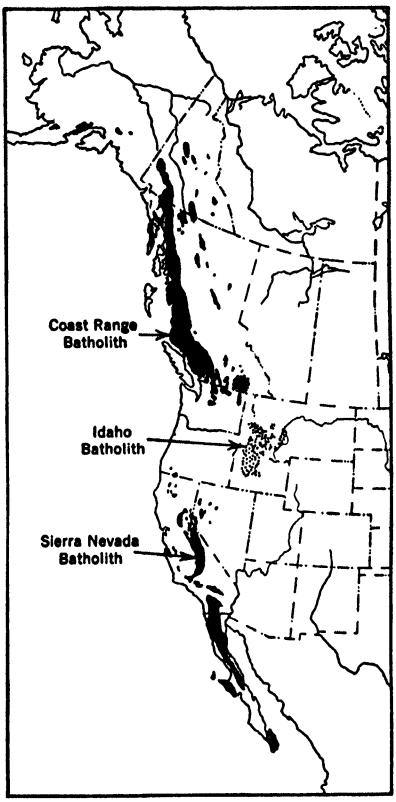


FIG. 69. Outcrops of Mesozoic batholiths in western North America. Late Jurassic intrusions in black; late Cretaceous stippled.

No plutonic injections on such a grand scale had occurred in this continent since before the Cambrian. The heat and pressure, as well as the escaping fluids and gases ascending from such vast bodies of magma, severely metamorphosed the overlying sedimentary rocks. The gold-quartz veins of the "Mother Lode" belt in the Sierras were deposited by ascending solutions which penetrated the Jurassic slates that then formed the roof of the Sierra Batholith.

Laramide Revolution and the Birth of the Rockies. Crustal unrest was again very marked during the closing stages of the Mesozoic in many parts of the world, but nowhere with more profound and far-reaching effects than in the western half of North America. At this time the floor of the vast Rocky Mountain geosyncline, so long covered by the Cretaceous seas, became the scene of folding and thrusting on a colossal scale. The orogenic belt stretched from Alaska to Central America and in the United States had a width of some 500 miles. It was clearly the most far-flung disturbance that has befallen North America since the Pre-Cambrian, and deserves to rank as one of the

great revolutions in geologic history. It was long ago named the *Laramide revolution* after the Laramie Range in Wyoming.

Most of the Rocky Mountain structures date from this movement, and so, in spite of later erosion, we can still restore the post-Cretaceous mountains in considerable detail (see Fig. 82, p. 135, for geographic relations). In the Southern Rockies the dominant structures are broad open arches now exposing the Pre-Cambrian granite floor, while remnants of the Paleozoic and Mesozoic formations are exposed in hogbacks along their flanks. The Front Range of Colorado and the Laramie Range in Wyoming are illustrations of this type (Figs. 70 and 71). Subparallel ranges farther west are separated from these by

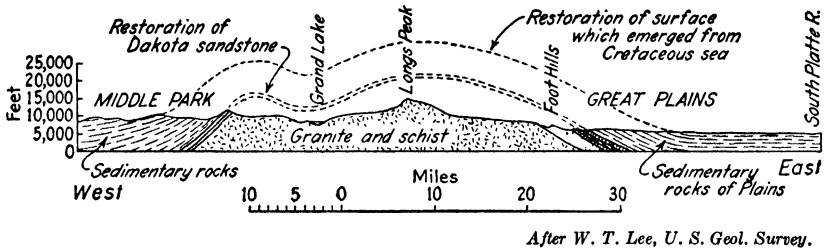
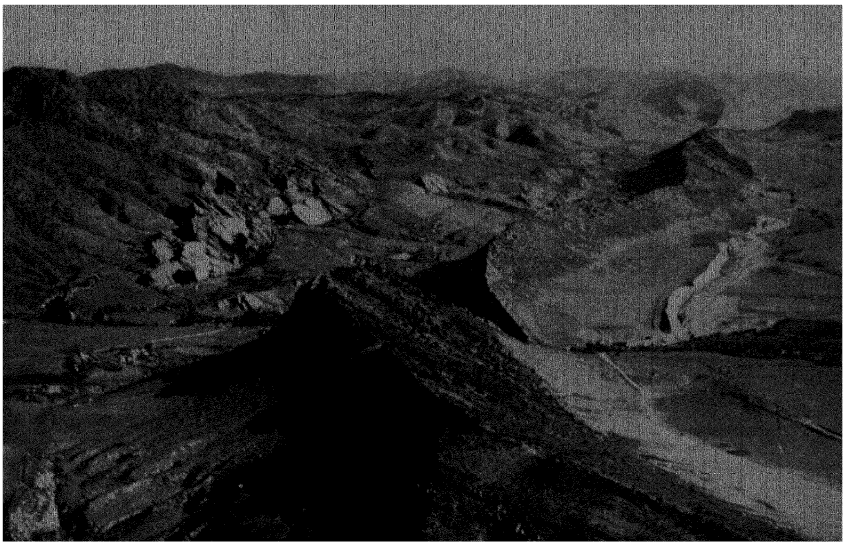


FIG. 70. Section across the Front Range near Denver, showing its arched structure and suggesting the amount of erosion that has occurred since uplift.

a major synclinal fold still recognizable in the "Parks" of Colorado (North, Middle, and South parks, and San Luis Valley). Farther east, in the plains, are outliers of simple domal structure such as the Black Hills and the Big Horns. The westernmost ranges, on the contrary, show a more complex structure, resulting from great thrusts that in places carried Pre-Cambrian rocks eastward over the Cretaceous. A belt of profound thrusts lies along the western border of the Middle Rockies and cuts obliquely across to the front of the Northern Rockies. In the Lewis thrust of northern Montana, the thick Proterozoic rocks were driven many miles eastward over the Cretaceous rocks of the plains (as illustrated in Figs. 252–257 of *Outlines of Physical Geology*).

With great overthrusts from the west predominating along the western border of the Rockies and giving way to open folds and great arches farther east, it is evident that the orogenic forces were coming from the west. But unfortunately we can not trace them to their probable source farther west or in the area of the Pacific Ocean, because the Columbia Plateau is covered with younger lavas and the Great Basin has been so much involved in later deformation and is



T. S. LOVERING AND F. M. VAN TUYL, U. S. GEOL. SURVEY.

Fig. 71. East flank of the Front Range near Denver, showing hogbacks of Cretaceous and older strata uparched by the Laramide revolution. An aërial view looking north, from an altitude of 7100 feet. The great hogback in the foreground is formed of the Dakota sandstone, and those in the middle distance at the left are of Pennsylvanian (Fountain) sandstone. The mountains at the left are of Pre-Cambrian granite. Longs Peak is at the horizon just left of the center of the view.

so largely covered by young deposits, that no clear reconstruction of its Laramide history can be presented. It should be said, however, that the entire Pacific coastal belt was uplifted enough to be completely emergent, for there is a great stratigraphic hiatus between the Eocene and the Cretaceous in that region even though it was not as strongly deformed at this time as was the Rocky Mountain country.

Volcanic activity preceded and attended the Laramide orogeny. Volcanoes were active intermittently on the old Mesocordilleran geanticline throughout the Cretaceous period and they spread eastward as the mountains rose. There is much volcanic agglomerate, for example, in the latest Cretaceous beds (Denver formation) of Colorado. In fact, it is probable that, during the Laramide folding, every state west of the Great Plains had its active volcanoes.

Idaho was the scene of a great granitic intrusion which produced the *Idaho Batholith* (Fig. 69). Its eroded summit is now exposed over an area of 16,000 square miles in the central part of that state. A related intrusion, the *Boulder Batholith*, underlies Butte, Montana.

Red Beds and Dune Sands of the Arid West. For this brief account the Triassic and Jurassic formations may be discussed together, since they have much in common.

The Newark series of the East has been briefly presented in connection with the Palisade disturbance. No other Triassic, and no Jurassic rocks are known east of the Great Plains. But if we compare the maps of Fig. 66 it is clear that two regions in the West were receiving deposits during both these periods. The first was an arid basin lying east of

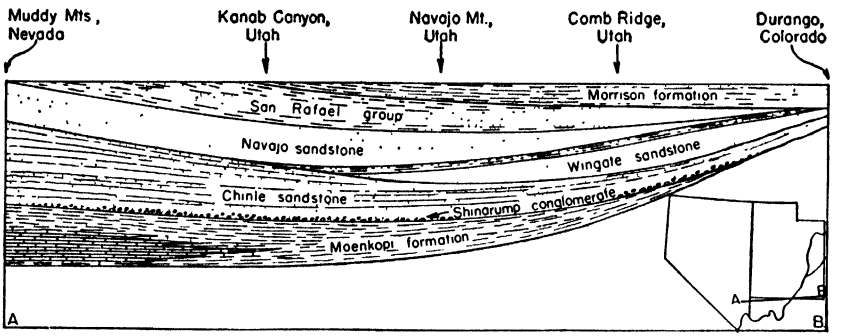


FIG. 72. Section across the Colorado Plateau from the Muddy Mountains of Nevada to Durango, Colorado, showing the relations of the Triassic and Jurassic formations.

Idaho and Nevada. The sea reached it briefly in Early Triassic time and more extensively in the Late Jurassic. Otherwise the formations laid down in this region are predominantly red beds and deposits of wind-blown sand. The exposures of these formations are very extensive in the Colorado Plateau where they form the Painted Desert, the walls of Glen Canyon, and Vermilion and White cliffs north of the Grand Canyon. Zion National Park is carved in towering cliffs of these red and white sandstones, and Rainbow Bridge is an erosion remnant in which the cross-bedding of ancient dunes is strikingly displayed.

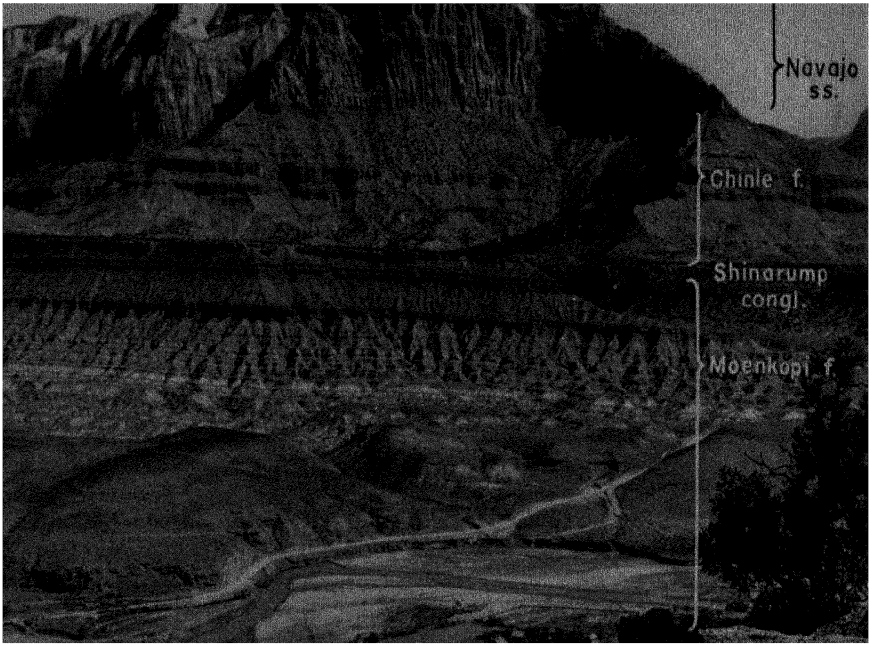
A section from the Muddy Mountains in southeast Nevada to the Uncompahgre Plateau in northwest Colorado shows the character and arrangement of these formations (Fig. 72), and a typical exposure of these rocks is shown in Fig. 73. As a whole they are thickest over the middle of the basin, thinning out unconformably toward its margins. A twofold division of the Triassic deposits is generally recognizable. The lower portion, known as the *Moenkopi* (mō′-ĕn-kō-pē), is typically

a weak formation of shale and siltstone, well bedded and evidently deposited by water. Both color and composition change systematically from west to east. Where typically developed southeast of the Grand Canyon, the Moenkopi siltstones and shales are variegated in color, with buff, chocolate-brown, and maroon predominating, and with some gray layers. Farther east the formation thins by overlap on the rim of the old Triassic basin, and there it is coarser and commonly bright red in color; but toward the west the red color is replaced by gray, and tongues of limestone appear and gradually replace the shale. Thus in the Muddy Mountains of eastern Nevada the whole formation, about 1500 feet thick, is mostly limestone and fully marine. The red part of the Moenkopi contains no marine fossils and apparently represents floodplain and delta deposits spread over the basin east of the Early Triassic sea.

The upper series of beds, known as the *Chinle* (chĭn-lee′), is generally more brilliantly colored. Red predominates, but bands of white, yellow, or bluish gray add variety. It rests with erosional unconformity on the Moenkopi over the eastern part of the plateau region, where it has a striking basal conglomerate, the *Shinarump* (shĭ-nă′-rump).

Fossils are extremely rare throughout the red beds. With the exception of those found in certain thin marine members that dovetail into the Moenkopi from the west, the only known fossils are remains or tracks of terrestrial or fresh-water animals, and land plants. River clams occur here and there, and certain horizons include " bone beds " filled with the remains of amphibians (*Stegocephalia*) and of crocodile-like reptiles (*Phytosauria*), all of which inhabited the stream channels of the time. Petrified wood is abundant locally in the Chinle sands, as at Fossil Forest, Arizona, and recently fossil leaves have been found in the lower part of this formation at several localities in Fossil Forest National Monument. These are chiefly of cycadeoids and ferns. The ferns indicate a swampy habitat along stream courses and the implication of all the fossil plants suggests a region of moderate rainfall concentrated into a rainy season, followed by a long, dry season. Such a climate now produces regions with timber along the stream courses and sparse shrubs and grasses on the uplands.

The fossils, like the physical features of the rocks, therefore indicate that the red beds were for the most part, at least, deposited above sea-level. The Moenkopi was in part deposited over a vast low floodplain sloping westward from the Colorado Mountains to the margin of a shallow inland sea whose shore fluctuated back and forth over the western part of Arizona and Utah. The Chinle was more completely independent of the sea and was spread by sluggish streams over a broad



UNION PACIFIC SYSTEM.

Fig. 73. West Temple of the Virgin, Zion National Park, Utah. A 4000-foot wall of Triassic and Jurassic rocks carved out of the Colorado Plateau by the Rio Virgin. The ranch houses at the bottom indicate the scale. Triassic rocks extend up to the base of the Navajo sandstone.



BARNUM BROWN, AMERICAN MUSEUM OF NATURAL HISTORY.

Fig. 74. Excavating a dinosaur skeleton in the Morrison formation near Shell, Wyoming.

basin of probable semiarid climate and seasonal rainfall; locally there were swamps and shallow lakes, while in the higher ground surrounding the basins there were scattered stands of conifers. From farther west explosive volcanoes spread ash falls over the basin.

Overlying the bright red Chinle formation is a remarkable group of cliff-forming sandstones, mostly light gray or pink in color and as much as 3000 feet thick. Its grandest exposures are in the White Cliffs north of the Grand Canyon. The "Great White Throne" in Zion National Park is an example. This group is composed almost entirely of fine-grained, pure quartz sand. The bedding is commonly obscure, and the sandstone appears exceptionally massive, outcropping in unscalable cliffs of commanding height. A single thin-bedded member separates two massive sandstones, the *Wingate* and the *Navajo*. These normally outcrop in two tremendous cliffs with a bench between. Over great areas the Navajo sandstone is a solidified dune sand, as clearly shown by the gigantic, curved cross-laminæ.

Overlying these desert sands is the *San Rafael group*, consisting of two marine formations and two sets of nonmarine red beds. These marine zones mark extreme southern limits attained by the Sundance sea. They thin southward and disappear near central Utah, being replaced by the nonmarine deposits. Northward, on the other hand, they thicken into Idaho where the marine section of the Upper Jurassic is very thick and includes much limestone. The sea evidently occupied the northern part of the geosyncline while desert conditions obtained in Utah and Arizona.

The *Morrison formation*, originally spread over most of the Rocky Mountain States, is the youngest of the Jurassic deposits and is remarkable for its great dinosaurs and associated land animals (Fig. 74). It varies locally in color and in coarseness, for it represents the deposits of aggrading streams crossing a humid and swampy lowland. It has yielded more than 150 kinds of fossils, including 69 species of dinosaurs, 25 of tiny primitive mammals, 3 crocodiles, and 24 river clams and land snails.

Triassic and Jurassic formations extend northeast of the region just discussed and underlie the northern Great Plains, outcropping along the front of the Rockies and in the rim of the Black Hills. The Triassic is represented by bright red shales and siltstone with much gypsum. It forms the Red Valley in the rim of the Black Hills and outcrops as the upper part of the "red beds" of Wyoming. In this region it is overlain by the Sundance formation of Late Jurassic age, which is predominantly gray in color and locally very fossiliferous, varying in composition from coarse sand to shale and impure limestone.

The red beds of Triassic age also extend southeastward from the Colorado Plateau into eastern New Mexico and southern Texas.

Marine Record of the Pacific Geosyncline. In the seaways bordering the present Pacific coast, marine deposits of Triassic and Jurassic age are both well developed, but the region has been so strongly deformed during later periods that they are well known only locally. In California the Triassic formations attain a thickness of 4000 feet and in the region of Vancouver Island and the Queen Charlotte Islands of British Columbia they exceed 13,000 feet, but approximately nine-tenths of this great thickness consists of submarine volcanic materials — lava, breccia, and tuffs — with which are interbedded shale and quartzite bearing Upper Triassic fossils. Alaska also has thick Triassic strata, chiefly limestones, which have local reef corals and are surmounted by a considerable thickness of black shale.

The Jurassic rocks are likewise thick, and are mainly of detrital material in California and Nevada. In central California, where the Mariposa slates are interbedded with much volcanic material, a thickness of possibly 10,000 feet is attained. The *Knoxville formation* of sandstone and siltstone in north-central California, along the west side of the Sacramento Valley, is equally thick. Highly deformed and much metamorphosed rocks of supposed Jurassic age form large areas in the Coast Ranges north of San Francisco where they are known as the *Franciscan series*, of great but not well-determined thickness. Special interest attaches to the fact that conglomerates in this series increase in coarseness toward the west, indicating their derivation from a borderland that lay west of the present coast.

Recently a very complete section of marine Triassic and Jurassic formations was described from west-central Nevada, indicating a marine record probably rivaling that of any other part of the world for its completeness. Over great areas in the Coast Ranges, as in the Sierras, these early Mesozoic rocks have been somewhat metamorphosed and are poorly dated.

Cretaceous Filling of the Rocky Mountain Geosyncline. The Rocky Mountain geosyncline subsided slowly during the Cretaceous, and the sea gradually encroached from both south and north, the Mexican and Arctic embayments finally meeting about the middle of the period and then spreading so as to cover the whole broad region from central Utah eastward to Minnesota and Iowa. Sediments converged from the land on both sides, but chiefly from the west, to be distributed by waves and currents over this broad sea floor, filling the basin about as rapidly as it sank. The Upper Cretaceous

formations thus deposited exceed half a mile in thickness over a great area and locally attain a maximum of probably 20,000 feet in western Wyoming.

The Lower Cretaceous is best developed in Mexico and Texas where richly fossiliferous limestones and marls formed before the sea advanced farther north. They constitute the *Comanche series*, so named for the Comanche Indians who formerly inhabited the Texas region.

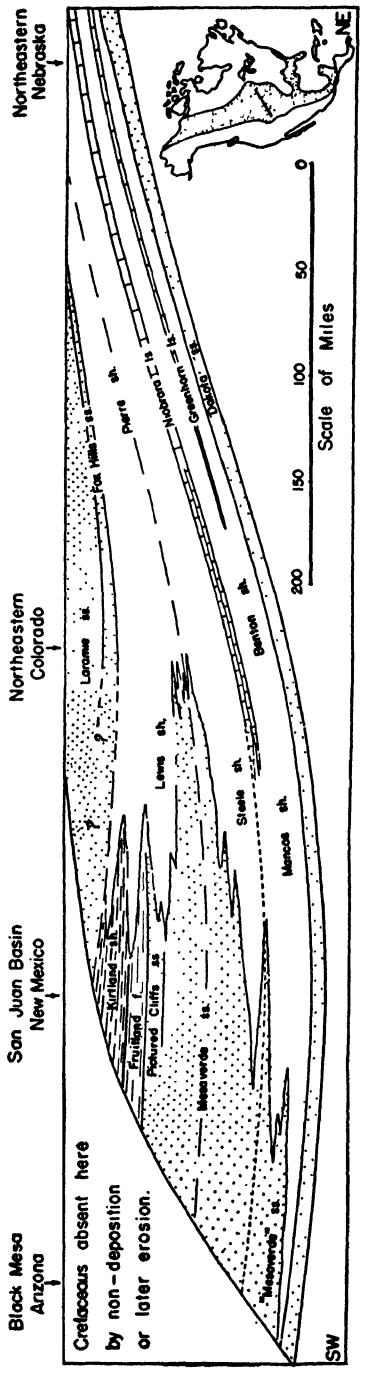
The Upper Cretaceous formations cover the entire geosyncline and spread widely over the foreland toward the Canadian Shield. They begin with a widespread basal sandstone, the *Dakota formation*, which is now important as a reservoir for artesian water under the northern Great Plains. It is plant-bearing and nonmarine, representing fluvial sand and mud spread by sluggish streams over the lowland just in advance of the sea.

The stratigraphy of the post-Dakota strata is complicated by the fact that the sediments were derived largely from the highlands west of the seaway (Fig. 75). As these highlands were repeatedly uplifted and actively eroded, vast quantities of sand and mud were carried down to the Cretaceous sea, the coarser material accumulating to form a coastal plain, locally extended into great deltas, while the finer material was distributed more widely over the sea floor.

The eastern land was so low as to supply only fine sediments in moderate quantity, and, at times, chalky limestone accumulated widely over the eastern part of the sea floor. Thus it happened that quite different types of deposit were forming simultaneously in different parts of the geosyncline. Sands, commonly nonmarine, were concentrated along the western border, grading eastward into marine shale, which still farther east included thin limestones. The resultant relations are shown in Fig. 75, a restored section across the geosyncline from northeastern Arizona to eastern Nebraska.

In the eastern part of this Late Cretaceous series the *Niobrara chalk* stands out as a key horizon, the repository of remarkable vertebrate fossils, notably the toothed birds, the greatest of all flying reptiles (pterodactyls), gigantic marine reptiles, and mighty fish (*Portheus* is 10 feet long). It also has a distinctive fauna of shelled animals such as oysters and ammonites, which range west of the limestone and mark the equivalent horizon in the marine shales; curiously, it has almost no corals, echinids, or brachiopods.

The *Mesa Verde sandstone* is a nonmarine, commonly coal-bearing formation representing the coastal-plain and delta deposits of the western shore zone. It ranges through nearly all the Upper Cretaceous


Northeastern Nebraska
Northeastern Colorado
San Juan Basin New Mexico
Black Mesa Arizona
Cretaceous absent here by non-deposition or later erosion.
Pierre sh.
Niobrara ls.
Greenhorn ls.
Graneros sh.
Fox Hills ss.
Laramie fm.
Lewis sh.
Steele sh.
Mancos sh.
Kirtland sh.
Fruitland fm.
Pictured Cliffs ss.
Menefee ss.
Point Lookout ss.
Gallup ss.
Gallup ss.
Gallup

with much coal. Fossil plants are, of course, abundant, and the last of the dinosaurs are represented by many fine skeletons, but no marine fossils are known.

Changes of Climate

Although the Late Paleozoic was marked by extensive glaciation in many parts of the world, there can hardly be a doubt that the climate was generally warm again in Triassic time and probably subtropical as far north as New England and Wyoming. This is indicated by the distribution of cold-blooded land animals. Dinosaurs were then extremely abundant in New England, and crocodile-like reptiles (phytosaurs) as well as large amphibians (stegocephalians) inhabited the stream courses of the West, ranging at least as far north as Wyoming. All living relatives of these cold-blooded land animals become torpid and helpless at freezing temperatures; small species creep into holes to hibernate and thus endure cold weather, but large types, unable to find such refuge, cannot survive a single freezing winter. Accordingly, the alligators and crocodiles, the great land tortoises, large lizards and such snakes as the python and boa constrictor, live only in the tropics and subtropics. Mesozoic reptiles, likewise, almost certainly lacked means of controlling their bodily warmth and so were limited by temperature as are the modern types.

If this indicates mild Triassic climate, the evidence is still more convincing for the Jurassic and much of Cretaceous time when the reptiles were in their heyday and the greatest of all dinosaurs were living. For example, the Late Cretaceous strata of the Red Deer River Valley in Alberta have yielded an amazing variety of dinosaurs, and the tracks of other species have been found as far north as Peace River in latitude 58°.

Fossil plants confirm the implications of the reptiles. During Middle Jurassic time, for example, the common species of North American land plants ranged northward into Siberia, arctic Alaska, Spitzbergen, and Scandinavia, and southward to Louis Philippe Land south of Cape Horn. Moreover, the Upper Cretaceous rocks, even in high latitudes, preserve remains of land plants belonging to genera now restricted to warm temperate or subtropical regions. In central western Greenland, for example, the Cretaceous beds have yielded leaves of the fig, breadfruit, cinnamon, and tree ferns, and in Alaska they contain cycads, palms, and figs. Although most of these are commonly thought of as strictly tropical, each of the genera has representatives in the temperate zone and it is not necessary to conclude that tropical climate extended into polar latitudes. Nevertheless, it is almost cer-

tain that Greenland was without an ice cap when these plants were growing and the climate then was temperate rather than frigid.

Of course, this does not prove that the climate remained so warm throughout the long Mesozoic era, or that it was equally mild in all parts of the world. Indeed, there is some evidence of reduced temperatures following the Nevadian disturbance at the end of the Jurassic, and again after the Laramide revolution at the close of the Cretaceous. For example, the corals had been widespread in the Jurassic but appear to be much more restricted in their distribution in early Cretaceous time, and there is clear evidence of local glaciation in eastern Australia where striated erratics, ranging up to 6 feet across, are found through some 600 miles of outcrop of mid-Early Cretaceous rocks. These glacial boulders seem to have been dropped by icebergs derived from glaciers that then existed along the eastern side of an inland sea in Australia.

The mildest climate doubtless came with the greatest spread of the shallow seas, and climatic extremes followed continental emergence and the growth of lofty mountains.

For example, the Ridgway tillite, flanking the San Juan Mountains in Colorado (see p. 146), indicates local glaciers following the Laramide uplift, though whether they formed in the closing stage of the Cretaceous or early in Cenozoic times is not yet known.

The humidity undoubtedly varied widely depending, just as it does today, on the relations of topography to the prevailing winds. In the low basins that lay east of the Mesocordilleran geanticline, semiarid to arid conditions apparently prevailed during much of Triassic and Jurassic time when the nonmarine red beds were accumulating. The red color is not, of itself, evidence of aridity. It merely means that the sediment was thoroughly oxidized and remained so after deposition. This could not be true if abundant vegetation accumulated with the sand and mud, for then the decaying plant tissue would create a reducing condition and change the red to gray or dark colors. Marked seasonal rainfall appears to provide the most favorable conditions for the accumulation of red sediments, because the rainy season provides adequate moisture and the long dry season limits the vegetation largely to small herbaceous plants that die and decay while the ground is dry.

But the layers of gypsum associated with these red beds in many places clearly imply at least temporary aridity, since gypsum is a chemical precipitate and its presence shows that evaporation exceeded the rainfall. Furthermore, the vast deposits of pure cross-bedded sand in the Jurassic rocks of Utah and Arizona indicate conditions under which vegetation was so sparse that dunes migrated over a great area of the basin of deposition.

On the contrary, the closing stages of the Jurassic period presented a very different scene, for then the Morrison formation was being spread widely over the Rocky Mountain States, forming a fluvial plain with abundant vegetation and animals of many kinds, some of which are believed to have lived chiefly in lakes and swamps.

During the Cretaceous period also, abundant rainfall and swampy conditions are indicated by the nonmarine deposits formed along the west side of the great Rocky Mountain geosyncline, which bear coal at many horizons.

At the same time, vast salt deposits in the Early Cretaceous beds of Arkansas and Louisiana, and thick gypsum deposits of the same age under Florida, indicate arid conditions in this region in which evaporation greatly exceeded precipitation.

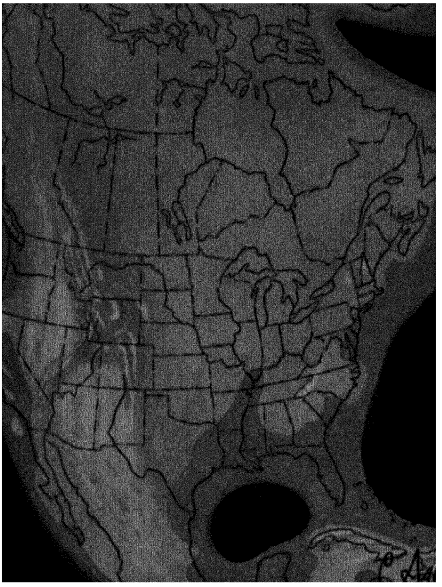


Fig. 76, A (left). North America in early Cenozoic (Eocene) time. Shallow marginal seas covered part of the Pacific Coast states and the Gulf and Atlantic coastal belts, the Mississippi embayment then reaching northward to Cairo, Illinois.

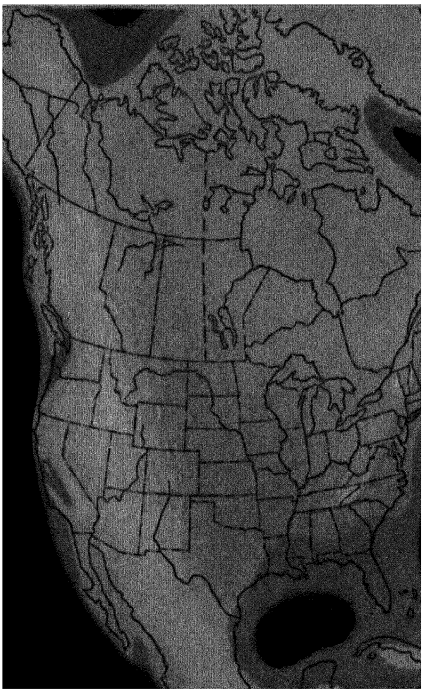


Fig. 76, B (right). North America in mid-Cenozoic (Oligocene) time, when the Rocky Mountain region was largely peneplaned.



Fig. 76, C (left). North America in late Cenozoic (Pliocene) time, after renewed uplift and deep erosion had restored strong relief in the Rocky Mountain region and the Basin and Range Province had taken on its modern form.

Chapter 8

THE MODERN WORLD UNFOLDS

The last, short era of geologic time has witnessed the shaping of every feature of the present landscape. During this time the Alps and Himalayas arose from the sea floor, the Rockies and the Andes came up to their present height, the streams attained the courses they now follow, and the climatic zones took on their modern character. The Cenozoic also saw the spectacular rise of the mammals to dominance upon the Earth, and witnessed the coming of Man.

The era was a time of exceptional unrest, lying between the Laramide revolution which brought the Mesozoic to a close, and the Cascadian-Alpine revolution from which we are just emerging. In many parts of the world, movement has not ceased and active volcanoes and violent earthquakes warn us of mobile zones still "alive." The climax of the disturbance is but recently past, if, in fact, we have really seen its culmination, and the Earth is at present in a rather exceptional stage of its history, the continents being abnormally large, the highlands more extensive and the mountains more lofty than they have been during much of the past, and the climatic zones exaggerated. By the same token, the landscape is more varied, the scenic features grander, and the Earth as a whole far more interesting than it has generally been.

Judged either by its sedimentary record or by radioactive minerals, the Cenozoic is the shortest era, including but a single period, and probably not exceeding 60,000,000 years of time. The Mesozoic era was at least twice, and the Paleozoic probably five times, as long.

With the retreat of the late Cretaceous seas and the building of the Rockies at the close of the Mesozoic era, North America assumed practically its present size and outline (Fig. 76). During much of Cenozoic time the Gulf Coastal Plain was largely submerged, and to a lesser extent the Atlantic Coastal Plain was covered by a shallow marginal sea. Small embayments also occupied parts of the coastal belt of California, Oregon, and Washington, but the maximum marine inundation covered less than 10 per cent of the present continent, and the average was about 3 per cent.

The Appalachians Are Etched into Relief

The Cenozoic history of the Appalachian region is represented in Fig. 77, and is also discussed on p. 310 of *Outlines of Physical Geology*. By early Cenozoic time, nearly all of it was peneplaned, the exceptions being a chain of monadnocks as much as 2000 or 3000 feet high along

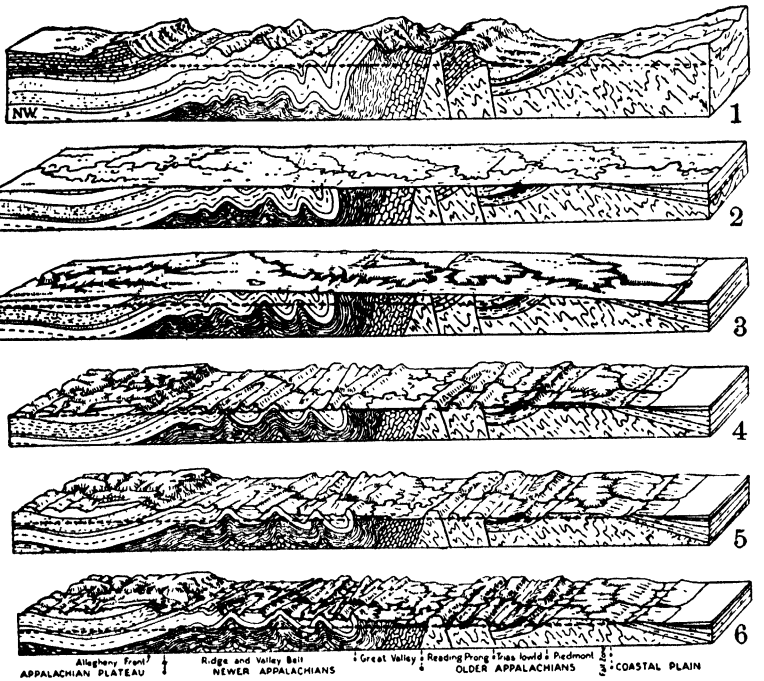


Fig. 77. Evolution of the modern topography of the middle Appalachian region:

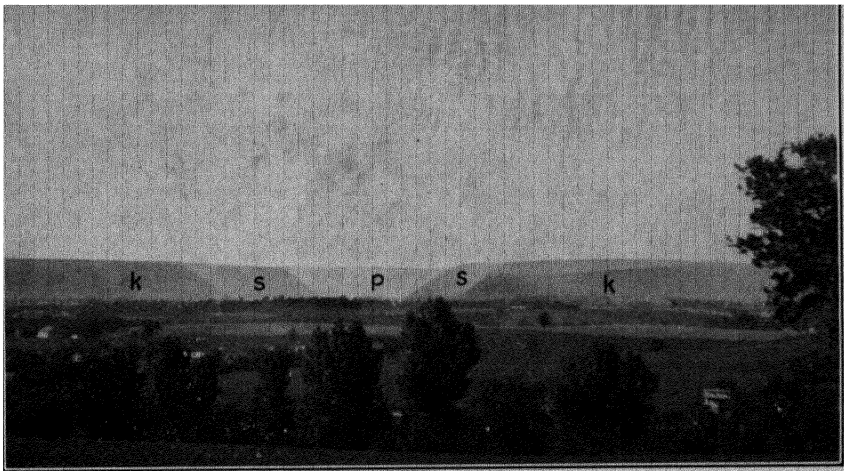
1. Rough topography of early Jurassic time, resulting from dissection of the structure produced by the Appalachian revolution and the Palisade disturbance.
2. Development of Schooley peneplane.
3. Arching of Schooley peneplane and incision of drainage.
4. Dissection of Schooley peneplane and local development of Harrisburg erosion surface beveling belts of weak rock.
5. Further uplift and dissection, with development of a lower erosion surface (Somerville) beveling only the weakest rocks.
6. Latest uplift and dissection.

Modified slightly from D. W. Johnson.

the border between Tennessee and North Carolina, and scattered hills in northern New England. These unreduced areas form the crest of the modern Great Smoky Mountains, the summit of the White Mountains, and of such scattered peaks as Mount Monadnock in New Hampshire and Mount Katahdin in Maine, none of which shows evidence of

having ever been reduced to a level surface. Elsewhere in the Appalachian region there are widespread remnants of a flat erosion surface preserved in the even crests of the highest ridges of the folded belt (Fig. 78), and possibly in the summits of the Allegheny Plateau. This surface, which is represented in block 2 of Fig. 77, has been named the *Schooley peneplane.*

It may be noted that this surface bevels across the complex structures of the Appalachian system, all of which had been produced long



George H. Ashley.

FIG. 78. Remnants of the Schooley peneplane are seen in the accordant crests of these Appalachian folds. The view is westward into the Susquehanna Gap at Harrisburg, Pennsylvania, showing Kittatinny Mountain (*k*) with Second Mountain (*s*) and Peters Mountain (*p*) beyond it.

before. At some Cenozoic date not yet accurately determined, the axis of the region was arched and uplifted a few hundred feet, as shown in block 3. The streams then incised themselves to the new baselevel and opened out extensive lowlands on the weak formations, while the resistant rocks stood up as ridges, as in block 4. Remnants of these flat lowlands are still conspicuous about Harrisburg, and this flat erosion surface, present on the weak formations only, has been named the Harrisburg surface.

A second gentle upwarp along the axis of the Appalachians caused the streams to incise their valleys into the Harrisburg surface and to excavate new lowlands of more local extent at a lower elevation, as in block 5. Still younger and more frequent uplifts of this sort have given rise to strath terraces along the major streams as they carved

their present deep valleys. Thus by a series of gentle uplifts the Schooley peneplane has been warped up to its present maximum height of about 4000 feet along the crest of a broad, simple arch, and the ridges and valleys have been etched into relief, as in block 6. From an axis running near the eastern edge of the Allegheny Plateau, the surface of the old Schooley peneplane slopes gently away to the east, and possibly to the west, declining but a few feet to the mile. It is preserved only on the most resistant rocks, and has been completely destroyed throughout most of the piedmont belt. If it could be restored it would have the form of a vast low arch several hundred miles wide and less than one mile high along the crest of the Appalachians. Near the present coast it would descend to sealevel and pass under one of the coastal-plain formations, for it is clear that, as the Appalachian arch came up, the continental shelf was depressed and tilted eastward.

The Coastal Plain Goes under the Sea

Because of the eastward tilting and depression of the continental shelf the Atlantic Coastal Plain was partly submerged several times during the Cenozoic, and deposits of sand, clay, and marl were formed that now dip gently seaward and are still largely unconsolidated. These formations are best developed about Chesapeake Bay and do not exceed a few hundred feet in thickness. They thicken seaward, and in cross-section would appear as a great wedge of sediments thinning out to a landward margin.

Florida was completely submerged throughout most of the era, for it is made of thick marine limestones resting on a late Cretaceous floor. Until Miocene time it was so far from shore that little detrital sediment reached it, but since that date fine sand from the Carolina streams has drifted southward with the shore currents to form beaches along the east coast like that of Daytona.

The Gulf border also was drowned during the Cenozoic, all the way from Florida to Yucatan. The submergence was greatest during the Eocene epoch and at that time the head of the Gulf embayment was at Cairo, Illinois (Fig. 76, *A*). But in the northern part of this embayment the Eocene deposits are largely lignitic clays and sand, indicating deposition over a swampy coastal plain rather than under the sea. From the distribution of the sandy sediments it appears that the Mississippi River system was even then established on about the lines it now follows.

Along the Gulf border the Cenozoic formations are much more continuous, more widespread, and much thicker than on the Atlantic side.

Here the Eocene formations are most extensive; the Oligocene is exceptionally displayed in Florida and Yucatan but elsewhere is far more limited than the Eocene; Miocene and Pliocene formations are in turn less widespread, showing that the continent was gradually assuming its present emergent condition.

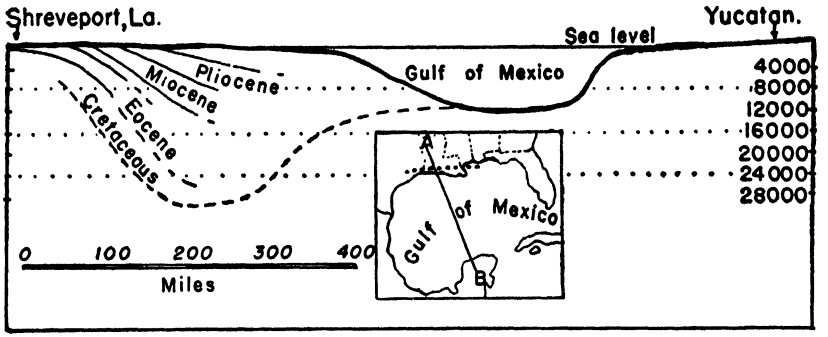


FIG. 79. Section across the Barton geosyncline and the Gulf of Mexico. The inset shows the position of the section, which runs from Shreveport, Louisiana, to Yucatan. The axis of the geosyncline follows the dashed line in the inset map. Depths below sea-level indicated in feet. Modified from Barton, Ritz, and Hickey.

The Cenozoic formations are thickest in the central and western Gulf region where rapid subsidence was counterbalanced by filling as the Mississippi delta grew southward. In parts of the western Gulf coast, the Eocene has not been penetrated even by the deepest oil wells, and recent seismic soundings have indicated that slightly indurated sediments, presumably Cenozoic, attain a thickness of more than 20,000 feet along the front of the Mississippi delta. A recent estimate based on regional dip of the formations and data from deep wells places the maximum thickness of these deposits at 30,000 feet. Since this is more than twice the greatest present depth of the Gulf, it indicates excessive downwarping during Cenozoic time, and suggests a geosyncline in the making. The axis of this trough (the Barton geosyncline) approximately parallels the present coastline of Louisiana and Mississippi (Fig. 79).

THE ROCKIES ARE WORN DOWN AND RISE AGAIN

Basin Filling and Peneplanation. The major structures of the Rocky Mountains date mostly from the Laramide revolution. The folding and faulting continued locally into the Eocene and died out gradually, leaving the region bold and mountainous at the beginning of Cenozoic time.

Among the ranges there were several great structural basins which have persisted, with little deformation, up to the present (Fig. 80).

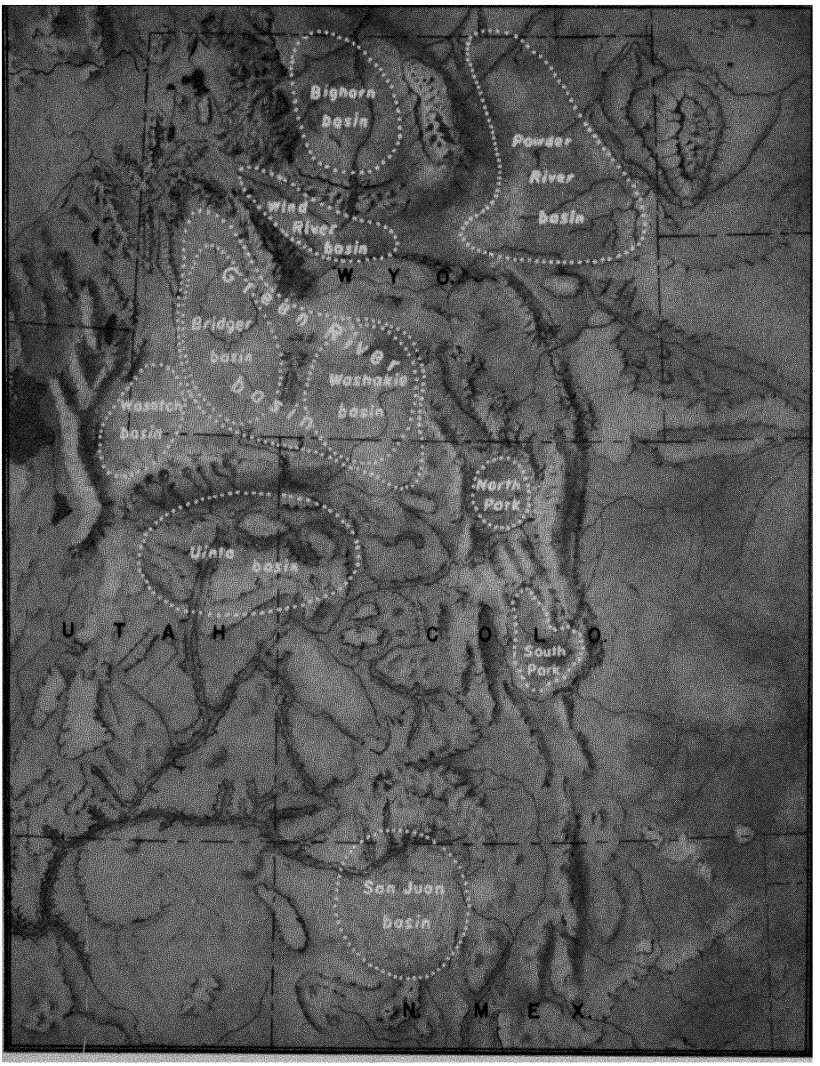


FIG. 80. Structural basins within the middle and southern Rocky Mountains. The topography is that of the present, but the structure dates from the Laramide revolution. Drawn by Milton Wallman.

Such are the Big Horn and Green River basins of Wyoming, and the Uinta Basin and North and South parks in Colorado. As the mountains were eroded, the sediment tended to converge into these basins, where

much of it was trapped. Fans formed about their margins, but most of the debris was spread as broad alluvial deposits across their floors. Thus they were gradually filled as the mountains were worn down. By the middle of the era the intermont basins were full and the mountains largely peneplaned to the level of this surface of aggradation, as represented in Fig. 81, *A*. Along the axes of some of the ranges rounded monadnocks stood a few hundred or even 2000 to 3000 feet above the peneplane, but for the most part the mountains were then buried in their own debris and the streams wandered widely over this thick alluvial cover.

Although very flat, this surface of combined erosion and deposition was probably 2000 or 3000 feet above sealevel, because the streams had hundreds of miles to flow before reaching the sea and even a very low gradient would leave considerable altitude at their source. Peneplanation had been accomplished by Oligocene or Miocene time.

Uplift and Erosional Sculpturing. In Pliocene time uplift was resumed, not in the form of local deformation but rather as a broad upwarp of the whole region into a low arch hundreds of miles across. It correlates in time with the Cascadian deformation farther west, and may therefore be spoken of as a Cascadian uplift. This movement continued intermittently, but with acceleration, to a culmination in the late Pleistocene, and brought the peneplaned surface to a maximum elevation of 10,000 to 11,000 feet along the continental divide. With this uplift the streams were rejuvenated and began to deepen their valleys, to re-excavate the basins, and to sculpture the exhumed mountain masses. Thus the *height* of the Rockies is due to broad regional upwarp, but their present *form* and *relief* were determined by late Cenozoic erosion (Fig. 81, *B*).

Thus far it has been assumed that all parts of the Rocky Mountain region were peneplaned at the same time, and only once. This picture is undoubtedly too simple. Within a region so vast, the ranges possess individuality in structure and lithology, and probably moved with some independence. The final uplift was long and intermittent, and a series of partial peneplanes were probably formed locally as the base-level changed — indeed, there is clear evidence of more than one in many of the ranges. Nevertheless, in most parts of the region remnants of one peneplane are so much more striking than any others that they appear to belong to one general *Rocky Mountain peneplane*. If, instead of one, there are several peneplanes in the Rocky Mountains, then the history is more complicated in its detail but in fundamentals it is essentially as outlined above.

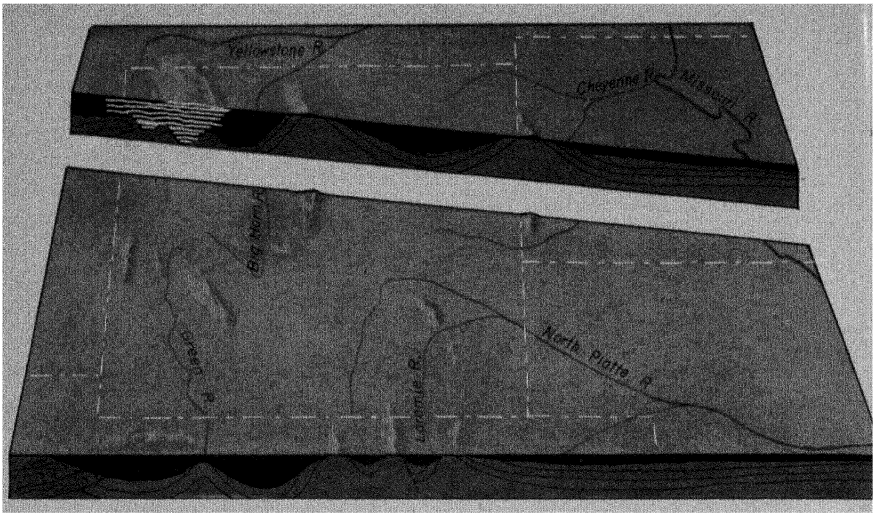


Fig. 81, A. Block diagram of the middle Rocky Mountains and part of the Great Plains as they were in Miocene time, when the basins were filled with Cenozoic deposits (black) and the ranges were peneplaned to the level of this aggraded plane. Monadnocks mark the sites of the chief ranges. The block has been cut in two and the pieces parted to show the structure along a line passing through Yellowstone Park and the Black Hills. In the area of Yellowstone Park and the Absaroka Plateau, volcanics (white) largely replace the sedimentary deposits. The streams flow for the most part upon alluvial deposits which hide the buried ranges.

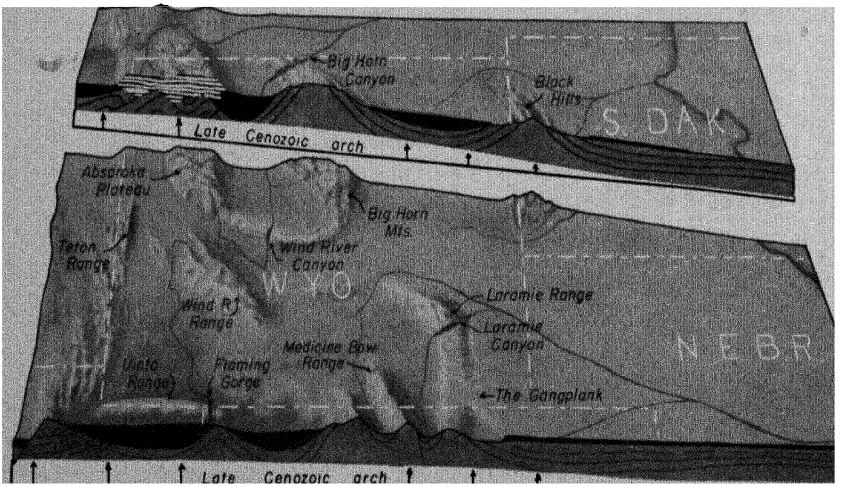


Fig. 81, B. Block diagram of the same region as Fig. 81, A, showing the present relief which is due to (1) broad regional arching during post-Miocene time and (2) excavation of much of the weak fill from the basins. In the removal of the Cenozoic fill the streams were in many places superposed on the ranges which they now cross in imposing canyons.

Evidence of the history just sketched may be seen in (1) peneplane remnants still preserved along the summits of most of the ranges, (2) remnants of the Cenozoic formations around the margins of the basins, and (3) superposition of many of the streams across the present ranges.

These features are illustrated in Fig. 81, *B*. A particularly fine peneplane remnant may be seen along the summit of the Laramie Range in southeastern Wyoming. Here, at an elevation of 8000 feet, is a nearly flat surface 10 or 12 miles wide, cutting across granite and other types of igneous rock of the mountain core. "Roads run in almost every direction; and the Union Pacific Railroad crosses the divide, not through a deep pass but across an open plateau. At the station of Sherman one may look for miles in almost any direction, and it is with difficulty that he realizes that his viewpoint is 8000 feet above sealevel, or as high as the summit of many of the rugged mountains of the Northwest." (Blackwelder.)

East of the Laramie Range lie the High Plains, capped by Miocene (and locally Pliocene) beds. Their surface is extraordinarily flat and slopes gently eastward to an elevation of not over 2000 feet in central Nebraska and Kansas. This great flat area is a remnant of the aggraded plain that existed when the mountains were peneplaned. Generally its most elevated western margin has been dissected and eroded back several miles from the mountain front, especially where large streams cross it, but locally in southeastern Wyoming it extends up to the mountains, rising to the level of the summit peneplane. This area forms the "Gangplank" (Fig. 81, *B*) by which the Union Pacific Railroad crosses the mountains from the plains. Even where the High Plains beds have been eroded back several miles it can be seen that if they were projected toward the mountains their surface would meet the peneplaned summit.

Several miles north of the "Gangplank," the Laramie River crosses the range in a granite gorge more than 1000 feet deep. It rises west of the range and flows northward for some 50 miles along the floor of Laramie Basin at an elevation of less than 7000 feet, and then turns east and cuts through the range instead of following the lowland northward to the Platte. Such an anomalous course is easily understood if the Laramie Basin was once filled with sediment that slightly covered the range as represented in Fig. 81, *A*, for then the stream flowed on a graded plain from which it was superposed on the range after uplift. The Cenozoic fill has been almost completely removed from Laramie Basin, but a telltale remnant still exists along its western margin, flatlying along the front of the Medicine Bow Range at an elevation of

8500 feet. The greatest remnants of Cenozoic deposits at high altitudes, however, are along the southern end of the Absaroka Range where Eocene and Oligocene strata are interbedded with, and protected by, volcanics. Here flat-lying Oligocene strata, at an elevation exceeding 10,500 feet, rim the northern side of the Wind River Basin.

The course of Laramie River in crossing the Laramie Range is not exceptional; the major streams flow radially out of the Rocky Mountains, crossing basins and ranges alike. As shown in Fig. 81, *B*, Big Horn River, originating in the Wind River Basin, cuts through the Owl Creek Mountains and flows for 100 miles across Big Horn Basin, only to turn east and cut across the north end of the Big Horn Range in an imposing chasm. Likewise, Green River flows south across Green River Basin, swings east along the north side of the Uinta Mountains, and then cuts through them in the magnificent Flaming Gorge. Farther south, South Platte River, heading in South Park at an elevation of about 9000 feet, flows northeast through the Front Range in another great gorge; and the Arkansas, after flowing across South Park Basin, cuts through the Front Range in picturesque Royal Gorge, whose sheer walls tower 1400 feet above the stream.

All these and other anomalous features of the drainage find a simple explanation in the fact that the basins were formerly filled completely with Cenozoic sediments until the ranges were covered where the streams now cross them.

Stripping and Canyon Cutting in the Colorado Plateau

The Colorado Plateau, lying west of the southern Rockies, is almost as high as the mountains (Fig. 82). Here the Mesozoic formations are still, for the most part, nearly horizontal, and the results of erosion, following broad regional uplift, are displayed in spectacular fashion.

The Grand Canyon of the Colorado, for example, is carved across the west-central part of the plateau, where the uplift has been greatest. North of the Grand Canyon, Triassic, Jurassic, and Cretaceous formations outcrop in plateaus that rise terrace-like, one above another, separated by colossal cliffs (Fig. 83) formed of the receding edges of formations more than 6000 feet thick that once extended across the region. If restored, they would form a broad, nearly flat-topped dome about 100 miles across, with its summit more than a mile above the present rim of the canyon.

The Cenozoic history following this broad doming of the Mesozoic formations is represented in Fig. 84. The first great uplift can not

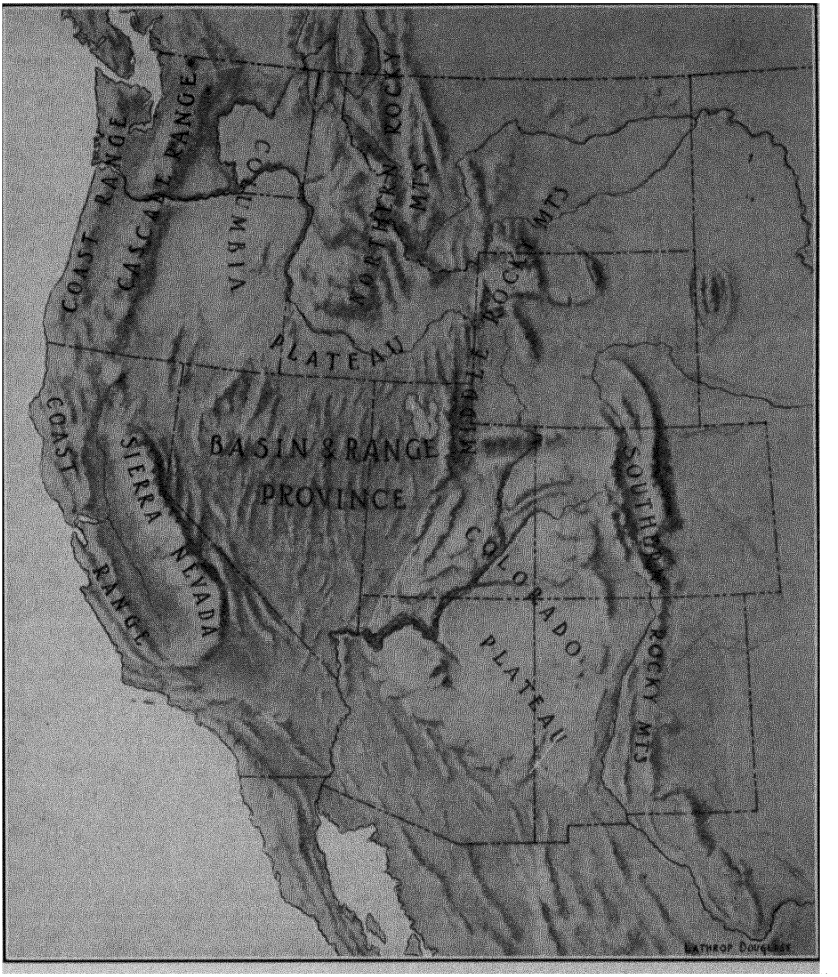


FIG. 82. Relief model of the Cordilleran region, showing the relations of its major structural elements.

now be accurately dated, but it probably occurred in mid-Cenozoic time. The summit of the dome (dashed line) was then probably 6000 or 7000 feet above sealevel. The long period of erosion that followed the uplift stripped away much of the Mesozoic formations, reducing the central part of the dome to a flat surface near baselevel, with a rim of great inward-facing cliffs formed of the receding Triassic, Jurassic, and Cretaceous strata. The profile at this stage is indicated by the dotted line. Renewal of uplift, amounting to some 6000 feet, gave the region its present height and started the cutting of the Grand Canyon, which is now approaching the new baselevel.

The date of this last great uplift can be determined indirectly west of Grand Wash Cliffs, where the Colorado River leaves its canyon and crosses the lower country, in which there are Pliocene formations bear-

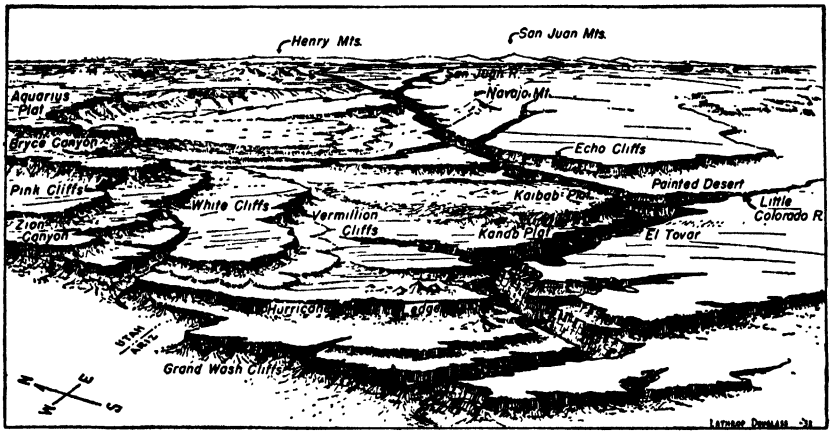


FIG. 83. Aërial view of the Grand Canyon district from the southwest, as seen east-northeast across the mouth of the canyon, where it cuts through Grand Wash Cliffs and enters the lower country to the west of the Colorado Plateau. The Grand Canyon proper extends up to the mouth of the Little Colorado River, above which the gorge is called Marble Canyon as far as Echo Cliffs, and above that, Glen Canyon. Width of front of block about 200 miles.

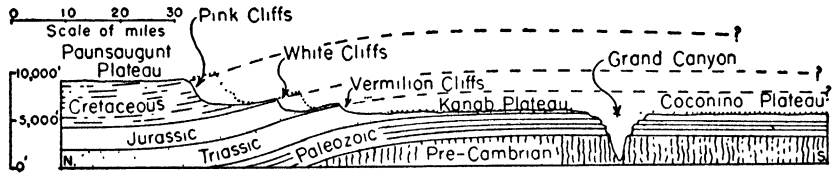


FIG. 84. North-south section across the Grand Canyon region south of Kanab, Utah, showing relation of the present surface to the structure. The base line is drawn at sea-level. Dashed lines indicate the position the Mesozoic formations would assume if the eroded portions were restored; dotted line indicates the profile before the last uplift, which initiated the cutting of the Grand Canyon.

ing thick salt and gypsum deposits that could only have formed in arid basins without exterior drainage. Obviously, therefore, the Colorado River did not exist, or at least did not have its present course, until after Pliocene time. Hence the great uplift of the plateau and the carving of the Grand Canyon are the work of Pleistocene and Recent times.

Fig. 84 makes it clear, moreover, that the Grand Canyon, in spite of its grandeur, represents but a fraction of the amount of erosion that took place following the mid-Cenozoic uplift of this region.

The Basin and Range Province Takes Shape

The Basin and Range Province is a great area of block mountains largely buried in their own debris. The ranges, mostly small in extent (from 10 to 50 miles long and from 5 to 10 miles wide), are uplifted and tilted blocks made mainly of Paleozoic and Pre-Cambrian rocks or of Cenozoic volcanics. The flat basins between the ranges are deeply filled with Miocene, Pliocene, and Pleistocene nonmarine deposits, covered for the most part with alluvium. In places these Cenozoic basin-fills have been faulted up and exposed (Fig. 86).

Miocene formations are locally of great thickness. Their character speaks eloquently of the events that were occurring. For example, in southern Nevada the Miocene deposits begin with coarse conglomerate that ranges up to 3000 feet in thickness and lies across the beveled edges of Early Mesozoic and Paleozoic strata. The conglomerate varies greatly in thickness within short distances and includes angular and subangular fragments of all the older rocks. Overlying the conglomerates are clays and silts, including thick beds of gypsum, magnesite, and borax. The conglomerate is clearly the coarse debris of fans formed in a region of bold relief, and the clays and silts, with their saline deposits, could have formed only in arid basins of interior drainage much like the present basins. In short, normal faulting had begun on a grand scale and the Basin and Range Province had its inception in the late Miocene. As the new ranges were greatly elevated during the Pliocene epoch, the intervening basins, all in the rain shadow of the Sierra Nevada, assumed a desert character like that of today. The faulting was only begun in late Miocene time, for the deposits of that age were themselves later steeply tilted and truncated so that they now lie with strong angular unconformity below the Pliocene beds. The latter, ranging up to 1800 feet thick and including gypsum and salt beds as much as 100 feet thick locally, bear witness to continued deepening of the basins. The well-defined fault scarps, as well as historically dated faulting, prove that the movements are still going on. In short, this province came into existence through profound normal faulting that began in Miocene time, reached its climax during the Pliocene, and has continued until today.

In view of the fact that Paleocene, Eocene, and Oligocene deposits are lacking in this region, we may assume that it was undergoing erosion and had exterior drainage throughout early Cenozoic time. In fact, it was the site of great Laramide thrusts at the end of the Mesozoic, and its surface may have remained high and mountainous until after Eocene time.

Building of the Columbia Plateau

North of the Basin and Range Province, and occupying the area between the Northern Rockies and the Cascade Ranges (Fig. 82), lies the Columbia Plateau, a vast upland built of Cenozoic basalt flows. The basalt covers an area of more than 200,000 square miles and reaches a maximum thickness of over 5000 feet, its total volume being estimated at 24,000 cubic miles. For the most part the lava emerged through fissures in a very fluid condition and spread widely in sheets a few feet to a few tens of feet thick. These flows sought the lowest places, filling

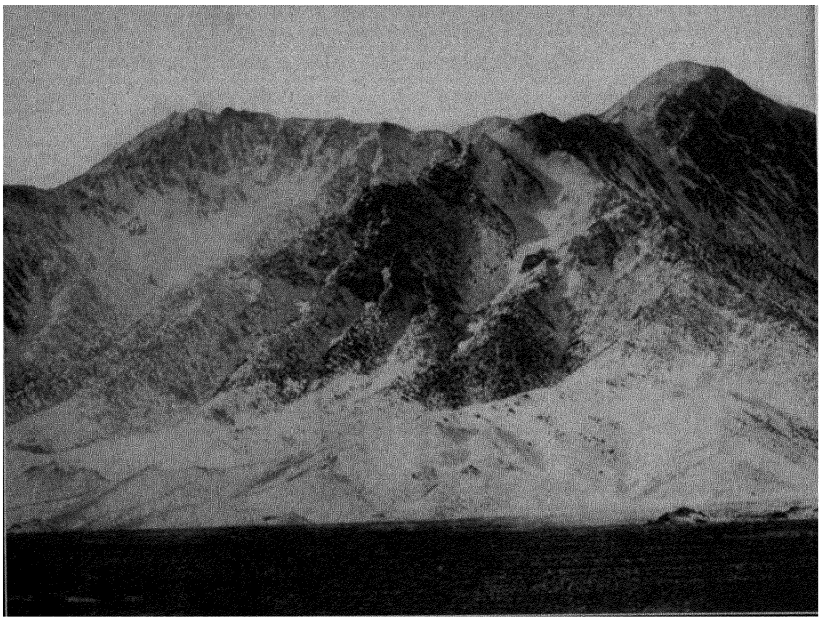


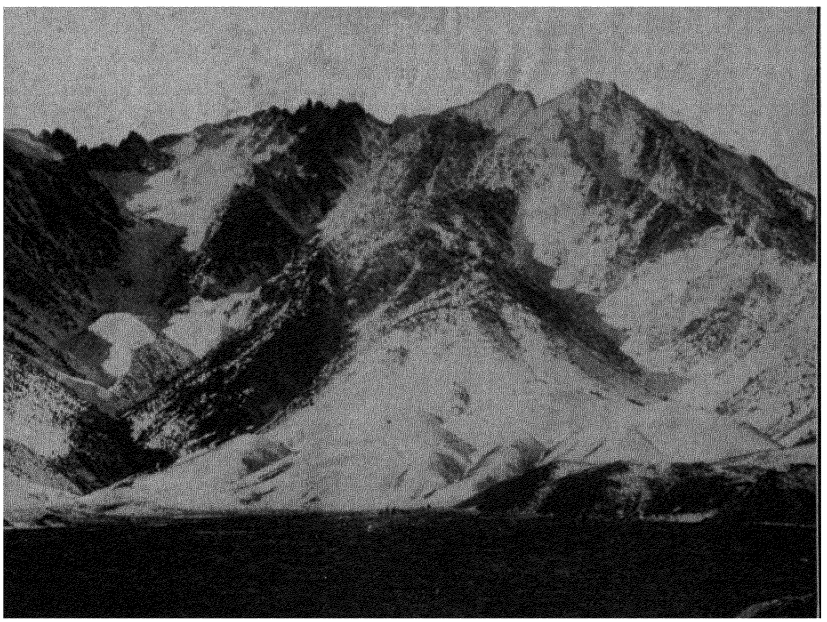
Fig. 85. East face of the Sierra Nevada, one of the world's greatest mountain ward across the floor of Owens

the old valleys and encroaching on the flanks of hills and mountains. In time the pre-basalt topography was buried and a relatively flat basalt plain was constructed.

The larger streams, such as Snake and Spokane rivers, have since cut through the lava flows in some places, especially near the eastern margin of the plateau, and this reveals a pre-basalt surface of considerable relief (at least 2500 feet), formed on schists, granites, and other pre-Cenozoic rocks.

As the flows spread over this region they interrupted the drainage, damming streams and giving rise locally to lakes and swamps in which

sediments accumulated, entombing plant and vertebrate remains. Such fossiliferous deposits now locally interbedded with the lavas serve to date the eruptions. A noteworthy example is the *Latah* formation exposed in the valley of Spokane River near Spokane, Washington. It consists of sands and clays and includes much reworked volcanic ash. It has an exposed thickness of about 500 feet, but deep wells reveal a thickness of 1500 feet of such beds with interbedded lava flows. The deposit lies at the eastern margin of the Columbia Plateau and was formed in swamps and lakes created when the lava, flowing eastward, dammed the streams that flowed westward from the Rocky Mountain



F. E. Matthes, U. S. Geol. Survey.

escarpments, here reaching a height of nearly 2 miles. This is a telephoto view west-Valley. See also Fig. 86.

region in Idaho. The Latah formation has yielded a large number of well-preserved Miocene plants.

A similar deposit is the *Payette* formation exposed in the Snake River Valley on the Idaho-Oregon boundary about 250 miles south of Spokane. It has yielded both plant and vertebrate fossils of Miocene date. These and similar fossiliferous deposits interbedded with the flows indicate that the major part of the basalt eruption took place during Miocene time, though in some areas it continued into the Pliocene. In fact, Snake River Valley (which forms a southeastern lobe of the Columbia Plateau) is covered by black lavas of Pliocene and Pleisto-

cene date in which the fresh appearance of spatter cones, like those of Craters of the Moon National Park, suggest activity within Recent time.

During eruption, and also in later epochs, the Columbia Plateau was broken locally by normal faults, and was subjected to extensive, though gentle, warping, hence the plateau surface now varies from 3000 feet to more than 8000 feet in elevation. In part, the warping may have compensated for the extrusion of the great volume of molten rock from beneath the crust.

The Pacific Border Develops its Modern Form

Fig. 86 shows the structure and mutual relations of the Sierra Nevada, the California Trough, and the Coast Ranges of California, the three most striking elements in the West Coast topography.

The Sierra Nevada represent part of a colossal fault block more than 100 miles wide and nearly 400 miles long. This block has been tilted so that the eastern part was uplifted to an elevation of about 13,000 feet along its margin (Fig. 86), and the western part depressed to perhaps 25,000 feet below sealevel. The uplifted part forms the Sierra Nevada and the depressed half the California Trough.

The Sierra Nevada are sculptured from this single fault block of Jurassic and older rocks, the chief mass being a granite batholith. All the structures within the range far antedate the Cenozoic. Its early Cenozoic history is obscure, but by Miocene time the region had been peneplaned. Then began an uplift accompanied by faulting along its eastern border, which transformed it into a mountain range of moderate height. Relative quiet ensued throughout Pliocene time and the westward-flowing streams opened out broad valleys. About the beginning of the Pleistocene, new uplift and westward tilting began, but the great uplift occurred near the middle of this epoch, after the second glacial age. This elevation of several thousands of feet brought the mountains to their present altitude and started the westward-flowing streams cutting canyons within their broad valleys.

Evidence of these distinct stages of uplift is found (1) in the cross-profiles of the valleys, and (2) in the character of the deposits formed by these streams in the California Trough.

Résumé of Cenozoic Orogeny and Volcanism: The Cascadian Revolution

From the foregoing account, it must be clear that the Cenozoic was an age of great crustal disturbance and extraordinary volcanic activity in the western half of North America. The Laramide thrusting died out irregularly during the long Eocene epoch, and the Oligocene was a

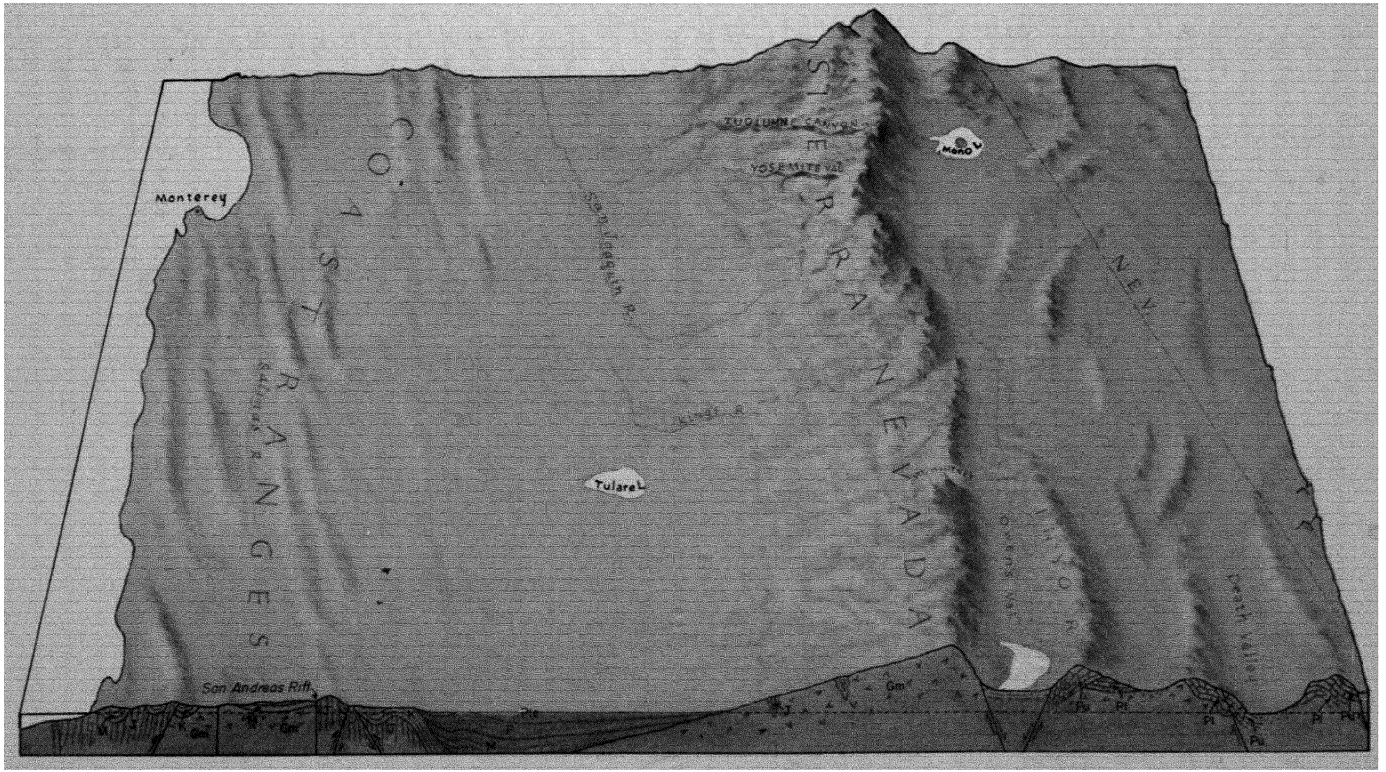


FIG. 86. Idealized block diagram of a part of the Coast Ranges, the California Trough, the Sierra Nevada, and the Basin and Range Province. The view is northward. Length of section along front face about 250 miles. Vertical scale exaggerated about 50 times. *Gm*, Mesozoic granite; *J*, Jurassic; *K*, Cretaceous; *M*, Miocene; *P*, Pliocene; *Ple*, Pleistocene; *Pl*, Lower Paleozoic; *Pu*, Upper Paleozoic.

time of comparative quiet during which most of the Cordilleran region was again reduced to lowlands.

A new revolution began in the Miocene and continued intermittently to its culmination in the far-flung regional uplift of the Pleistocene. This last great orogeny has been called the *Cascadian revolution.* The Cascade Mountains were in the midst of the vast area of disturbance but actually comprised only a small part of it. The movements were complex and diversified, but on the whole they were predominantly vertical movements accompanied by normal faulting — a marked contrast with the Laramide revolution, which involved great horizontal forces and eventually produced enormous thrust faults and great folds. During the Cascadian movements, folding was confined largely to the Coast Ranges and the Puget Sound Basin. In the former it probably resulted largely from the squeezing or wedging effect of differentially subsiding fault blocks. In the Puget Sound area, where the thick Eocene beds are steeply upturned, the horizontal compression may have come from the intrusion of a large granitic batholith into the northern part of the Cascade Mountains during Miocene time.

Throughout the Cordilleran region the last movements were chiefly those of regional uplift in late Pliocene and Pleistocene time. The greatest crustal movement in California evidently took place in middle Pleistocene time, because the later deposits lie unconformably on the deformed early Pleistocene strata.

In every respect the Pleistocene epoch is allied with the Pliocene, and if it were not for the extensive glaciation that characterized the Pleistocene, the two would probably never have been differentiated. The Pleistocene is clearly a part of the Cenozoic era. Whether the climax of orogeny and uplift is now past, only the future can tell; we are too close to it to judge.

Volcanic activity occurred in the Cordilleran region during this era on a scale not approached at any other time since the remote Pre-Cambrian. Volcanoes were active at the beginning of the era in most if not all of the western states. Great basalt flows during the Eocene covered an area in western Washington and Oregon more extensive than all New England. At the same time andesitic flows built up the Absaroka Range and the plateau upon which Yellowstone Park is located, covering fault-block ranges of Mesozoic and older rocks to a depth of many hundreds of feet. Here the lavas overwhelmed forests at successive intervals of hundreds of years, as seen in Amethyst Cliff, where the stumps of eighteen successive forests stand petrified (Fig. 87).

Sedimentary beds interstratified with the lava and volcanic breccia along the southern border of the Absaroka Plateau prove that volcanoes

were active there during middle and late Eocene as well as Oligocene time. The older volcanics of the Yellowstone Park are also of Eocene age and the younger ones chiefly Miocene, though present geysers and hot springs indicate that volcanic heat still smoulders.

Many explosive volcanoes were active during Oligocene time. John Day Basin in central Oregon was filled during this epoch to a depth of 2000 to 3000 feet with reworked volcanic ash that has preserved an amazing array of fossil mammals.

The Miocene was, however, the time of truly colossal volcanism. At this time occurred most of the basic eruptions of the Columbia Plateau, Snake River Valley, and the Cascade Mountains, a vast field of basalt covering an area of more than 200,000 square miles. At the same time a great field of volcanoes in southwestern Colorado built up the San Juan Mountain mass. Volcanoes were scattered over the Basin and Range region and the Colorado Plateau, and there was extensive igneous activity in Mexico.

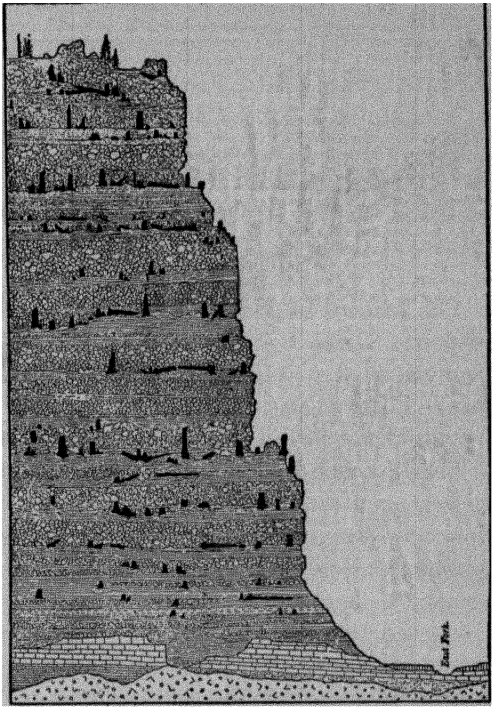
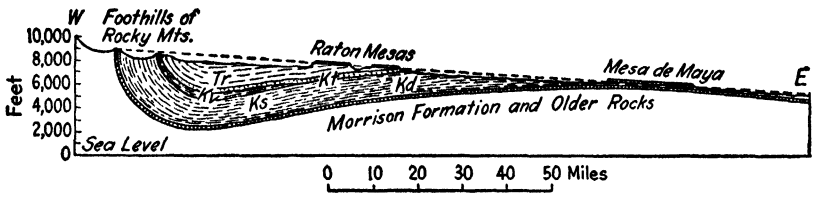


FIG. 87. Profile section of Amethyst Cliffs in Yellowstone Park, showing remains of eighteen successive forests, each killed and buried in turn by volcanic materials. Section about 2000 feet thick.

In many of these regions volcanism continued with decreased vigor through the Pliocene and into the Pleistocene, no fewer than 120 fields of volcanoes being known with cones that were still active in the Pleistocene. Near Trinidad in the foothills of eastern Colorado there are impressive features of Cenozoic igneous activity. Spanish Peaks are a majestic pair of denuded Eocene intrusives with a unique display of great radial dikes. A short distance southeast of these lie Raton Mesas and Mesa de Maya (Fig. 88), which are remnants of Pleistocene basalt flows that spread eastward over the plains almost to the Kansas line.



After W. T. Lee, U. S. Geol. Survey.

FIG. 88. East-west section through Raton Mesas and Mesa de Maya, near Trinidad, Colorado. The mesas are remnants of a Pleistocene lava flow that spread from the foothills of the Rockies almost to the Kansas line. The lava rests on beveled Eocene strata, which in turn rest on Cretaceous. *Tr*, Eocene; *Kv*, *Ks*, *Kt*, *Kd*, Cretaceous.

CENOZOIC EVENTS IN OTHER CONTINENTS

The history of the Andes paralleled that of the Rockies in many respects. Folded at the close of the Mesozoic, they were extensively peneplaned during the early half of Cenozoic time and then, chiefly in the Pliocene and Pleistocene, were elevated by several thousands of feet to their present height.

The Alps and Himalayas, stretching from western Europe to the East Indies, are almost entirely the product of Cenozoic orogeny. The area they now occupy was the site of a great geosyncline in Mesozoic time. Although folding had begun before the close of the Mesozoic, the first decided thrusts in the Alpine region came late in the Eocene. During Oligocene time marine waters returned between the rising folds, but later in this epoch occurred the first great paroxysm of Alpine orogeny, as compression from the south caused great recumbent folds to rise out of the sea as mountain arcs and to ride forward over the plains to the north of the geosyncline, where they piled up as a series of thrust sheets or nappes.

In front of these great thrusts lay a lowland, now the Swiss Plateau. Over this was spread, during the late Oligocene and Miocene, a vast piedmont deposit (*Molasse*) of sand and coarse gravels derived from the rising mountains. Most of it is of fresh-water deposition like the Great Plains beds east of the Rockies, but marine horizons show that the sea still had access to the northern border of the Alps as late as Miocene time. In the Pliocene came further great thrusts from the south that caused the older nappes to ride out over the Molasse and buckled up the Jura folds that now form the northwest front of the Alps. This also gave a great regional uplift to the entire mass, an uplift that reached its culmination in the Pleistocene.

The history thus sketched for the Alps is, in general, that of the Carpathians and the Dinaric Alps of Dalmatia. In the southernmost of the

three ranges that make up the Himalayan system, marine Eocene formations now occur at an elevation of 20,000 feet, bearing witness to the tremendous uplift experienced by that region since Early Cenozoic time.

Many countries also had volcanic activity during Cenozoic time. In Central America especially, and in Mexico, the Antillean islands, and the Andean Plateau, there were great outpourings of lava. The North Atlantic was also the scene of large basalt flows, now displayed in northern Ireland (Giant's Causeway), northwest Scotland, the plateau of Iceland, and eastern Greenland. The great rift valleys of East Africa constituted another arena of major eruptions. Finally, during Pliocene and Pleistocene time, volcanic chains became active in the Mediterranean region and in Alaska, Japan, and the East Indies, completing the "Ring of Fire" around the Pacific.

Cenozoic Climates

Fossil plants throw much light on the climate of Cenozoic time. The forest trees have come down to us with only trivial change since early Cenozoic time and probably have not changed their preferred habitat appreciably. And it is well known that most of them are restricted in their distribution by rainfall and temperature, each preferring a definite environment. Accordingly, the vegetation of a subtropical lowland like Florida has little in common with that of a desert basin, or with the forests of a temperate mountain slope, or with the subarctic barrens. Thus it is possible to infer the climatic conditions under which a Cenozoic flora lived.

A comprehensive study of such material throughout western North America has shown a striking change of climate since early Cenozoic time. During the Eocene and Oligocene epochs subtropical types of trees, now restricted to moist lowlands, ranged widely over the United States and Europe. Palms and alligators were then common as far north as the Dakotas, suggesting a climate like that of modern Florida and Louisiana. At the same time a moist temperate forest existed in high northern latitudes, notably in Alaska, Greenland, Spitzbergen, and northern Siberia. It was dominated by the giant redwood and included such deciduous trees as the basswood, beech, chestnut, and elm. Even cycads, magnolias, and figs then lived in Alaska. The climate was not only milder and more humid, but also more uniform than now over the western United States, evidently because the region was generally low and the mountains were not lofty enough to interfere seriously with the moisture-bearing westerly winds.

After Eocene time there was a slow but general southward migration of the various plant assemblages, indicating a gradual cooling of the

climate that became more marked in Pliocene time and culminated in the Pleistocene glaciation. Meanwhile, in Miocene and Pliocene time, the climate became more diversified in the western United States as the rising mountains intercepted the winds, producing moist western slopes and arid regions in their lee. This diversity was not nearly so extreme or so widespread in Miocene time as it is today, though the salt and other precipitates entombed in the Miocene deposits of southern Nevada indicate rather intense local aridity in the basins then forming. But even as late as early Pliocene time a flora like that of southern California was still living in western Nevada (the Esmeralda flora), indicating a rainfall of 12 to 15 inches a year in a region where the present rainfall is only 4 inches. The final uplift of the Cordilleran ranges in the late Pliocene and Pleistocene gave the intermont basins and the Great Plains their present degree of aridity.

Mention should also be made of local evidence of cold climate at the very beginning of the era. About the flanks of the San Juan Mountains in southwestern Colorado there is a deposit of tillite up to 100 feet thick (Ridgway tillite) lying unconformably on the Cretaceous and overlain by tuffs of Eocene date. These glacial deposits are so distributed as to indicate a source in the crest of the mountains some 40 miles away. The presence of such extensive valley glaciers in a region where now there are none clearly indicates that the snowfall was then vastly greater than now, or the average temperature was considerably lower, or else both conspired to produce glaciers. Unfortunately, the tillite can not be more closely dated, but it probably was formed at the time of maximum uplift at the end of the Mesozoic era, or shortly thereafter. The widespread plant evidence indicated above shows that by Eocene time warm temperate climate had spread as far north as the Arctic Circle.

Chapter 9

ICE SCULPTURES THE FINAL SCENE

During the last geologic epoch, glacier ice spread over probably one-fourth or more of the land surface of the world. We are just emerging from this prolonged refrigeration, and the marks of glaciation are on every hand. We see them in the serrate summits of the lofty mountains carved by valley glaciers, in the lakelands of Canada and Scandinavia, and in the drift plains of northern United States and north-central Europe.

Besides sculpturing the modern landscape in many parts of the world, the glaciation influenced human industry and culture profoundly over vast areas, stripping the soil of some regions, making swamp land of others, piling coarse boulder till in some, and spreading over others the materials of a rich and inexhaustible soil. The history of the *Ice Age*, therefore, deserves our special interest.

Distribution of the Glacier Ice

Three vast systems of ice sheets formed in the northern hemisphere. One system centered over Canada and spread south into the United States. Another centered over Scandinavia and reached the plains of northern Germany and western Russia. The third occupied much of Siberia (Fig. 90). Greenland also was ice-capped then as now, but more extensively. The Scandinavian sheet extended far east into northern European Russia and southwest across what is now the floor of the North Sea until it covered all of the British Isles except the southern edge of England.

It is remarkable that the glacier ice covered great areas of lowland, and in eastern North America reached south of latitude 40° where, at present, summer temperatures of 100° F. are common and the snow limit lies at least 6000 feet above sealevel.

In the southern hemisphere, Antarctica was ice-covered, as it is today, and a smaller ice sheet occupied southern South America. In addition, nearly all the lofty mountains of the world were capped by snow, and valley glaciers pushed far below the present snow limit. In the United States the higher Rockies were glaciated as far south as New Mexico, and the Sierra Nevada and the Cascade mountains were heavily burdened with glaciers. Yosemite Valley in the Sierra Nevada and Glacier

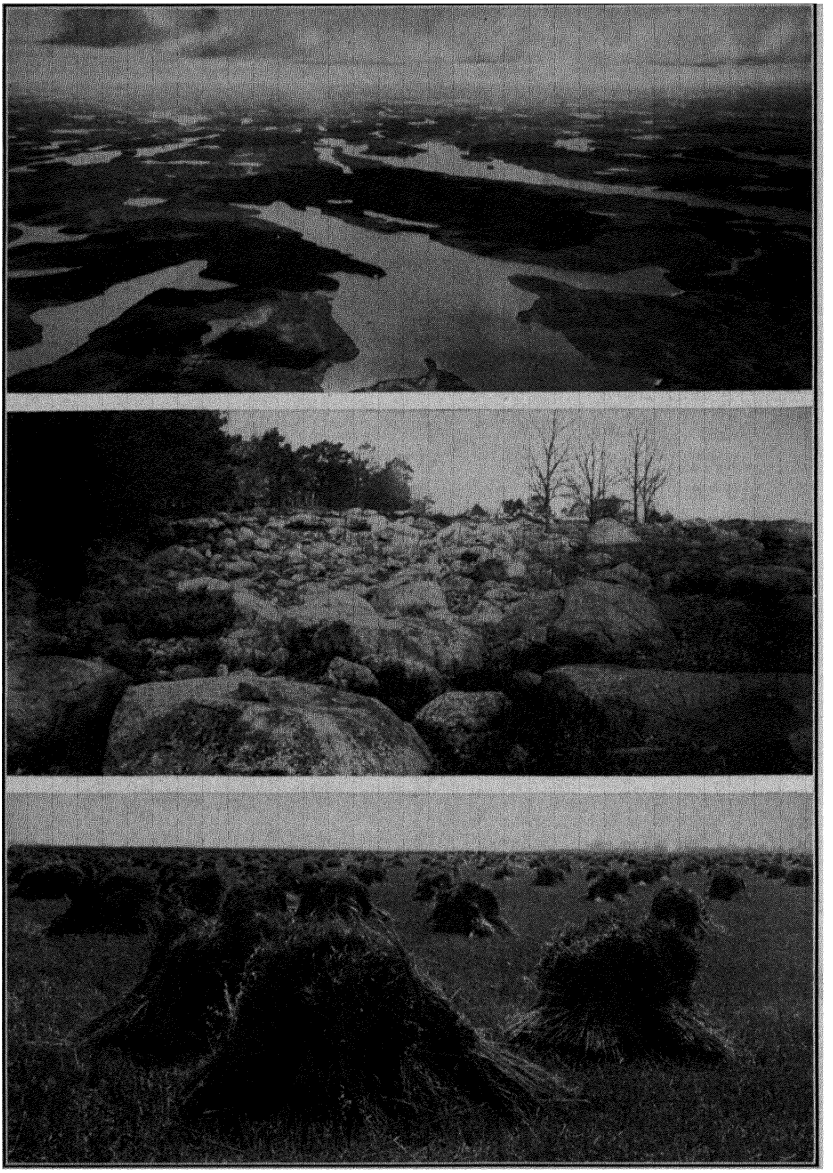


FIG. 89. Economic and cultural consequences of the Ice Age in North America. Above, aërial view of the lake country of northern Manitoba, where glacial scour removed the mantle and scooped out lake basins in solid rock. Center, a boulder field in New England, where coarse drift makes clearing of the land a formidable task. Below, wheatlands of the Red River Valley, part of the floor of glacial Lake Agassiz. Photographs from Royal Canadian Air Force, U. S. Geological Survey, and North Dakota Agricultural Experiment Station, respectively.

National Park in the Rockies are well known illustrations of the work of these Pleistocene glaciers. The Alps, the Himalayas, the Caucasus, the Pamir, and other lofty ranges of Eurasia carried vast snowfields from which valley glaciers pushed out beyond the foothills on to the plains. The Andes and the mountains of the South Island of New Zealand carried vast glacier systems.

The directions of flow of the glaciers in North America are indicated in Fig. 91. These have been determined by mapping the trends of end moraines, by plotting the directions of glacial striæ, and by noting the distribution in the drift of distinctive types of rocks that can be traced back many miles to their outcrops. The striking fact is that the ice did not spread southward from a center at the North Pole but radiated from centers of accumulation in the latitude of Hudson Bay. The *Labrador center* occupied the plateau east of James Bay, whence the ice moved northward into Baffin Island and eastward into the Atlantic, while a broad lobe followed the lower slope southwest across the Great Lakes and into the Ohio Valley, through a distance of 1600 miles from the center of dispersal. The *Keewatin center,* lying over the lowland northwest of Hudson Bay, sent its ice flowing north across the Arctic Circle, west to the foothills of the Rockies, and south to the Missouri River, its major southern lobe following the lowland of the Mississippi Valley as far as St. Louis. The ice from these two centers, possibly with subsidiaries, united to form one vast sheet. A third area, the plateau lying between the Rocky Mountains and the Coast Ranges in Canada, was not truly a center of radiation, but a basin in which valley and piedmont glaciers from the surrounding mountains coalesced. In Greenland the glacier flow was radial, as at present.



FIG. 90. Pleistocene ice fields of the northern hemisphere.

It must be noted that much of Alaska was unglaciated. The nonglaciated areas have very slight precipitation; and their freedom from ice serves to emphasize the fact that glaciation is conditioned by heavy snowfall as well as by low temperature.

Special interest attaches also to the *Driftless Area* of some 10,000 square miles in Wisconsin. It escaped glaciation only because south-

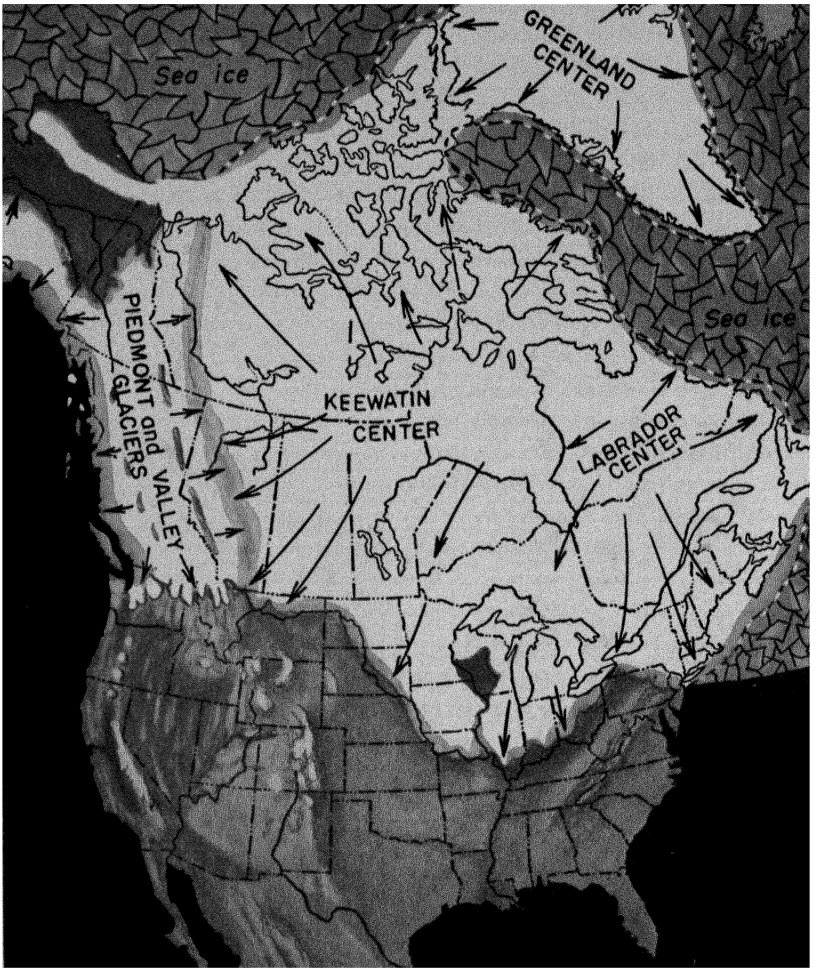


FIG. 91. Pleistocene glacier ice in North America. Somewhat generalized to show maximum extent of glaciation. Arrows show generalized directions of glacier flow. Compiled by Richard F. Flint.

flowing lobes from the Labrador and Keewatin centers were deflected from it, in part by the Wisconsin highlands on the north, and in part by the contour of the Great Lakes basins; but since maximum advances from the east and west were not simultaneous, it was not at any time an island in the ice, as represented in Fig. 91.

There is no direct evidence of the thickness attained at the centers of the North American ice sheets, but it may have been comparable to that of the modern ice cap of Antarctica, which has about the same

area, namely, 4,000,000 square miles. In Antarctica, as in Greenland, the vast interior of the ice field is nearly flat, the surface slope increasing toward the wasting edges. The maximum thickness of the ice in Antarctica is unknown, but the surface rises about 10,000 feet above sealevel; recent investigations with sonic depth finders have shown that in north-central Greenland the ice reaches a thickness of 6200 feet.

During the time of maximum glaciation the ice flowed southward over the White Mountains and probably over the Adirondacks, which have elevations exceeding 5000 and 4000 feet, respectively. It also flowed westward from the Keewatin center across the plains which rise from near sealevel at Hudson Bay to about 4000 feet along the foothills of the Rockies. The surface of the ice at the center of radiation must have been considerably higher than any objects over which the ice moved, since ice, like water, flows in the direction of its surface slope. It is probable, therefore, that the Canadian ice sheet reached a maximum thickness of at least 10,000 feet.

Glacial and Interglacial Ages

When erratic boulders strewn over the New England landscape challenged the attention of Louis Agassiz a century ago, and led to the recognition that the region has been covered by glacier ice in relatively recent geologic time, the glaciation was assumed to have been the result of a single episode of refrigeration. But when the study of the glacial deposits was carried westward into Illinois, Wisconsin, and Iowa, two distinct sheets of drift were found at many places, separated by old soils, beds of peat, and deposits of gravel leached and decayed by long weathering (Fig. 92). The surface drift, like that of New England, appeared fresh, but the buried drift showed the effects of chemical weathering and therefore was obviously much the older. Moreover, fossil wood was commonly found in the old soil, and leaves and bones occur in associated beds of stratified sand and gravel, indicating plants and animals of temperate climate. Thus it was realized, about 1870, that two distinct advances of the ice had been separated by a relatively long interval of warm climate when forests grew over the older drift, and plants such as the pawpaw ranged considerably north of their present limit.

By further application of the same type of evidence, it was soon discovered that more than two glacial ages are recorded in the upper Mississippi Valley. Meanwhile similar discoveries were made in northern Europe; and now four glacial and three interglacial ages seem to be established in both Europe and America. These have been

named for localities in which their deposits are typically developed, each glacial age in America bearing the name of a state. Independent names have been used in Europe, but it now appears probable that the glacial ages correspond on both sides of the Atlantic.

The history of the Pleistocene epoch may thus be tabulated in the form of a calendar, as follows:

CALENDAR OF PLEISTOCENE TIME

Epochs	Subepochs	Ages (of time) Stages (of deposits)	Roughly estimated dates
PLEISTOCENE	Eldoran	Recent	25,000 B.C.
		Wisconsin (4th) glacial	125,000
	Centralian	Sangamon interglacial	250,000
		Illinoian (3rd) glacial	350,000
	Ottumwan	Yarmouth interglacial	650,000
		Kansan (2nd) glacial	750,000
	Grandian	Aftonian interglacial	950,000
		Nebraskan (1st) glacial	1,000,000
PLIOCENE			

The Pleistocene is here regarded as an epoch of the Cenozoic period, distinguished solely by the glaciation. Each subepoch represents a natural cycle of history, beginning with an expansion of glacier ice and the deposition of a sheet of drift. As the ice later wasted away, its deposits were exposed to stream dissection and chemical weathering. In time, a soil formed over the surface of the deposits, lakes and swamps were gradually filled by the growth of peat and the influx of sediments, and drainage was re-established. This orderly change was interrupted only by the next advance of the ice, which spread a new sheet of till and started a new cycle. As shown below, the interglacial intervals greatly exceeded the time that has elapsed since the last expansion of the glaciers. Furthermore, the 5,000,000 cubic miles of ice still stored in Greenland and Antarctica show that we are not yet completely out of the Ice Age. Hence the Recent is combined with the Wisconsin glacial age as the final episode of the Pleistocene.

Stratigraphy of the Drift

The southern limit attained by the ice during each glacial age may be noted in Fig. 93 and the stratigraphic relations of the several sheets of glacial drift are suggested in Fig. 92.

The *Wisconsin* drift is most easily mapped. Its end moraines loop across the Central Lowland in festoons that outline the great southern lobes of the ice. Its surface still retains the characteristic features of glacial deposits — the irregular topography of end moraines, and the broad undulations with innumerable swamps and lakes of the ground

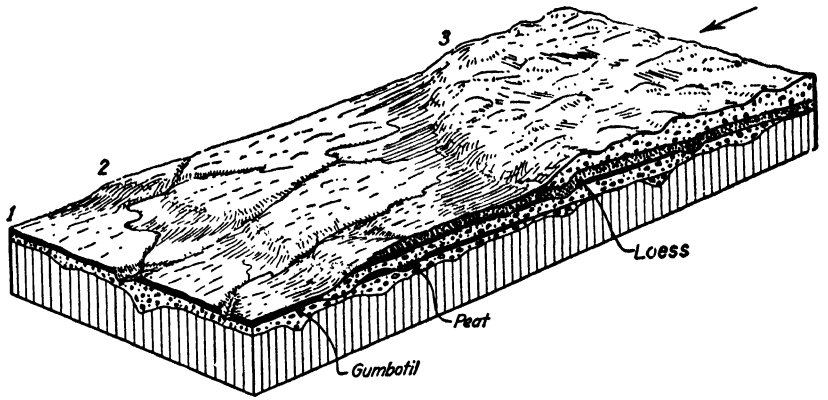


Fig. 92. Idealized block diagram showing the relations of three imbricating drift sheets. The block represents an area many miles across, and the vertical scale is exaggerated. The first glaciation spread till across the entire region. In the long interglacial age that followed, the surface of this first till was weathered to gumbotil (black). The second advance of the ice fell short of the first, and in a broad marginal belt the glacier ice overrode the older till, gumbotil, and peat deposits. During the second interglacial age this till in turn suffered long weathering and developed a gumbotil. In connection with the third glaciation, loess was spread widely over the older drift and this in turn was overridden by the glacier ice which fell short of the middle of this area. No gumbotil has yet formed on the youngest till.

moraine, diversified locally by drumlins. The few thousands of years since the final deglaciation have sufficed for only a limited amount of dissection and chemical change. Everywhere the Wisconsin till is fresh. A thin soil has formed over its surface, and peat has accumulated extensively in the swamps, but chemical decay, even in the fine material, is limited to slight leaching to an average depth of 2 or 3 feet; most of the boulders are still as fresh as quarried stone.

In New England, the Wisconsin ice flowed out beyond the present coast, largely destroying or concealing any marks of earlier glaciation; some of its end moraines may be seen on Long Island. In the Central Lowland, on the contrary, it fell short of the earlier glaciations, leaving

there an unequaled record of the whole Glacial epoch. After its maximum expansion, the ice of this glaciation fluctuated considerably, with two times of marked shrinkage separating three expansions. Hence the Wisconsin drift is in places represented by three layers of till unconformably superposed. It is believed, however, that the breaks represent deglaciations of only limited extent and relatively short duration; hence the three tills are grouped together as part of one glacial cycle.

The *Illinoian* ice sheet extended as far south as the Ohio River, its greatest lobe having developed from the Labrador center. The an-

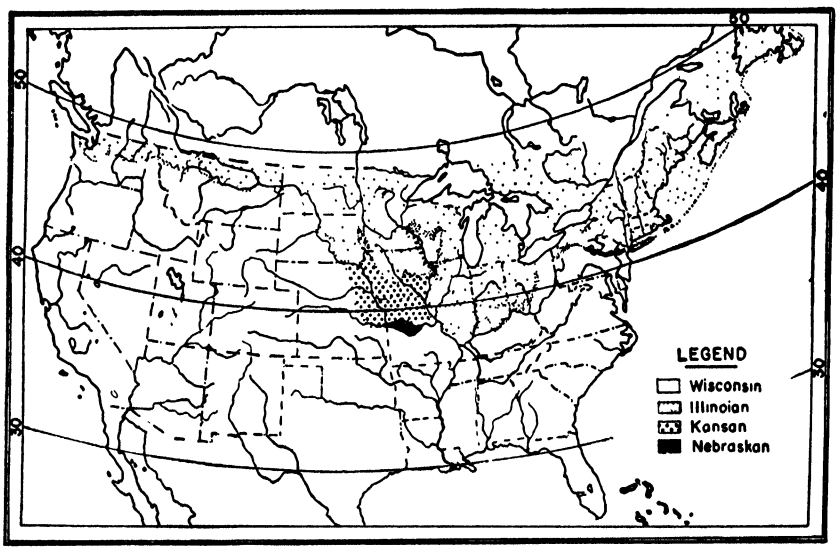


FIG. 93. Map showing the southern limit of glacial drift in the United States. Note that in the Mississippi Valley the older drift sheets extend farther south than the Wisconsin drift, and here four sheets are differentiated.

tiquity of the Illinoian drift is evident if we compare its dissection and chemical alteration with those of the Wisconsin drift. The surface features left by the Illinoian ice have been greatly subdued; the swamps and lakes are mostly filled or drained, and the stream pattern is well organized; long chemical decay in the areas originally not well drained has resulted in deep leaching and in the formation of 4 to 6 feet of *gumbotil*, a dark gray, sticky subsoil so named because the gumbo has formed through the weathering of till. The presence of this deposit beneath the Wisconsin drift proves that the preceding interglacial time was far longer than that since the last disappearance of the ice.

Overlying the Illinoian drift, and extending far beyond its margin, is a layer of loess several feet thick. This is an important key horizon in tracing the glacial deposits and in correlating them from one exposure to the next, because it spread over and beyond the ice-covered areas and can be traced even where the gumbotil is lacking.

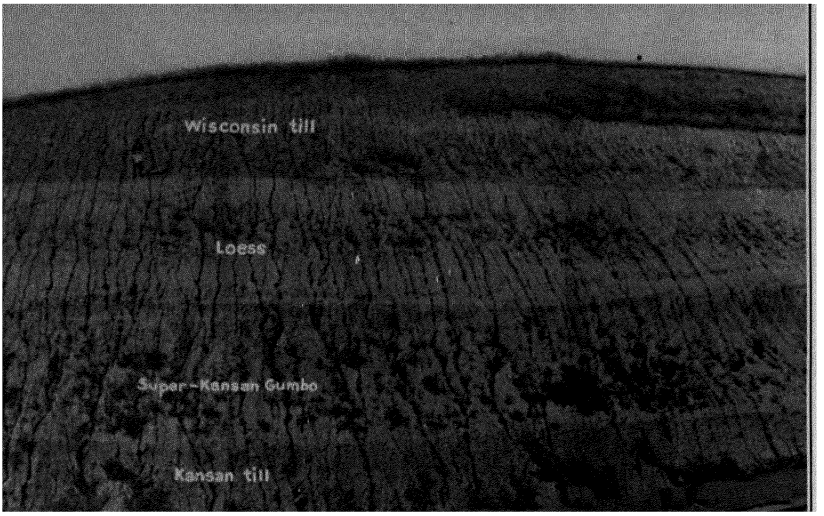
There is no evidence of undoubted Illinoian drift west of the Driftless Area, and if the Keewatin region was a center of glaciation during the Illinoian age, its glaciers apparently failed to expand beyond the limits later attained by the Wisconsin ice.

During the *Kansan* glaciation, on the contrary, the Keewatin sheet was the more extensive, with a vast lobe covering Iowa, northern Missouri, and northeastern Kansas and Nebraska, its southern limit reaching approximately to Kansas City and St. Louis. The Labrador sheet, on the other hand, fell short of the later glacial advances, except possibly in Pennsylvania.

Where typically developed, the Kansan till had an original thickness averaging about 50 feet. During the long Yarmouth interglacial age its surface was deeply leached and decayed, and a gumbotil was formed averaging about 11 feet thick. In places it is covered with gravel beds representing outwash material that has been deeply leached. In these the boulders of granitic rocks are not fresh, as is common in the Wisconsin drift, but commonly crumble and fall to pieces when struck with a hammer. The Kansan till is also extensively covered with loess (Fig. 94). In western Illinois the Kansan drift is overlain by the Illinoian, but in central Iowa it is succeeded by the Wisconsin drift where the Illinoian ice failed to reach so far south.

The *Nebraskan* drift had approximately the same distribution as the Kansan, and its exposures are very limited, but it lies buried beneath most of the area mapped as Kansan. It was a thick sheet of till spread over an irregularly eroded preglacial surface and averaging more than 100 feet in thickness. It is capped by a gumbotil about 8 feet thick, which was formed during the first interglacial age.

It should be noted that each expansion of the ice sheets tended to destroy the records of preceding glaciation in the areas of accumulation and growth, but resulted in deposition in a broad marginal belt where the ice was thinned by wastage. There its carrying power was reduced until it tended to drop and override its own debris, commonly failing to disturb the pre-existing soil or drift. Thus a declining series of glaciations is fully recorded in a peripheral belt where successive sheets of drift are imbricated, as in Fig. 92. But in areas where the last advance was much the greatest, evidence of former glaciation was largely destroyed. In New England, for example, the record of pre-



George F. Kay.

FIG. 94. Superposed sheets of till with gumbotil and loess, exposed in a cut southwest of Rhodes, Iowa. Scale indicated by man near top at left.

Wisconsin glaciation is scanty, and in much of Canada there is a good record of only the last glacial age.

DURATION OF THE ICE AGE

Post-Wisconsin time can be measured from two types of record: the gorges cut by postglacial waterfalls, and the deposits of varve clay and silt laid down in proglacial lakes, i.e., those that formed at the margins of the wasting ice. The most acceptable estimates now indicate that the ice began its final shrinkage at least 35,000 years ago. This unit forms a yardstick against which the longer, interglacial ages may be estimated.

The Falls of St. Anthony in the Mississippi at Minneapolis illustrate the first method of calculation. Below them, and extending nearly 7 miles to Fort Snelling, there is a gorge 75 to 100 feet deep and about a quarter of a mile wide, produced by the recession of the falls. It can be demonstrated that the cutting of this gorge began when the ice margin, during the last deglaciation, stood near the position indicated in Fig. 95. In the nearly 250 years since the falls were first observed by white men, they have retreated at an average rate of about 2.44 feet per year. At this rate, 15,000 years would be required to cut the postglacial part of the gorge. But the ice had already wasted back about



Fig. 95. St. Anthony Falls and their postglacial history. The ice front and the regional drainage are shown as they existed when cutting of the gorge below the falls began. Details about the falls are shown by the inset, in which buried preglacial channels are indicated in white, and modern valleys in deep shading. Based on data from Leverett and Taylor, and G. M. Schwartz. Drawn by Milton Wallman.

700 miles from its southern limit before the cutting of the gorge began. Hence, if we allow 10,000 years for this part of its shrinkage, at least 25,000 years is indicated for the time since the periphery of the Wisconsin ice stood in central Iowa.

The reasons for believing that the cutting of the gorge began at about the stage represented in Fig. 95 are worth recounting. In preglacial time the Mississippi had cut a wide valley, its main trunk following approximately the course of the present Minnesota River. The last glaciation filled all preglacial valleys with drift, and, when the ice melted back, the streams at first wandered over the surface of the drift, eventually incising themselves in new valleys. As Minnesota was exposed, three main streams, the St. Croix, the upper Mississippi, and the Minnesota, united near St. Paul. As they cut down through the drift, the trunk stream discovered the old preglacial valley just below St. Paul (see inset of Fig. 95) and proceeded to remove the loose fill below this point with relative ease. But from St. Paul to a point just south of Fort Snelling the new stream found itself superposed upon the old upland of horizontal limestone beds. Here its downcutting was greatly retarded and, as it plunged from the surface of the limestone into the old valley, a fall was initiated that gradually migrated upstream until it again cut through into the buried preglacial valley a short distance southwest of Fort Snelling. The recession of this great fall produced

the narrows in the valley at St. Paul, which are therefore obviously postglacial.

For a time after the deglaciation of the region around Minneapolis, all three stream branches carried great volumes of meltwater, but after the ice margin had reached the Canadian border, the drainage through the upper Mississippi dropped to something like its present volume, whereas that of the Minnesota River increased greatly as it became the outlet of the vast glacial Lake Agassiz, which formed over the Red River Valley while the ice still prevented drainage to the north. Thus, until the disappearance of Lake Agassiz, the stream we now know as the upper Mississippi was but a second-rate tributary to a great glacial stream that followed the present valley of the Minnesota River above St. Paul. The cutting of the narrows at St. Paul was chiefly the work of this great glacial stream and was accomplished while Lake Agassiz was discharging the meltwater from a great area of the ice. This gives us the clue to the position of the ice margin when the postglacial narrows at St. Paul were cut.

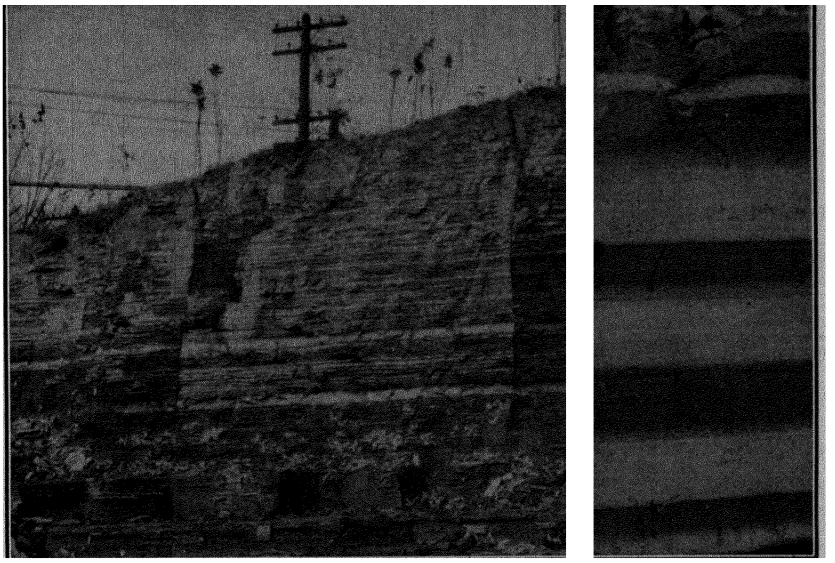
After the great falls in the glacial Minnesota River had receded past the mouth of the Mississippi tributary, the latter plunged from its limestone bed into the new valley and thus initiated the Falls of St. Anthony.

Niagara Falls likewise came into existence after a shrinking Wisconsin ice sheet uncovered a pre-existing escarpment, and the Niagara gorge has also been used as a measure of postglacial time, but the history here is more complicated than that of the Falls of St. Anthony, and the calculations involve more uncertainties.

Some years ago the Swedish geologist DeGeer discovered that clays and silts deposited in proglacial lakes afford a means by which the years since the ice receded may be counted directly. These deposits present a striking layered appearance due to the alternation of thin laminæ of silt and fine clay (Fig. 96), the silt being normally light in color and the clay dark. Such deposits have been named *varve clay*. Their distinctive lamination results from the peculiar conditions that exist in lakes marginal to melting glaciers. During the summer months the meltwater bears abundant fine sediment in suspension, giving the water a milky or turbid appearance. Currents entering the lake and wave action both serve to spread the turbid water, from which the coarser particles gradually settle as silt on the lake floor. Eventually winter comes, the meltwater ceases to flow, and the lake is frozen over. Then for some months no silt is introduced into the lake, the water is free from any disturbance by either waves or currents, and even the colloidal particles of sediment slowly settle to make a thin layer of fine,

unctuous clay. With the coming of summer a new cycle of deposition is started and a new layer of silt forms over the last year's deposit. Thus the layers of clay, like the growth rings in trees, record actual years of time, and it is a simple matter to count the layers in such a deposit and determine how many years were required for its formation.

Of course, no single proglacial lake existed throughout the shrinkage of the ice sheet, but DeGeer discovered an ingenious way of matching the bands in contemporaneous deposits of different lakes or of different



Richard F. Flint.

FIG. 96. Varve clay from a glacial lake at South Hadley, Massachusetts. At the right a small detail, natural size, showing gradation of light gray, summer layers upward into dark winter layers.

outcrops, and thus was able to piece together many of the fragments of the record. Lakes tend to form about the margins of a melting ice sheet, occupying depressions behind moraines or inequalities in the rock floor where the ground moraine is thin, and, thus, much of the time represented by deglaciation was probably recorded in varve clay in one place or another. DeGeer pieced together the records of about 1500 outcrops lying between the southern tip of the Scandinavian peninsula and the modern proglacial lakes in central Sweden, and on this basis inferred that the shrinking ice exposed southern Sweden about 13,500 years ago. The ice margin lay in the plains of southern Germany during the maximum glaciation, and it has been impossible to find varve

clay deposits to measure the duration of the recession from that limit to southern Sweden, but obviously it was several thousands of years. Recent estimates, based in part on DeGeer's work, place the date of maximum expansion of the last glaciation in Europe at about 35,000 years ago. Similar study of the varve clays in New England and eastern Canada has been undertaken, but numerous breaks in the record have made it impossible to establish a complete chronology.

There is no such direct method of determining the length of the interglacial ages, and estimates of their duration are based upon a comparison of the weathering and decay of the older tills. For example, the Wisconsin till is almost fresh, showing but slight leaching in the upper 2 or 3 feet; but the Illinoian till is deeply leached and has developed a gumbotil about 5 feet thick. It is certain that this long decay took place before the Wisconsin glaciation, because the last

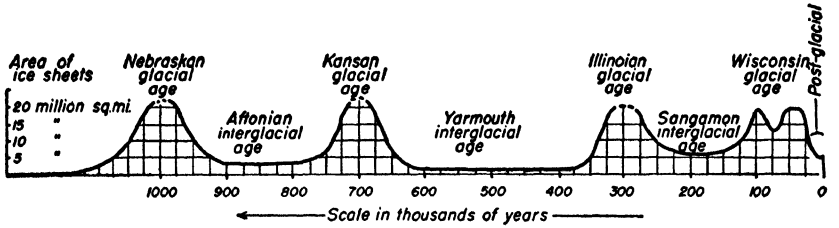


FIG. 97. The scale of glacial time. Time is shown from left to right in units of 1000 years; the extent of glacier ice is represented by height in units of 5,000;000 square miles. Breaks in the curve indicate uncertainty as to the duration of the Nebraskan, Kansan, and Illinoian glaciation.

sheet of till has protected the buried drift from weathering. Obviously the Sangamon interglacial age was several times longer than all postglacial time. The Kansan drift is even more deeply weathered, and its gumbotil is about 11 feet thick. Its boulders also have been weakened by long decay. The underlying Nebraskan drift has a somewhat thinner gumbotil, and the first interglacial age was somewhat shorter than the second. Although there is no rigorous criterion for the comparison, it is the judgment of the most profound students of glacial deposits that the Sangamon interval was not less than five times the length of the postglacial age, the Yarmouth not less than twelve times, and the Aftonian about eight times. The resulting estimates are 125,000, 300,000, and 200,000 years, respectively. To this must be added the quite uncertain duration of the several glacial ages, giving a total duration for the Pleistocene epoch estimated roughly at a million years. We get a better perspective of the Recent by plotting the duration of the glacial and interglacial ages to scale, as in Fig. 97.

General Effects of the Glaciation

Fluctuations of Sealevel. If the modern ice sheets of Greenland and Antarctica were melted, sealevel would rise, it is estimated, more than 100 feet, drowning the low coastal plains and transforming the lower courses of many streams into estuaries. But if, on the contrary, the great Pleistocene ice sheets were restored, the water thus withdrawn from the oceans and piled up on the lands would lower sealevel by 250 feet or more, shifting the shoreline seaward almost to the present 50-fathom line.

There is clear evidence that such striking fluctuations of sealevel did take place in the Pleistocene. During times of maximum glaciation, streams were extended across the exposed parts of the continental shelves, cutting valleys that are now submerged. In subtropical regions the reduced temperatures at the same time inhibited the growth of corals and permitted the waves to cut wide benches about oceanic islands and along exposed coasts. These benches have since been transformed into lagoons by the growth of barrier reefs along their margins as the sealevel rose. Some of the low wave-cut benches extensively preserved along the modern coasts may have been cut during interglacial ages when the ice sheets of Greenland and Antarctica were reduced and the sealevel stood higher than now.

The lowering of sealevel by 200 or 300 feet made dry land out of extensive areas of shallow sea and permitted migrations of land animals and plants that would now be impossible. England, for example, was united to the continent, and Borneo and Sumatra in the East Indies were a part of Asia, so that elephants, rhinoceroses, and other large mammals crossed the lowlands now submerged to form the floor of the Java and Sunda seas. Alaska and Siberia were also united by land, and the woolly mammoth crossed freely.

Depression of the Ice-Covered Regions. The ice caps formed over Canada and Scandinavia were loads too great for the Earth's crust to support, and both regions sagged to the extent of hundreds of feet. The depression was greatest where the ice was thickest, and in Canada it amounted to about a thousand feet in the area midway between the Great Lakes and James Bay. Since the ice wasted away, there has been almost complete recovery, but before the upwarping took place, unmistakable records of the depression had been made in the form of beach ridges and wave-cut cliffs along the shores of vast proglacial lakes. These features, still recognizable, have been studied and mapped. One of them, marking the shore of glacial Lake Algonquin, is at an elevation of nearly 600 feet in west-central Michigan but rises to

935 feet at Sault Ste. Marie, 1150 feet at North Bay on Lake Huron, and apparently 1450 or 1500 feet at Goudreau Lake, 150 miles north of Sault Ste. Marie. This indicates a relative upwarp in postglacial time of 335, 500, and 850–900 feet, respectively, at the places named. The beaches of glacial Lake Agassiz (Fig. 95) in Manitoba show a similar upwarp toward the north amounting to at least 400 feet.

When the ice had wasted back far enough to free the St. Lawrence Valley, the region was still so much depressed that marine water spread up the St. Lawrence and into the Champlain Valley and probably into Lake Ontario, depositing a layer of blue clay with abundant shells of an arctic molluscan fauna. This is the *Leda clay*, so called for a small but characteristic clam. The recent discovery of two whale skeletons in bogs above the glacial deposits in Michigan indicates that for a brief time the sea was directly connected with the Pleistocene Great Lakes. Marine shells and the bones of whales have been found in the Leda clays at least 500 feet above sealevel at the Vermont-Quebec boundary, nearly but not quite up to the Lake Ontario level at Kingston, and at about 600 feet in the Montreal-Quebec area. The postglacial upwarp thus indicated is probably a minimum measure of the depression caused by the ice.

Glacial Erosion beneath the Ice Sheets. Radial movement of the ice from the Keewatin and Labrador centers stripped the mantle from a vast area of the Canadian Shield, leaving a floor of fresh bedrock scoured unevenly into thousands of shallow basins now occupied by lakes (Fig. 89). The areas of bare rock showing through the scant cover of vegetation advertise the fact that the glaciation cost eastern Canada one of her greatest resources, the soil that had formed during the ages before the coming of the ice.

Over a broad peripheral belt the ice spread its load of drift, filling pre-existing valleys with till and smoothing the inequalities of the surface. Thus the material stripped wholesale from the southern part of Canada was spread widely over the north-central United States to form the source of a very deep rich soil.

Drainage Changes. As the ice sheets advanced southward into the United States, all north-flowing streams were blocked and the meltwater was turned along the margin of the ice until it spilled over divides into south-flowing streams. The channels thus formed at the maximum advance were in many places held after the disappearance of the ice, because former channels were obliterated by the drift. The present course of the Ohio River is due, thus, to the welding together of many short tributaries to different streams, several of which had flowed northward in preglacial times (Fig. 98). The course of the

Missouri was also locally shifted to the southwest. For this reason the Ohio and Missouri rivers record rather closely the southern limits attained by the ice sheets at their greatest extent.

Development of the Great Lakes. Before the glaciation the basins now occupied by the Great Lakes were probably broad lowlands eroded by preglacial streams. The Lake Superior basin marks an ancient

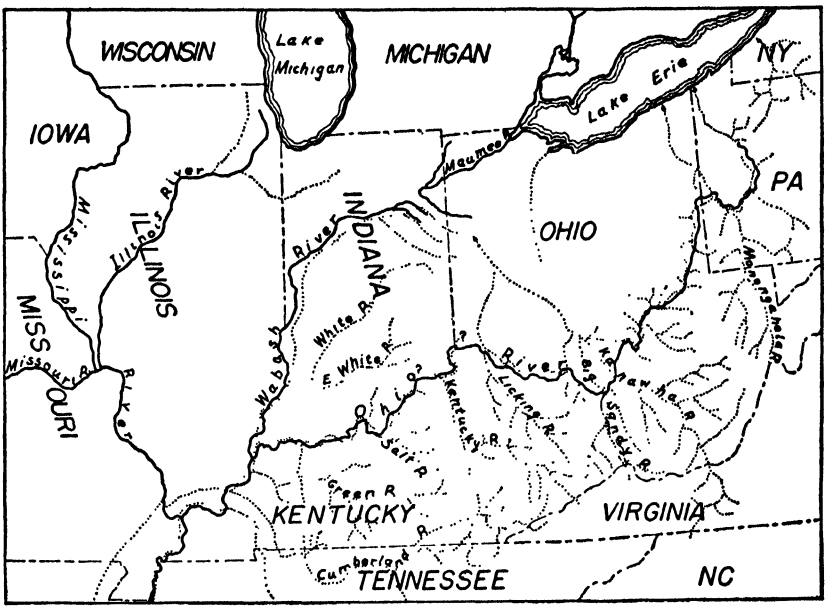


FIG. 98. Drainage changes in the Ohio Valley due to glaciation. Preglacial drainage courses are shown by dotted lines. Data from Leverett (1930), Ver Steeg, and Flint.

synclinal structure occupied by relatively weak rocks in which a broad valley had been eroded; the other lake basins were carved on the outcrops of relatively weak rocks in front of or between the cuestas that had been sculptured by Cenozoic erosion of the Paleozoic formations overlapping on the Canadian Shield. These lowlands were drained by streams, some of which probably flowed southward through gaps in the cuestas, while others may have flowed northeastward into the St. Lawrence. As the ice sheets flowed outward, they filled these lowlands with thick ice lobes that gouged and deepened them, especially where, as in the case of Lakes Superior and Michigan, the axis of the depression nearly coincided with the directions of flow of the ice.

South of the Great Lakes basins, on the other hand, the ice sheets spread a thick mantle of drift that filled and deeply buried the old

valleys for distances of scores of miles. As a result, when the ice later retreated northward over the Great Lakes region, its front became deeply lobate, with a great tongue of ice occupying each of the deepened basins. As these shrank back, lakes formed about the end of each of the lobes, the water standing at the level of the lowest spillway that would lead southward across the drift into the Mississippi drainage system. At first the overflow was southward via both the Wabash and Illinois rivers, but somewhat later it was westward along the front of the ice to the vicinity of Chicago (Fig. 99, *A*), where an outlet was found via the Illinois River. Eventually the Mohawk Valley in New York was freed of ice, and this opened a much lower spillway whereby the drainage was for a time diverted east into the Hudson River (Fig. 99, *B*). At a still later stage the St. Lawrence Valley was opened, and all the drainage of the Great Lakes escaped northeast from the Lake Huron basin across southern Ontario by way of the Ottawa Valley (Fig. 99, *C*). As the ice wasted away, there was gradual recovery from the depression it had caused, resulting in progressive upwarp of the region northeast of a hinge line that ran through central Michigan and southern Ontario (Fig. 99). This ultimately raised the Ottawa outlet until the lowest spillway was across the edge of Niagara cuesta at Lewiston. At this stage, the Niagara River came into existence and the cutting of the gorge at Niagara began. Estimates based on the modern rate of recession of the Falls place this event about 10,000 years ago, but they involve uncertainties that make this figure unreliable.

Various other important lakes were formed by the glaciation. The Finger Lakes of central New York, for example, mark open valleys carved in the margin of the Allegheny Plateau by northward-flowing streams in preglacial times. As the ice rode southward, it gouged deeply where it was crowded into these narrow valleys. Upon the retreat of the ice, these overdeepened places became lakes. The greatest of all the glacial lakes was *Lake Agassiz* (Fig. 95), which formed in the plains of eastern North Dakota, northwestern Minnesota, and Manitoba, while the ice still occupied the basin of Hudson Bay, impounding the water until it overflowed the divide to the south by way of the Minnesota River. Although the lake attained an area nearly five times as great as that of Lake Superior, it was relatively shallow, the old strandlines indicating a probable maximum depth of about 400 feet at the international boundary. The disappearance of the ice allowed the lake to drain away into Hudson Bay. The floor of the former Lake Agassiz is now the remarkably flat and fertile wheat land of North Dakota and the Red River Valley of Manitoba (Fig. 89).

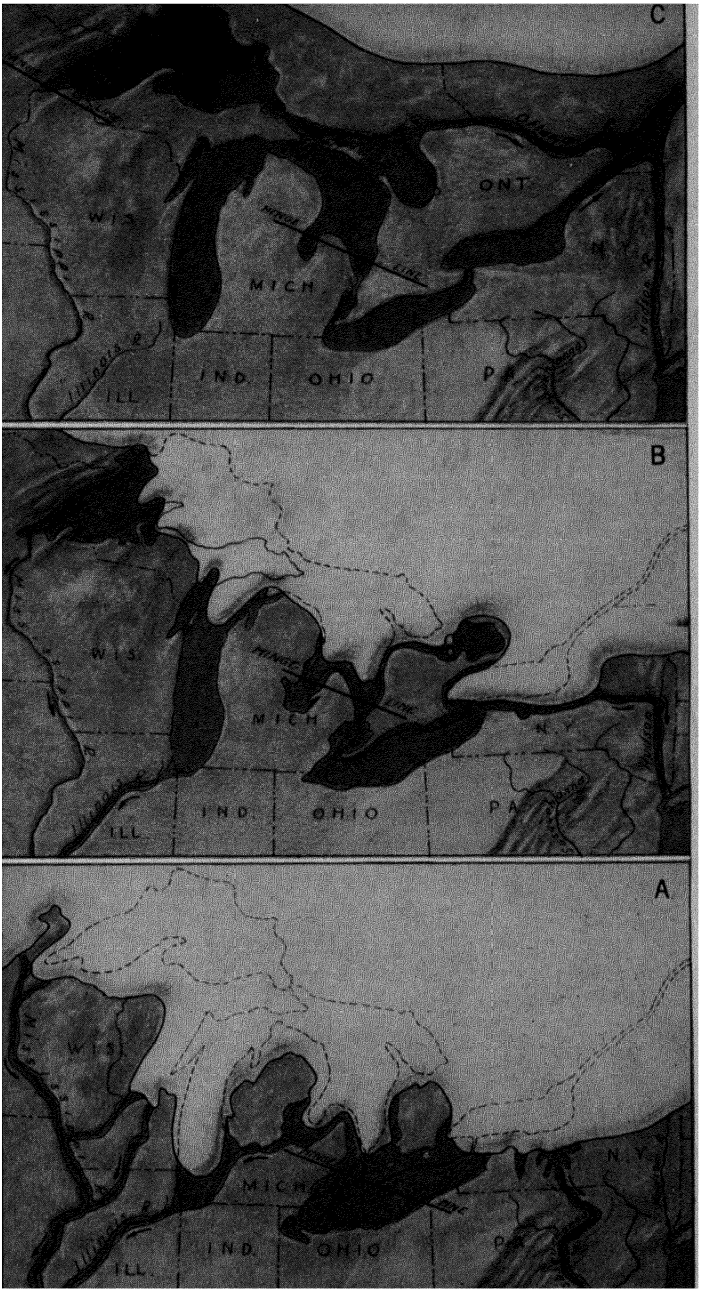


FIG. 99. Three stages in the development of the Great Lakes as the last glacier ice wasted away. Adapted from Leverett and Taylor, U. S. Geol. Survey.

Other great lakes not directly associated with the ice sheets were Lake Bonneville and Lake Lahontan in Utah and Nevada (see *Outlines of Physical Geology*, p. 122).

PART III. THE PAGEANT OF LIFE

CHAPTER 10

PALEOZOIC INHABITANTS OF THE EARTH

"The race of man shall perish, but the eyes
Of trilobites eternal be in stone,
And seem to stare about in mild surprise
At changes greater than they yet have known."
—T. A. CONRAD.

THE CURTAIN RISES

At the dawn of the Cambrian, life had already existed on the Earth for possibly a thousand million years. It is small wonder, therefore, that nearly all the great branches of the animal kingdom were represented, and that complex forms of Crustacea, such as trilobites, held the center of the stage. Although exceedingly rare in the Pre-Cambrian rocks, fossils appear in abundance at the base of the Cambrian, revealing this highly varied life as though a curtain had suddenly lifted on a drama already long in progress.

The lands must then have presented scenes of stark desolation, for Cambrian rocks bear no direct evidence of terrestrial life of any sort. Primitive soft-tissued plants, such as lichens, probably clothed the moist lowlands, but, lacking roots and vascular tissue by which to draw moisture from the ground, they could not thrive in the dry regions. Animals had not yet learned to breathe air and did not appear on the land until nearly three long geologic periods had passed.

The seas, however, teemed with invertebrate animals of many kinds which found both food and shelter among the varied and abundant seaweeds. On the whole, it was a strange and unfamiliar assemblage of animals, primitive in many respects and all of comparatively small size.

The chief types of shell-bearing animals are shown in Plate 1. Trilobites were at once the dominant and the largest forms, *Paradoxides* (Fig. 100), the largest Cambrian animal, having a length of about 18 inches. It is a striking commentary on the history of life that such small and lowly creatures held complete dominion in the seas throughout the long Cambrian period—a span exceeding that of human existence on Earth by perhaps sixty times.

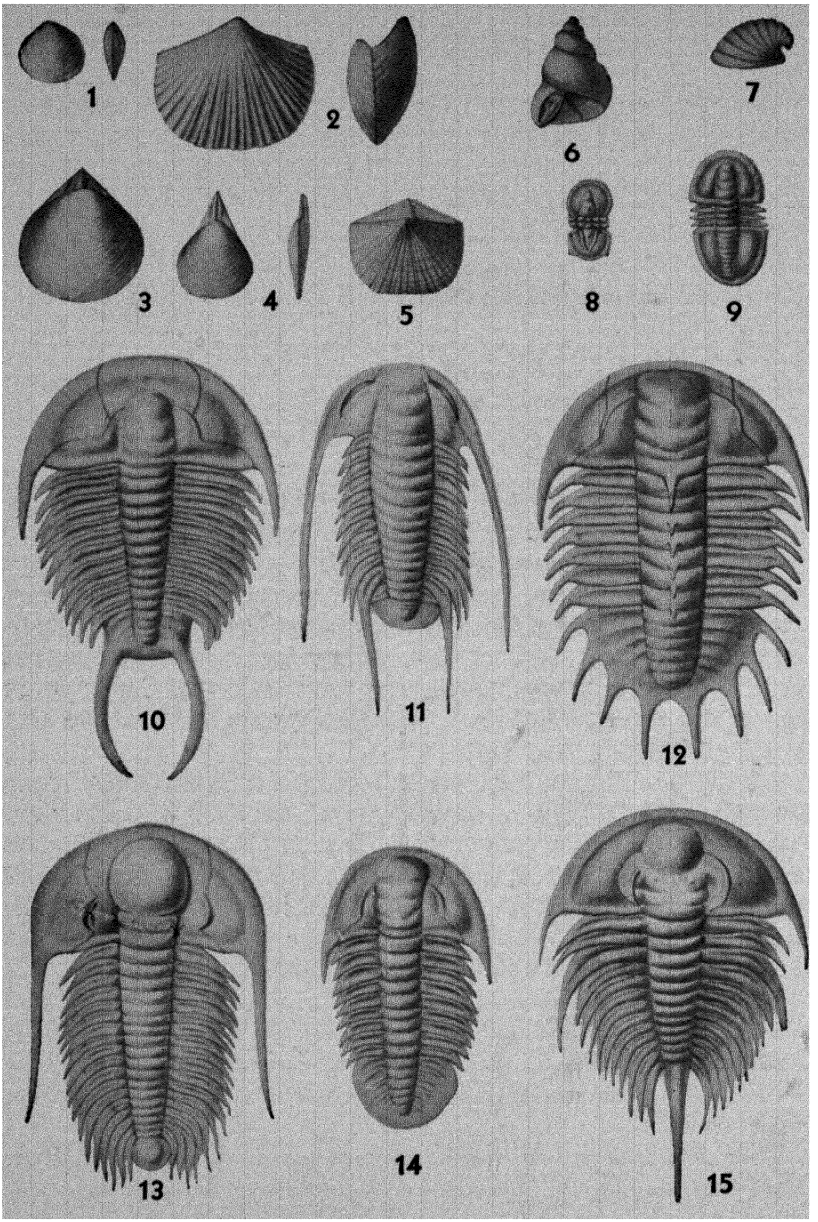


Plate 1. Cambrian Animals.

BRACHIOPODS: Fig. 1, *Dicellomus politus*, ventral and lateral views; 2, *Eoorthis texana*, ventral and lateral views, × 1½; 3, *Obolus aurora*, × 2; 4, *Lingulepis pinniformis*, dorsal and lateral views, 5, *Billingsella coloradoensis*, × 1½. GASTROPODS: 6, *Matherella saratogensis;* 7, *Helcionella rugosa*. TRILOBITES: 8, *Agnostus interstrictus;* 9, *Eodiscus speciosus*, × 1½; 10, *Tricrepicephalus texanus;* 11, *Bathynotus holopyga;* 12, *Olenoides curticei*, × ½; 13, *Paradoxides harlani*, × ¼; 14, *Bathyuriscus rotundatus;* 15, *Olenellus thompsoni*. Natural size, except as otherwise stated. Drawn by L. S. Douglass.

The fossil record is chiefly that of animals with hard parts to preserve, but there is one miraculous deposit of black slaty shale of Middle Cambrian age (the Burgess shale), high up in the flank of Mount Wapta, near Field, British Columbia, where soft-tissued organisms are preserved as carbonaceous films on the bedding planes (Pl. 2). Here have been found well over a hundred species, including seaweeds, sponges, soft-bodied marine worms, and a great variety of primitive, delicate crustaceans, as well as trilobites and brachiopods. This remarkable occurrence of soft-tissued animals, most of them otherwise unknown, assures us that life may also have been abundant and varied in the Pre-Cambrian seas, even though unrecorded.

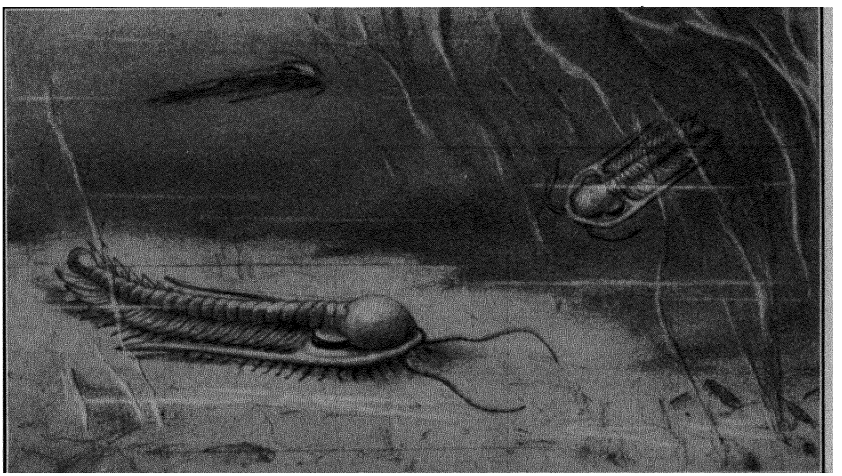


FIG. 100. Restoration of the Cambrian trilobite, *Paradoxides harlani*. About 1/10 natural size.

The sudden appearance of abundant fossils in the Cambrian is remarkable, and not easily explained. From the whole Pre-Cambrian we have but a meager record of wormlike animals, a jellyfish, lime-secreting seaweeds, and sponge spicules; but the Cambrian rocks of America alone have yielded more than 1200 kinds of animals. Such a difference in the record implies that some great change had taken place in the organization of animals during the hiatus that preceded the Cambrian. This appears to have been the invention of armor. Earlier animals were probably soft-bodied and therefore scarcely capable of preservation; the development of shells or tests provided the hard parts that we know as fossils.

The development of armor may have taken place over a considerable span of time, for the hiatus preceding the Cambrian is a great one,

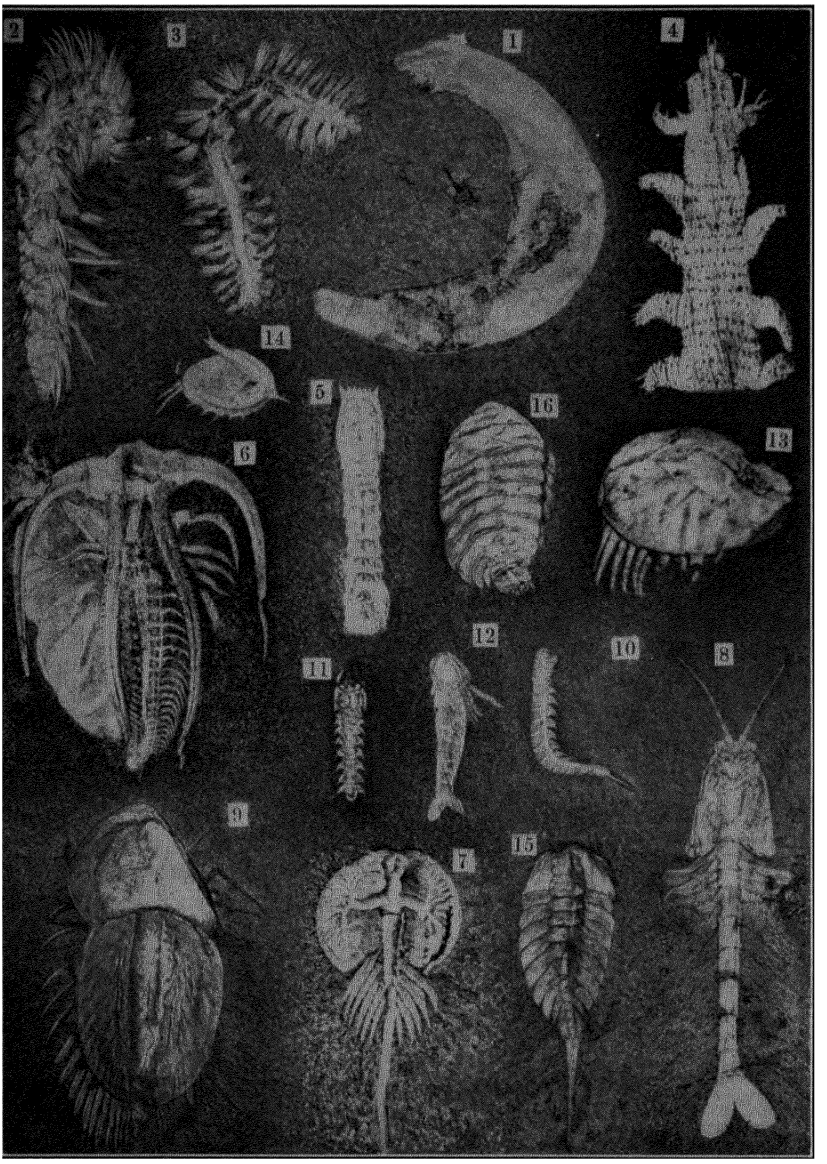


Plate 2. Middle Cambrian Fossils from the Burgess Shale, near Field, British Columbia.

Figs. 1–3, annelids (Chætopoda); 4, Onychophora; 5–14, Crustacea (5, 6, 9, Trilobita; 7–8, 10–12, Branchiopoda; 13–14, Phyllocarida); 15, 16, Merostomata.

Fig. 1, *Ottoia prolifica;* 2, *Canadia spinosa;* 3, *C. setigera;* 4, *Aysheaia pedunculata;* 5, *Mollisonia gracilis;* 6, *Marrella splendens;* 7, *Burgessia bella;* 8, *Waptia fieldensis;* 9, *Naraoia compacta;* 10, 11, *Yohoia tenuis;* 12, *Y. plena;* 13, *Hymenocaris ? circularis;* 14, *H. ? parva;* 15, *Molaria spinifera.* All after Walcott (1911–1912).

hence the " sudden " appearance of shells may be more apparent than real. Nevertheless, the simultaneous development of armor in so many stocks of animals at this time has been the subject of much speculation. The suggestion has been made (by Brooks) that earlier animals had been chiefly small, free-floating or swimming creatures like the larvæ of existing types, and that shortly before the Cambrian they began to colonize the bottom, then rapidly increased in size, for the first time experienced crowding and keen competition, and hence felt the need of protective armor. The Pre-Cambrian animals may have been mainly herbivorous and scavenging, but many of the Cambrian types were carnivorous; it is not improbable that the development of active predatory habits coincided with the development of shells and the beginning of a fossil record.

Denizens of the Sea

Since the beginning of the Cambrian, life has been varied and abundant in the seas. Probably all the phyla except vertebrates were represented in the Cambrian, and most of the classes and orders of invertebrate animals had appeared before the close of the Ordovician. In this brief survey we can hope to touch only a few of the major groups of these Paleozoic creatures.*

Trilobites and Their Kin. Trilobites (trī'-lō-bīts) were the most distinctive animals of the Paleozoic seas, appearing in great diversity early in the Cambrian, reaching their greatest variety in the Ordovician, and then gradually declining to extinction late in the Permian. Figs. 8 to 15 of Plate 1 show the characteristic appearance of these depressed and trilobed crustaceans, and Fig. 100 suggests their probable habits, groveling over the sea floor or swimming near it. Most of them were less than 4 inches long, but a few attained about 20 inches. Most of them could roll up, armadillo-like, to protect the ventral side of the body and the limbs. Probably the chief reason why they appear more abundant than other fossils in the earliest part of the Paleozoic is because their upper surface was armored with a strong chitinous test (like that of a lobster) that was relatively insoluble and thus easily preserved.

Somewhat distantly related to the trilobites are the *ostracods* (Fig. 101), which bear minute bean-shaped shells consisting of two valves hinged along the back like the shell of a clam. They first appeared

* The chief groups of animals and plants are briefly described and defined in the Appendix, pp. 256–281.

in the Ordovician seas and occur in rocks of all later ages, being common in modern faunas and inhabiting both marine and fresh waters. Most of them are less than an eighth of an inch long and so are easily overlooked, but they lived in such abundance at many places in the Paleozoic seas that they are readily found in well cuttings and thus serve as useful guide fossils for subsurface correlation.

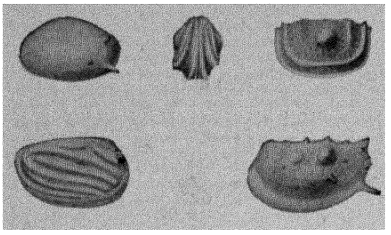


FIG. 101. Shells of ostracods, enlarged about 5 times.

Neither lobsters, crayfish, nor crabs existed in Paleozoic time, but ancestors of these, resembling shrimp, appeared toward the close of the era.

Shellfish. The shells on modern beaches represent mostly two great groups of molluscs, the *gastropods* (snails, etc.) and the *pelecypods* (clams and their kin). A third group, the *cephalopods,* is represented by the pearly nautilus and by shell-less relatives such as the devilfish and squids. All three groups were abundant in Paleozoic seas.

Gastropods (see p. 270 and Fig. 171) appeared early in the Cambrian but these earliest types were very small and possessed not over two or three coils (Pl. 1, Figs. 6–7). By Ordovician time they were numerous and varied in shape, some having low coils and others high, graceful spires (Pl. 3, Figs. 1–7). They were common marine animals throughout the rest of the era, though less numerous and varied than they are in the modern seas. The oldest known *land snails* appeared in the Pennsylvanian period and were found associated with petrified logs in Nova Scotia.

Cephalopods (see p. 270 and Figs. 172, 173) were common shellfish during most of Paleozoic time, and their chambered shells, some straight and others coiled, are common fossils (Pl. 3, Figs. 15–19; Fig. 102). But they appear to have evolved later than the snails, since the oldest certainly known representatives occur in late Cambrian rocks and even there are very rare and small. Once started, they specialized rapidly and became numerous and varied in shape early in the Ordovician. By the middle of that period, one species (Fig. 102), had become the largest animal of its time, with a shell more than 10 feet long and 14 inches in diameter.

All the Ordovician and Silurian species were *nautiloids* (having smoothly curved partitions like the modern nautilus), but primitive *ammonites* (having fluted septa) appeared in the Devonian and evolved rapidly during the latter part of the Paleozoic era, foreshadowing the dominant role they were to play in the Mesozoic.

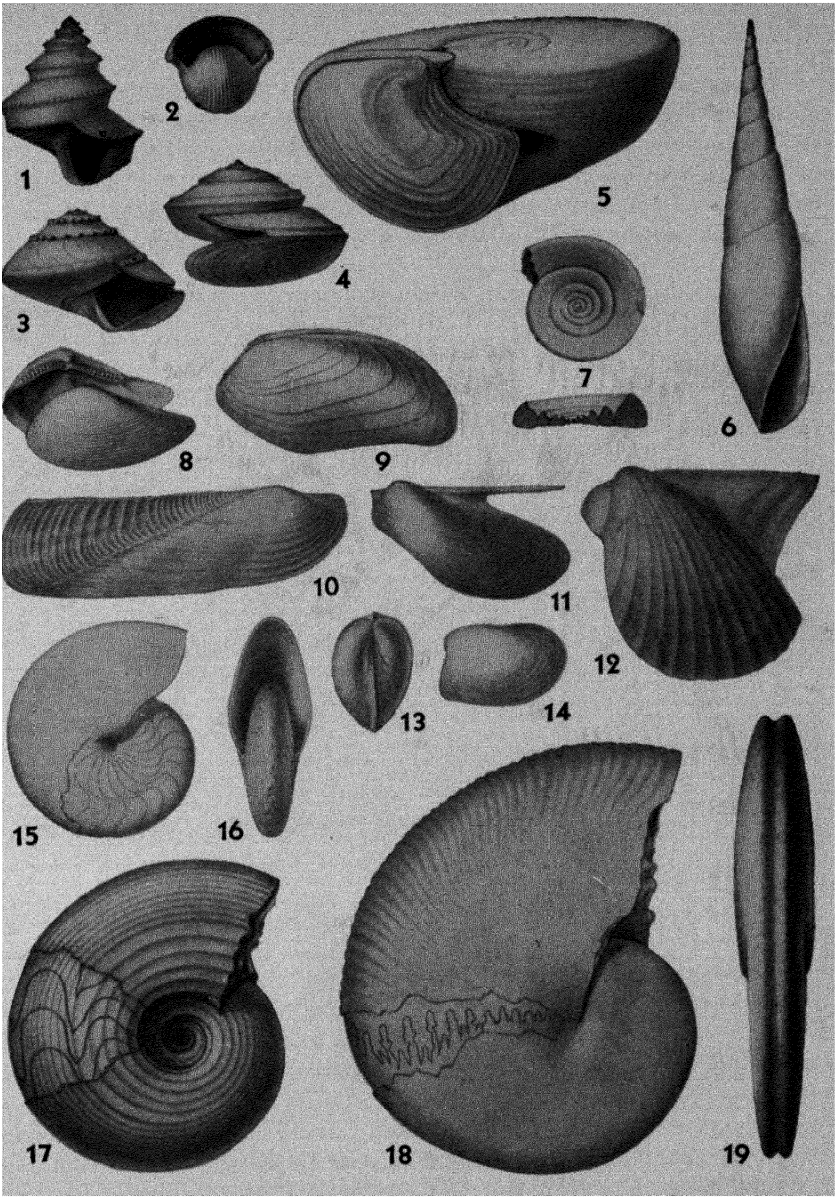


Plate 3. Paleozoic Invertebrates.

GASTROPODS: Fig. 1, *Worthenia tabulata;* 2, *Euphemites carbonarius,* and 3, *Trepospira sphærulata,* all of the Pennsylvanian; 4, *Eotomaria supracingulata;* 5, *Maclurites logani* with operculum; 6, *Subulites canadensis,* and 7, *Lecanospira compacta,* all of the Ordovician. PELECYPODS: 8, the Pennsylvanian *Nuculana arata;* 9, *Nyassa arguta,* × 2; 10, *Orthonota undulata;* 11, *Leptodesma longispinus;* and 12, *Pterinea flabellum,* of the Devonian; 13, 14, *Nuculopsis ventricosa,* of Pennsylvanian age. CEPHALOPODS: 15, 16, *Tornoceras uniangulare,* of the Devonian; 17, *Gastrioceras roadense,* and 18, 19, *Medlicottia whitneyi,* lateral and edge views, both of Permian age. All natural size, except Fig. 9. Drawn by L. S. Douglass.

Pelecypods (see p. 269 and Fig. 170) were the last of the three great classes of molluscs to appear, being unknown in the Cambrian. The oldest known examples are small, simple clams found near the base of the Middle Ordovician. The group has evolved gradually since Ordovician time to its present prominence. Characteristic Paleozoic species are shown on Plate 3, Figs. 8–14. Clams appear generally to



Field Museum of Natural History.

FIG. 102. An Ordovician sea beach on which specimens of the great cephalopod, *Endoceras*, are stranded. From a painting by Charles R. Knight.

have preferred the muddy sea floors and are most abundant as fossils in shaly formations, where they are commonly preserved only as molds and casts. The poor preservation is probably the result of the fact that their shells were pearly and therefore more soluble than those of most other animals.

Fresh-water clams first evolved from marine forms during Devonian time and the oldest ones known appear in the fluvial part of the Catskill delta in New York, in beds of late Middle Devonian age. Small river clams are locally common also in some of the coal fields of the late Paleozoic.

Brachiopods (see p. 263 and Fig. 165) were the commonest shellfish of the Paleozoic seas. Their shells consist of two valves hinged together at one edge and thus superficially resemble the shell of a

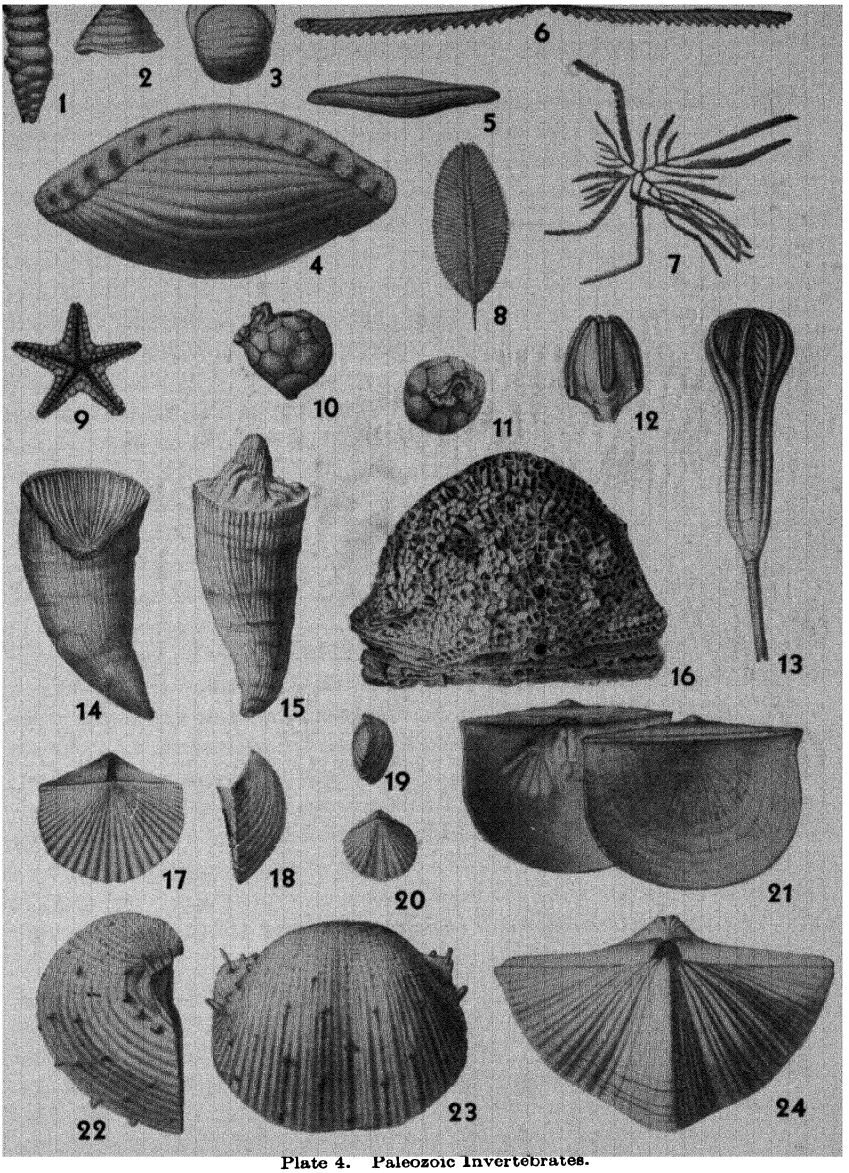


Plate 4. Paleozoic Invertebrates.

PENNSYLVANIAN FORAMINIFERS: Fig. 1, *Climacammina cylindrica;* 2, *Tetrataxis palæotrochus;* 3, *Staffella keytei;* 4, *Triticites ventricosus;* 5, *Wedekindellina euthysepta.* All enlarged. ORDOVICIAN GRAPTOLITES: 6, *Didymograptus nitidus,* a two-branched colony; 7, *Clonograptus flexilis,* a colony of many branches; 8, *Phyllograptus typus,* side view of a specimen flattened in the shales. ECHINODERMS: 9, *Hudsonaster narrawayi* of the Ordovician, one of the oldest known starfishes; 10, 11, *Malocystites emmonsi,* an Ordovician cystoid, side and upper views; 12, *Pentremitidea filosa,* a blastoid from the Devonian; 13, the Ordovician crinoid *Ectenocrinus grandis.* CORALS: 14, *Streptelasma rusticum* of the Ordovician; 15, *Lophophyllum profundum* of the Pennsylvanian, × 2; 16, the Devonian *Favosites conicus.* BRACHIOPODS: 17, 18, *Hesperorthis tricenaria,* and 19, 20, *Zygospira modesta,* both of the Ordovician; 21, the Devonian *Stropheodonta demissa,* dorsal view of shell, and interior of pedicle valve; 22, 23, *Dictyoclostus portlockianus,* and 24, *Neospirifer dunbari,* of the Pennsylvanian. Natural size except as stated. Drawn by L. S. Douglass.

clam, from which they may be easily distinguished because of their symmetry. The brachiopod shell has unequal valves, each of which is bilaterally symmetrical (Pl. 1, Figs. 1–5; Pl. 4, Figs. 17–24).

Brachiopods were abundant at the beginning of the Cambrian, rivaling the trilobites in number; and they retained a dominant position throughout the Paleozoic era, presenting an amazing variety of shapes and ornamentation. Some were thin and flat (Pl. 4, Fig. 21), others concavo-convex (Pl. 4, Figs. 22, 23), and still others strongly biconvex (Pl. 4, Figs. 19, 24). Many were smooth, but the majority were ribbed and some were spiny.

Although more than 150 kinds of brachiopods live in the modern seas, few are found near the shores of Europe or America and so these animals are usually known only to specialists; but in Paleozoic time they would have been the commonest shells on the beaches in most parts of the world.

Corals (see p. 262 and Fig. 164) made their appearance early in the middle of the Ordovician period, and a few kinds formed small reefs in late Ordovician seas, but their first great expansion came in the Middle Silurian. Then, and again in the Middle Devonian, corals of numerous kinds thrived in the warm, clear seas and made reefs in many parts of the world. This marked the climax of Paleozoic types and throughout the rest of the era they were less common and varied, and formed only local reefs.

The Paleozoic corals belonged to two great groups, the *tetracorals* and the *tabulate corals*. The former included solitary species known as *horn corals* (Pl. 4, Figs. 14, 15) because of their hornlike shape, and also colonial species which formed masses of greater size. Among the tabulates the *chain corals* and *honeycomb corals* (Pl. 4, Fig. 16) were most common and distinctive.

Sea Lilies and their Kin. *Starfish* (see p. 267 and Fig. 168) and *echinoids* (see p. 266 and Fig. 167) were both represented in the Ordovician and later seas, but neither group was even relatively important until Mesozoic time. A greater role was played in the Paleozoic seas by two groups of stalked echinoderms (see p. 268, Fig. 169), the *crinoids* (sea lilies) and the *blastoids* (sea buds), whose limy plates contributed to the making of the "crinoidal limestones" that are widely distributed in the Paleozoic systems. Pieces of stems and isolated button-shaped stem plates are common fossils (Fig. 103). The blastoids are occasionally seen in Devonian rocks but are especially characteristic of the Mississippian.

Bryozoa. The bryozoans (see p. 265 and Fig. 166) were more varied and more common in Paleozoic seas than they are today, forming

small stemlike or incrusting limy colonies or delicate lacy fronds. Locally they built up small reefs.

Minor Groups. Other types of animals deserving a word of mention are the foraminifers, sponges, and graptolites. The *foraminifers* (see p. 259 and Fig. 161) are single-celled animals that form chambered limy shells, commonly of minute size (Pl. 4, Figs. 1–5). They appeared late in the Cambrian and are rather rare fossils in Early and Middle Paleozoic rocks, but during the Pennsylvanian and Permian periods they were more common, and one family (the *fusulines*) developed relatively large size and formed shells resembling grains of wheat or oats (Pl. 4, Figs. 4, 5). These were so common as to form coquina-like deposits (fusuline limestones) in many parts of the world.

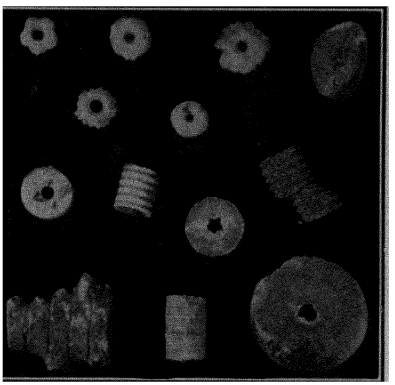


FIG. 103. Button-like stem joints of Paleozoic crinoids. Natural size.

Sponges (p. 260, Fig. 162) are represented in each of the Paleozoic systems but are relatively unimportant as fossils.

Graptolites (Pl. 4, Figs. 6–8) occur abundantly in the dark shales of the Ordovician and less so in the Silurian. Their carbonaceous remains appear like heavy pencil lines on the bedding planes.

SPREAD OF THE FORESTS

The first adequate record of land plants is found in the Devonian rocks. Seaweeds are abundantly indicated as far back as the Pre-Cambrian, and low types of plant life such as moss and lichens were probably widespread on the lands before the Cambrian, but the development of vascular plants — i.e., those having woody fibers for the circulation of fluids — apparently took place in the Devonian, since fossil wood is unknown in older rocks and is abundant in those of all later ages. Few events in the history of life have had such far-reaching consequence, for the higher types of plant life, exemplified in the prairies and the forests, influence the weathering of the rocks, modify the work of erosion, and provide the ultimate food supply for all the higher forms of land animals.

The oldest known deposit of well-preserved land plants is that of the Lower Devonian at Rhynie, Scotland, which seems to be a silicified por-



NEW YORK STATE MUSEUM.

Fig. 104. Reconstruction of the Middle Devonian forest at Gilboa, New York. Remains of this old forest were discovered during construction work for the Catskill reservoir. The foreground represents actual rock outcrops with three horizons of petrified stumps in place; the background gives a vista into the forest as it existed in Devonian time. e, seed fern, Eospermatopteris; p, primitive scale tree, Protolepidodendron.

tion of a bog. Here the plants are of several species but all are small and structurally as simple as a vascular plant could be. Once adapted to land life, the vascular plants evolved rapidly, and before the close of the Devonian were represented by ferns, seed ferns, scouring rushes (calamites), scale trees, and precursors of the conifers (cordaites). Petrified logs and stumps in the Middle and Upper Devonian strata of the Catskill delta in New York record clearly the oldest known forests, with stumps more than 2 feet in diameter.

The Coal Measures of the Pennsylvanian bear an exceptionally rich record of this Paleozoic plant life. In the vast swamps of the Pennsylvanian period, forests of fast-growing, soft-tissued trees grew in rank luxuriance (Fig. 62, p. 98). Among these were none of the deciduous forms like those of modern forests, for these had not yet evolved. The giants of the time were strange spore-bearing trees whose present relatives are small and insignificant (such as the ground pines and scouring rushes).

Primitive *ferns* were common, and they alone gave a modern aspect

to the dells of these ancient forests. The leaves of some species attained huge proportions, single fronds reaching a length of 5 or 6 feet, and the slender, unbranched tree ferns grew to be as high as 50 feet.

Seed ferns resembled the true ferns in every respect save one: they bore small nutlike seeds instead of spores appended to their fronds. They may have descended from ferns and in turn may have given rise to all the higher, seed-bearing plants. They were more common than the primitive ferns in Pennsylvanian time and have been confused with them, since the two groups can be distinguished only when fruiting fronds are found.

Scouring rushes of giant size grew in solid stands like " cane brakes " in portions of the swamps. Like their humbler modern descendant, the scouring rush, they are easily recognized by their vertically ribbed and regularly jointed stems. The Paleozoic forms bore at each joint a whorl of slender simple leaves which in modern rushes are represented only by bractlike vestiges. The leaf whorls commonly present a false resemblance to flowers. The largest of the Pennsylvanian rushes belongs to the genus *Calamites* (Fig. 105). Some of these exceeded 12 inches in diameter and had a height of 30 or more feet. Their trunks were not solid woody stems but rather thin woody cylinders filled with a core of pith and surrounded by thick bark, the woody layer rarely having a thickness of 2 inches.

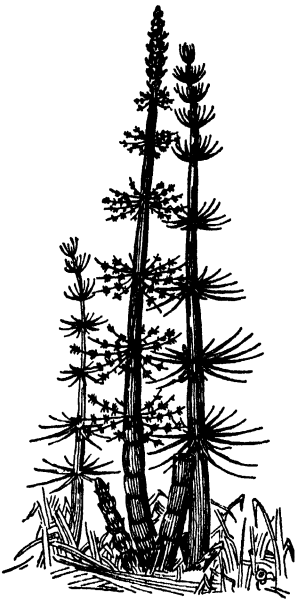


FIG. 105. A scouring rush, *Calamites*.

The *scale trees* were the most imposing plants of the forests and in many places the most common. Their name is derived from the fact that their close-set leaves left permanent leaf scars over the trunk and limbs that made them appear scaled (Fig. 107). So striking is this deception that twigs have been mistaken by amateur fossil hunters for petrified snake skins. The scale trees grew to a large size, their stumps reaching a diameter of 4 to 6 feet and their slowly tapering trunks an extreme height of more than 100 feet. Most of them belonged to one of two well-defined types, *Lepidodendron* or *Sigillaria*.

Lepidodendron (Fig. 106) grew a tall slender trunk branching repeatedly near the top to present a spreading crown of stubby twigs

covered with slender straplike leaves. These leaves, like immensely overgrown pine needles, in some species were 6 to 8 inches long and half an inch wide. The older leaves were shed as new ones formed at the tips of the branches, leaving sharply defined diamond-shaped leaf scars which were normally arranged *in spiral rows* about the limbs and trunk. The branching was normally dichotomous (with equal forks). Spore cases were borne as cones at the tips of the limbs.

Sigillaria (Fig. 106) possessed a thicker trunk which rarely branched and was clothed for several feet from the top with large bladelike leaves, resembling those of *Lepidodendron* but larger. In these trees the bark was vertically ribbed and the leaf scars were normally *in vertical rows*. Trunks have been found with a diameter, just above the



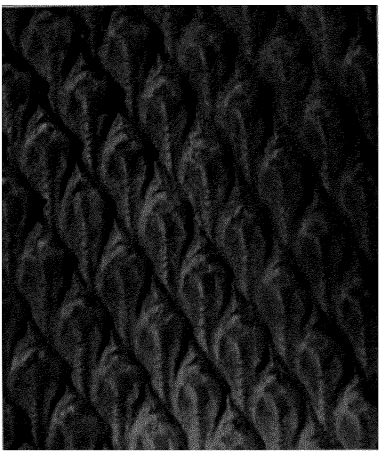
FIG. 106. Pennsylvanian trees. Left, *Lepidodendron;* center, *Sigillaria;* right, *Cordaites.*

roots, of 6 feet, and one specimen is known to be 100 feet long without a branch.

About a hundred species each of *Sigillaria* and *Lepidodendron* have been described. Although many of them were large trees, some were relatively small. In all of them the structure of the trunk and limbs was peculiar in that they had a relatively large center of pith surrounded by a woody cylinder and this in turn by two very thick layers of corklike bark. The leaf scars are impressed only on the bark. The root system likewise was peculiar, the main trunk roots spreading almost horizontally without a tap root; moreover, they branched but a few times and so were stubby and thick. The real rootlets sprang directly from the sides of these trunk roots, radiating thickly away to

a distance of several inches. Such root stocks are common in the fire clays under coal beds and not infrequently appear in the coal.

The *cordaites* (named after the Bohemian botanist Corda) were the forerunners of the modern conifers, which they resembled in their sturdy softwood trunks and their parallel-veined leaves (Fig. 106). They differed from true conifers in two chief regards: (1) their leaves were not needle-like but bladelike, attaining a length of several inches to 5 or 6 feet, and (2) their seeds were borne in racemes instead of the more compact form of a cone. Many of them were tall, graceful trees, some attaining a height of 120 feet and a diameter as great as 3 feet. In such trees fully two-thirds of the trunk was without branches, though the top was a dense crown of branches and large simple leaves. The wood of the cordaites was much like that of modern pines, but the pith at the center was larger. They appear to have been one of the chief contributors to the vegetation that made the Pennsylvanian coal.



Yale Peabody Museum.

FIG. 107. A bit of the bark of the scale tree, *Lepidodendron modulatum*, showing the characteristic leaf scars. Slightly less than natural size.

True *conifers* appeared about the middle of the Pennsylvanian and were locally common in the Permian.

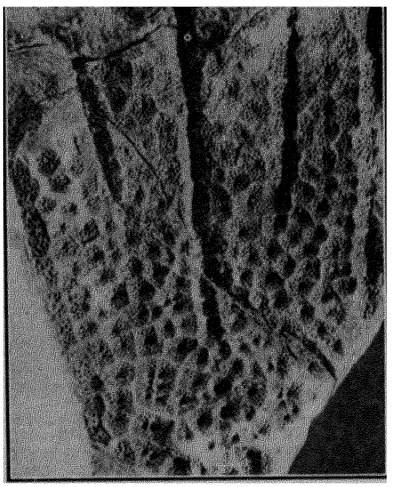
It is obvious that our knowledge of the Pennsylvanian land plants relates almost wholly to the swampy lowlands. Possibly the most rapid advances were being made in the uplands where the climate was more rigorous and more stimulating but where the chances for preservation of the record were slight.

One of the striking features of the Pennsylvanian floras is the marked similarity of the species in different parts of the world. They were as nearly *cosmopolitan* as any in the Earth's history. This must mean that their migration from one continent to another was favored by extensive land connections and by freedom from climatic barriers.

The chief groups of plants persisted from Pennsylvanian time into the Permian, but nearly all except the ferns died out at the end of that period.

Coming of the Vertebrates

The oldest certain remains of vertebrate animals are fragments of the bony armor of primitive fishes found in the Middle Ordovician rocks of Colorado and Wyoming (Fig. 108). These were transported after death and the small scattered plates give little evidence of the size and character of the living animal, but comparison with later types leaves no doubt that they represent an extinct order of primitive fishes known as *Ostracoderms*.



W. L. Bryant.

Fig. 108. Fragment of the bony armor plate of the oldest known fish, *Astraspis desiderata*, from the Harding sandstone at Canon City, Colorado. Natural size.

The first adequate record of early vertebrates is found in the latest Silurian rocks of Scotland, Norway, and Spitzbergen, where small fishes are locally abundant and well preserved (Fig. 109). Most of these belong to primitive stocks which had not yet developed a lower jaw. The modern hagfish is the only living example of this primitive type. Small sharks also occur in the Silurian.

By Devonian time fishes were widely distributed and highly specialized, including both fresh-water and marine types. In the sea, sharks of various kinds were common, and one highly specialized tribe, the *Arthrodires*, attained a conspicuous size, a species of *Dinichthys*, with a length of 20 feet, having greatly exceeded any other animal in the Paleozoic world.

Greater interest attaches to the fresh-water fishes of the "Old Red" Devonian strata of Great Britain and equivalent formations in Gaspé, Quebec. Among these the dominant types are "lungfish," so called because the swim-bladder was openly connected with the throat so that air could be inhaled and expelled as in breathing. The walls of the swim-bladder were fed by a plexus of blood vessels which could absorb oxygen and give off carbon dioxide. The swim-bladder was, in fact, a lung supplementing the gills.

Fortunately, some of the lungfish have persisted with little change (Fig. 174, p. 275), so their remarkable structure and habits can be studied in living examples. There are two major groups, the *Dipnoans*

and the *Crossopterygians*, the former having a single-lobed swim-bladder and weak fins, whereas the latter have a strongly bilobed swim-bladder (i.e., paired lungs) and stout muscular fins. All the living lungfish dwell in regions of markedly seasonal rainfall where their lungs are of real use during the long periods of drought, and the physical characters of the " Old Red " strata indicate a similar habitat for the Devonian lungfish. Their preponderance in these beds, more-

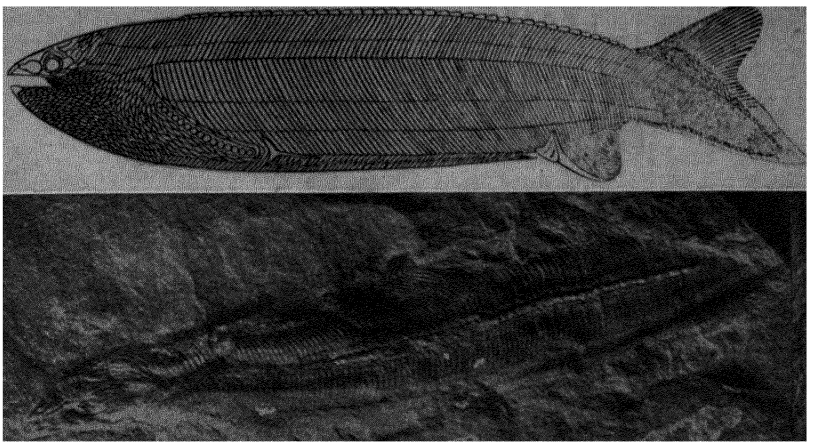


FIG. 109. A primitive fish (*Pharyngolepis oblongus*) from the uppermost Silurian (Downtonian beds) of Norway. Above, a reconstruction; below, dorsal view of a specimen in the rock. After Kiaer. About ⅔ natural size.

over, suggests that the evolution of the lungs was an adaptation to an environment in which droughts were recurrent. As we shall see, it was but a single further step to the development of land animals.

In the marine strata of the Devonian, sharks of various kinds predominated, and in the Mississippian the " shell-crusher " sharks (cestracionts) evolved rapidly, their blunt teeth being the commonest of fish remains. The modern Port Jackson shark is a living descendant of this late Paleozoic group.

EMERGENCE OF LAND ANIMALS

Many years ago a small slab was found in the uppermost Devonian strata near Warren, Pennsylvania, bearing a depression that appeared to be a crude footprint. Although hailed as the earliest evidence of land vertebrates and named *Thinopus antiquus*, it has always been looked upon with some suspicion as possibly only the imprint of a con-

cretion. But the existence of land animals in the late Devonian was clearly established in 1928 when the Danish expedition to East Greenland under the leadership of Lauge Koch reported numerous skulls and incomplete skeletons of small amphibians (stegocephalians).

The amphibians (see p. 276) have never become perfectly adapted to land life. Although the adults may live on dry land, they return to the water to spawn, laying small eggs that hatch into tadpoles, the young being fishlike in habit and structure for a considerable period before they develop legs and emerge from the water. Nearly all the

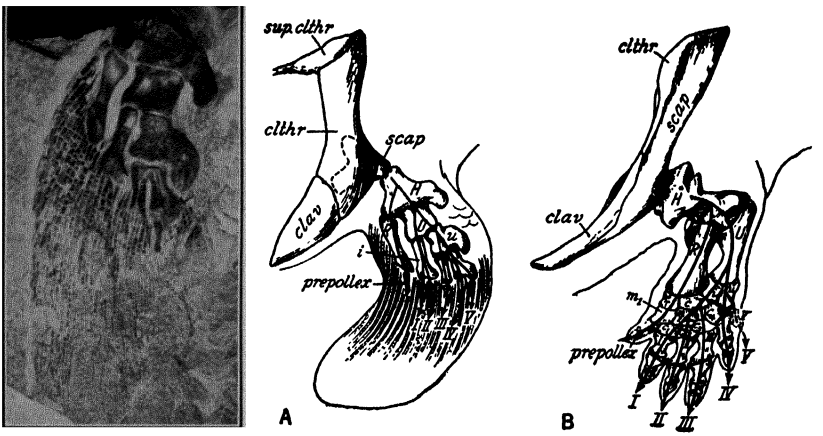


FIG. 110. Resemblances between a crossopterygian fin and the limb of a primitive land animal. Left, unretouched photograph of the left front fin of *Eusthenopteron foordi;* center, diagram of the skeletal elements of the same fin; right, corresponding limb of a late Paleozoic amphibian, *Eryops.* Photograph from W. L. Bryant; diagrams after W. K. Gregory.

Paleozoic amphibians had the head armored with dermal bones which gave the skull a massive, solid appearance. The group having the skull thus plated is known as the *stegocephalians* (Gr. *stegos*, roof, + *cephale*, head). These were sprawling four-footed animals with large heads, long bodies, and weak legs, somewhat resembling the modern "giant salamander." They were the dominant land animals of the Paleozoic and persisted until late Triassic time.

The early stegocephalians show unmistakable resemblances to the contemporary crossopterygian lungfishes. For example, the skull bones can be matched, bone for bone, in amphibian and fish. Moreover, both have simple conical teeth in which the enamel was infolded in a peculiarly complex pattern.

The Devonian stegocephalians bear two further resemblances to the fishes that are not equaled by any later forms, namely, the marginal position of the external nasal openings and the persistence of a distinctive sense organ, the lateral-line system, as a series of open grooves. Finally, some of the Devonian crossopterygians had a cartilaginous skeleton in their stout fins from which the bones of the five-toed limb could be very simply derived (Fig. 110).



American Museum of Natural History.

FIG. 111. Stages in the transition of the lungfishes into stegocephalians, as reconstructed by W. K. Gregory. Left, the Devonian crossopterygian, *Eusthenopteron*, leaving the water to flounder about on its strong muscular fins; right, an early stegocephalian, *Diplovertebron*, from the Lower Carboniferous beds of Bohemia.

This chain of circumstances, supported by other technical details of skull and skeleton, proves with exceptional clarity that the early land vertebrates developed from crossopterygian lungfishes in Devonian time; and, knowing the remarkable habits of modern lungfishes such as *Polypterus*, which inhabits the tropical rivers of Africa, we can visualize the transition that freed our remote ancestors from the water and started them on their conquests of the lands. The "Old Red" formations indicate that deposition in basins of markedly seasonal rainfall persisted throughout much of Devonian time. Here the fishes had to endure annual droughts generation after generation for some millions of years. Again and again the shrinking water holes brought death and destruction — but always there were some that did not go dry, and here the

survivors were crowded in stagnant water deficient in oxygen. A great premium was placed on the ability to gulp air and use the oxygen undiluted. The lungfishes met the emergency; as the water became foul they were more active, their swim-bladder serving as a lung. Those with stout fins could forsake their pools in the cool of night and flounder about on the banks in search of food (Fig. 111). Once the lungs had reached a certain stage of efficiency and the fins had grown into stubby limbs, they were able to remain for long periods out of water and seek their fortunes on the land. The Devonian stegocephalians of Greenland represent approximately this earliest stage in the history of land animals. It is because of this ancestry that all the Paleozoic land animals were sprawlers, with relatively weak legs springing from the sides of their bodies. It was not until the very close of the era that some of the reptiles began to get their legs under the body so they could *walk* instead of sprawl.

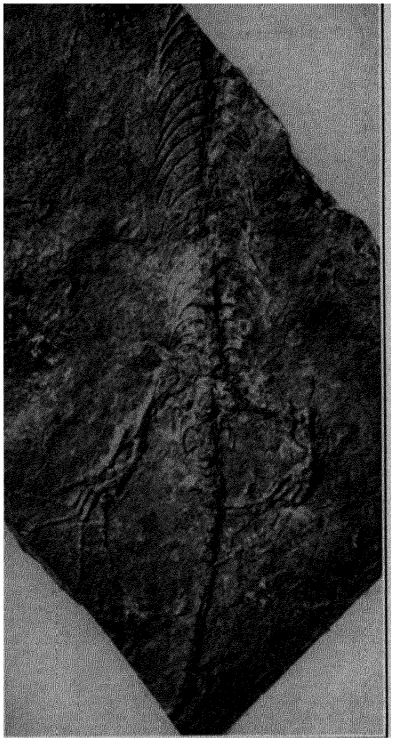


FIG. 112. The oldest known reptile, *Eosauravus copei*. Natural size. The hind legs and most of the backbone are preserved. Lower middle Pennsylvanian beds at Linton, Ohio. From Roy L. Moodie, by courtesy of the U. S. National Museum.

Once established, the stegocephalians evolved rapidly, and, where conditions for preservation were suitable, their remains were abundantly fossilized in the Pennsylvanian and Permian sediments. The swamps of the Coal Measures were especially favorable, and these beds in America alone have yielded no fewer than 7 orders, 19 families, 46 genera, and 88 species of amphibians. These range in size from a few inches to about 10 feet in length.

Reptiles show an advance over amphibia in that they are completely independent of the aquatic habitat, laying their eggs on the land. These eggs are relatively large because they contain food to nourish the young until they hatch and are able to shift for themselves. It is not surprising that reptiles appeared almost two geologic periods

later than the first amphibians. The oldest known reptile is a small one found near the middle of the Coal Measures in Ohio (Fig. 112). They were rare until Permian time, when they began a rapid evolution foreshadowing their dominance in the next era. The older forms are best known from the red beds of Texas, and higher Permian forms are abundant in South Africa, India, and Russia.

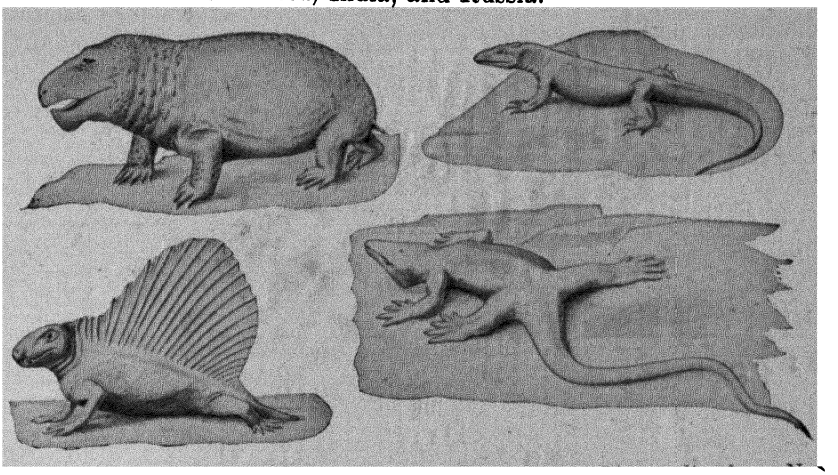


FIG. 113. Characteristic Permian reptiles. Lower right, *Limnoscelis*, from New Mexico; lower left, *Dimetrodon*, the ship lizard, from Texas; upper right, *Varanops*, from Texas; upper left, *Endothiodon*, from South Africa.

Most of the Permian reptiles had long bodies, long tails, and short legs (Fig. 113). Some were agile and lizard-like (*Varanops*), others sluggish and semiaquatic like alligators (*Limnoscelis*), and a few were thick-bodied and had stumpy tails and thick legs. Special interest attaches to one rare tribe in which the teeth were beginning to differentiate and the lower jaw to undergo specialization. In the Triassic this order (*Theriodontia*) gave rise to the mammals.

INVERTEBRATE LAND LIFE

The invertebrate land life of the Paleozoic is not well recorded. Rare *millipeds* and *scorpions* have been found in the late Silurian of Wales, and *spiders* of several kinds are known from one locality (Rhynie) in Scotland. All three groups are represented in the Coal Measures, occurring locally in some abundance. The oldest known *land snails* have been found in the lower Pennsylvanian Coal Measures at Joggins, Nova Scotia, associated with small amphibians in the hollows of petrified stumps; few others had been found in Paleozoic rocks.

The oldest known *insect* is a primitive, wingless type represented by fragments in the plant-bearing Lower Devonian rocks at Rhynie, Scotland. No others are known before the early Pennsylvanian. They are, of course, rare fossils because of their delicate nature. In occasional localities where conditions were especially suited for preservation, large collections have been made from both the Pennsylvanian and the Permian systems. In the earliest of these, the insects are fully developed and considerably diversified, cockroaches predominating. This diversity clearly implies a long antecedent evolution whose record may yet be found in Mississippian and Devonian rocks.



Yale Peabody Museum.

FIG. 114. A small stone-fly, *Lemmatophora typica*, from the Early Permian near Elmo, Kansas, with color spots and microscopic hairs preserved. Actual size about that of a house fly.

The Pennsylvanian insects belong mostly to primitive extinct orders, and many of them were of notable size. The greatest of all insects, either fossil or modern, was a dragon-fly-like form, *Meganeuron*, found in the Coal Measures of Belgium, with a wing spread of 29 inches. In the Permian there was, in general, a reduction in size and rapid specialization, leading to the origin of several of the modern orders, notably those that embrace the may-flies, the wasps, the

true dragon-flies, and the beetles. A single locality in the Early Permian near Elmo, Kansas, has yielded about 10,000 specimens, many of which retain color markings and microscopic " hairs " on the wings (Fig. 114).

CHAPTER 11

THE REIGN OF REPTILES

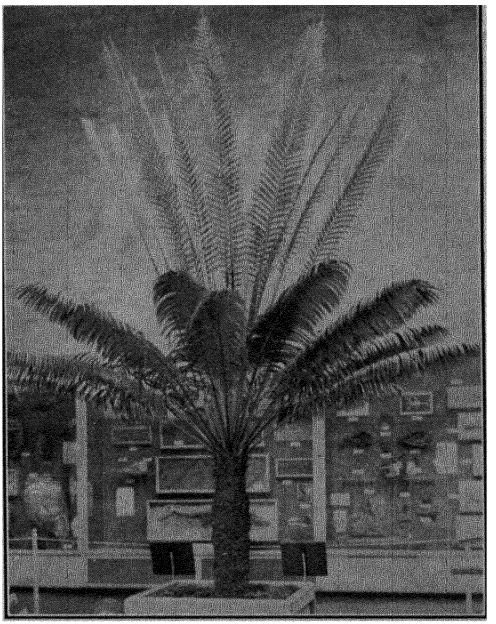
FORESTS PROVIDE A BACKGROUND

Forests of Evergreens. The plant life of Mesozoic time was less strange than that of the Paleozoic, even the Triassic plants belonging to groups still extant. However, two features challenge the attention. In the first place, the common flowering plants and hardwood trees did not appear until Cretaceous time, and the early Mesozoic forests were therefore comprised of evergreens, chiefly conifers and ginkgoes, with a strong admixture of cycadeoid palms. A second peculiarity was the absence of grasses and the common seed-bearing weeds, all of which appeared much later. The timbered areas had an undergrowth of scouring rushes and ferns as many open timber lots do today, but it is hard to imagine the semiarid plains utterly devoid of grass. Nevertheless, it would seem that large areas of this sort must have presented a naked and barren surface. Possibly this is one reason for the prominence of wind-blown sand in the Triassic and Jurassic deposits of the West.

Plant fossils are not commonly preserved in red beds, and as the early Mesozoic nonmarine deposits are chiefly of this type, the plant record of Triassic time is still imperfect. In America we get two glimpses of the plant life, one in dark shales of the Newark basins from Connecticut to North Carolina, the other in the Fossil Forest of Arizona. The first is a swamp flora of ferns and scouring rushes, to which are added, where streams entered the swamps, the transported leaves of conifers and cycads (Fig. 115) that formed the forests of the slopes and uplands.

The Fossil Forest of Arizona, on the contrary, includes chiefly petrified logs, although foliage has recently been found in several places, recording cycadeoids and ferns that grew along the stream courses. The logs are of conifers, not unlike the great pines that now stand in stately grandeur upon the rim of the Colorado Plateau overlooking the Great Basin. Many of these fossil logs are of noble size, the trunks attaining a diameter of 10 feet and a length in excess of 100 feet. It has been estimated that some of the trees stood nearly 200 feet high. They now lie imbedded in the red shales of the Chinle formation, all petrified as agate.

These two occurrences give a fair representation of the Triassic land plants of America. The chief groups of Paleozoic plants were extinct, or nearly so. The seed ferns had largely vanished, and the great scale trees were represented only by rare specimens of *Sigillaria* found in Early Triassic beds.



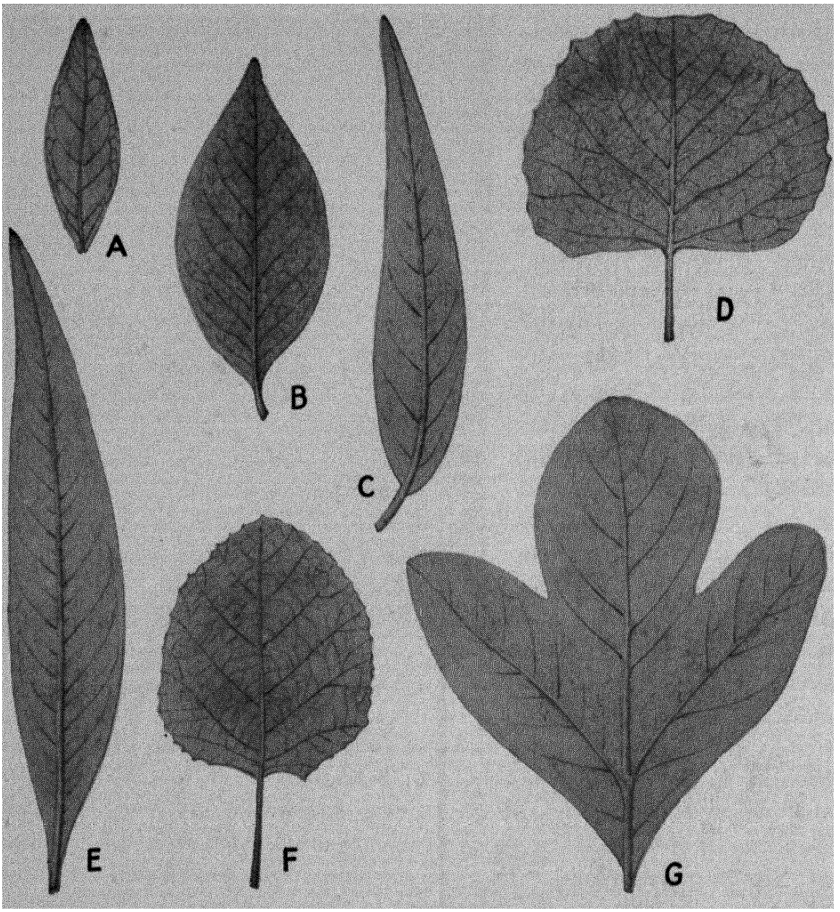
Yale Peabody Museum.

FIG. 115. A living cycad.

The Jurassic record is much fuller, especially in the Old World, but it shows no striking change or advance over the Triassic. The forests presented thick stands of pines and other conifers, mingled with ginkgoes and tree ferns; the undergrowth was of herbaceous ferns and scouring rushes. On the less humid slopes cycadeoid palms were conspicuous. One remarkable feature of the Mid-Jurassic floras is the wide distribution of many species. If we exclude the cycads, about half the plants known in North America are found also in Japan, Manchuria, Siberia, arctic Alaska, Spitzbergen, Scandinavia, or England. Even the plants collected by the Shackleton expedition in Louis Philippe Land south of Cape Horn (lat. 63° S.) are practically the same as those of Yorkshire, England. In this cosmopolitan distribution of land plants there is striking testimony of mild climates even in high latitudes.

Nut- and Fruit-bearing Plants Arrive. *Deciduous trees* with net-veined leaves suddenly became conspicuous in the Early Cretaceous, and long before the close of the period they dominated the landscape in all the continents just as they do today. Among the oldest of these were the magnolia, fig, sassafras, and poplar, all of which appear in the middle Lower Cretaceous deposits. By the middle of the period the forests were essentially modern, including such trees as beeches, birches, maples, oaks, walnuts, planes, tulip trees, sweet gums, breadfruit, and ebony, along with shrubs like the laurel, ivy, hazelnut, and holly (Fig. 116).

With these, of course, there were evergreens, just as now, but they no longer dominated the landscapes as they had done during the earlier Mesozoic. Among the conifers a conspicuous type was the sequoia;



E. W. Berry, L. F. Ward.

FIG. 116. Cretaceous plants. A, *Andromeda snowi*, a relative of the rhododendrons; B, *Magnolia pseudoacuminata;* C, *Salix lesquereuxi*, a willow; D, *Populites elegans*, a poplar; E, *Ficus lanceolato-acuminata*, a fig; F, *Betulites westi latifolius*, a birch; G, *Sassafras parvifolium*, a sassafras.

although none are known so large as the modern giants of California, the race was widely distributed over the northern hemisphere at this time.

Most deciduous trees belong to the *angiosperms*, the highest order of the plant kingdom and the one that includes all the true flowering plants (the exceptional deciduous trees that are not angiosperms are

the ginkgo, the larches, etc., which have parallel-veined leaves). The strong deployment of the angiosperms in the Cretaceous was one of the most significant advances in the whole evolution of plant life, second only to their spread over the lands. The angiosperms are the most highly specialized of all plants and the ones destined to dominate the Earth during later geologic time.

The effect of the angiosperms upon the advances of the higher animals can hardly be exaggerated, for they supply nearly all the plant food for the higher animals. Angiosperms provide the nuts and fruits of the forest, the grasses of the prairies, the cereals which furnish fodder and grain for man and his domestic animals, and the vegetables and fruits, to say nothing of the flowers that add so much pleasure and inspiration to human surroundings. It would hardly be too much to say that the evolution of the mammals and birds had to wait upon the evolution of the flowering plants; it was certainly no accident that in the period following the Cretaceous the reptilian hordes gave way to a spectacular rise of warm-blooded vertebrates.

The oldest known angiosperms appeared almost simultaneously in New Zealand and in Texas, near the base of the Lower Cretaceous. Three types of deciduous tree leaves were found in the Texas locality, of which one is a species of cinnamon. From middle Lower Cretaceous rocks angiosperms are known also in Portugal and Maryland. The oldest Cretaceous formation of the Atlantic Coastal Plain has yielded none of these modern plants, though it has plenty of evergreens like the Jurassic floras. In the next formation, however, several species of deciduous trees are represented. Before the middle of the period they had spread over the Rocky Mountain region, and they comprise more than 90 per cent of the known plants of the Upper Cretaceous.

The resting stage represented by the ripening of the seeds and the shedding of the foliage of angiosperms is clearly an adaptation to seasonal and rigorous climates, either winter cold or drought. It is thought probable, therefore, that the evolution of these plants out of the older types took place on the highlands where the climate was cool and the growth seasonal, and that this may have occurred in Jurassic or even earlier time, although our oldest fossil record was made after they had migrated and adapted themselves to the lowlands where sediments accumulate and make up the geologic record.

The Reptilian Hordes

Land life in the Mesozoic was abundant and varied, including insects, snails, birds, small mammals, and reptiles. But the last group so

outweighed all the rest in abundance, variety, and sheer size that the era is well called the *Age of Reptiles.*

Dinosaurs. Dinosaurs (Gr. *deinos*, terrible, + *sauros*, reptile) made their appearance in the Triassic and by the middle of the period outnumbered all other groups of reptiles and held complete sway over the lands — a dominion they were destined to hold until the close of the Mesozoic era. Unlike other reptiles, they were adapted to a running

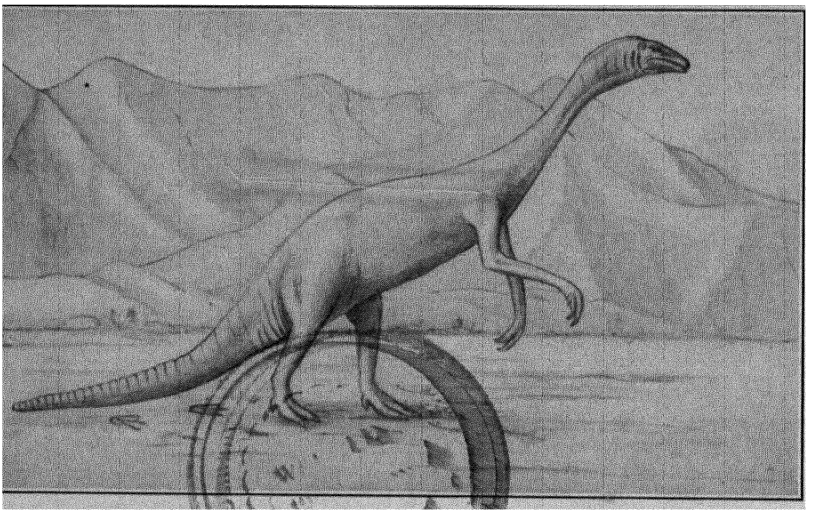


FIG. 117. A Triassic dinosaur, *Anchisaurus caluru*. After a model by R. S. Lull, based on a skeleton in Yale Peabody Museum. Animal about 6 feet long.

locomotion, since they carried their bodies up off the ground like mammals and had the legs under the body, not at its sides. Other reptiles sprawl. This is the only obvious feature that ties the diverse types of dinosaurs together as a natural group, for they vary by the widest extremes in size, bodily form, and habits. Indeed, they constitute, as we now know, not a single great order of reptiles but two that are only remotely related, having had very different origins.

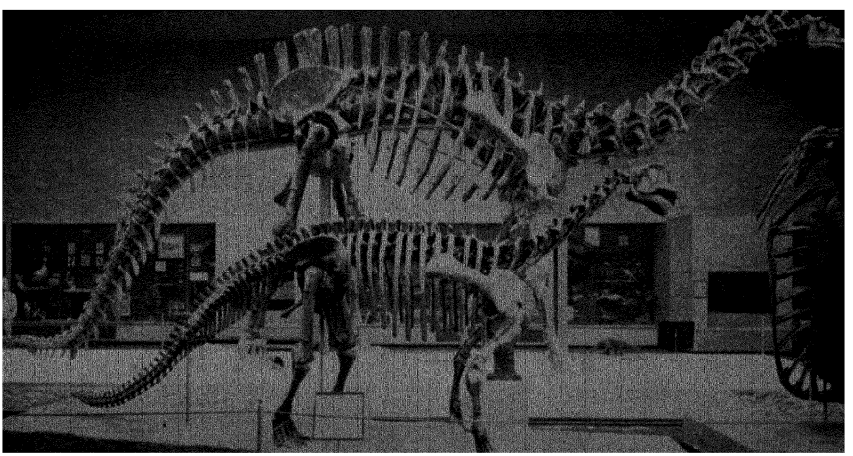
Compared with the giants of later Mesozoic ages, the Triassic dinosaurs were hardly " terrible reptiles," for nearly all of them were slender of build and few reached a length of more than 10 or 15 feet. Almost all the known Triassic species were bipedal (Fig. 117) and shaped somewhat like a kangaroo, with powerful hind legs and a thick, powerful tail which aided in balancing the body as they ran. However, the bipedal dinosaurs did not leap like a kangaroo, but ran like an ostrich. The nature of their abundant tracks makes that fact quite certain.

The side toes on the hind feet were already vestigial in most of the Triassic species, so that they made three-toed footprints that were for a long time mistaken for bird tracks. Although the dinosaurs were very numerous in the eastern United States, skeletal remains are extremely rare, because the red beds were a poor environment for the preservation of bones. As the dinosaurs crossed and recrossed the playas and mud flats of the Connecticut trough, however, they left an amazing record, not of dead but of living creatures now hurrying in search of food or water and again stopping to rest and to leave in the soft mud an impression of the body and the tiny front feet. The best-known American form is *Anchisaurus* (Fig. 117), a slender, graceful animal that reached a length, over all, of probably 5 to 6 feet; its birdlike tracks have a length of 3 or 4 inches. Some of the larger tracks 5 or 6 inches long indicate larger species. The largest track of all is that of a ponderous type, probably larger than an elephant, for its foot was more than 18 inches long and almost half as broad. Dinosaurs similar to those of America were present in Europe.

By Jurassic time the dinosaurs were represented by four major tribes. Of these the *sauropods* (*sauros*, reptile, + *pous*, foot) were largest and most distinctive. A well-known example is *Brontosaurus* (Fig. 118), the giant whose length was about 65 feet and whose weight must have been many tons. Like *Brontosaurus*, all the sauropods had pon-

YALE PEABODY MUSEUM.

Fig. 118. Mounted skeleton of the great sauropod dinosaur, Brontosaurus excelsus, having a length of 67 feet. In the foreground, a half-grown specimen of a different species, Morosaurus lentus, 21 feet long. Both from the Upper Jurassic (Morrison formation) at Como Bluff, Wyoming.



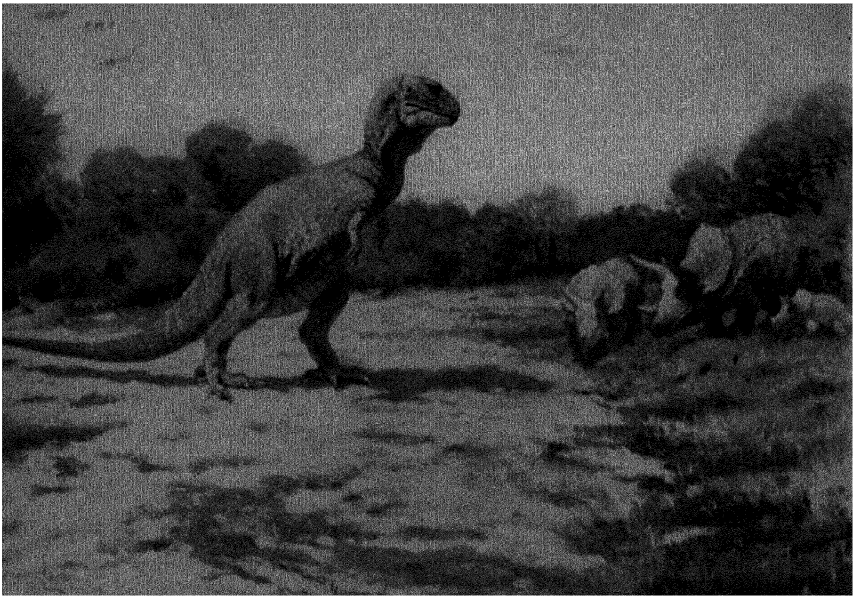
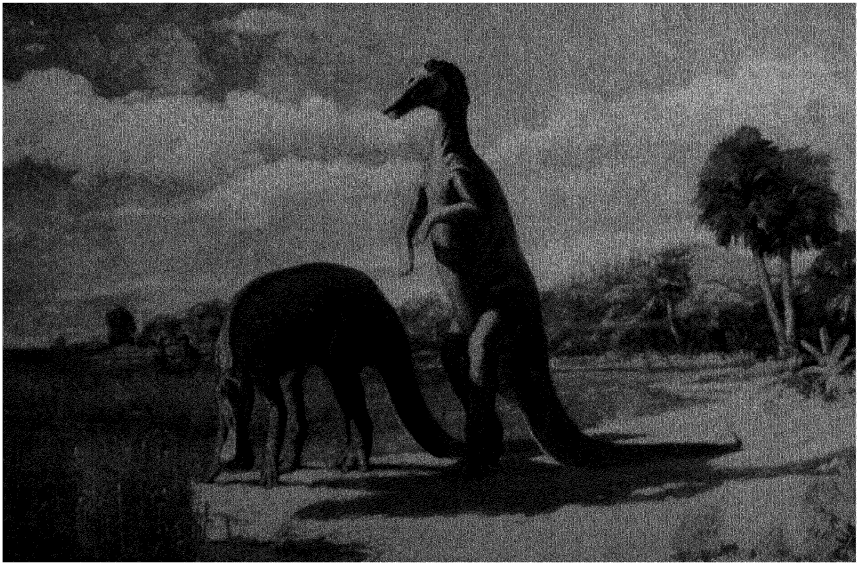


Fig. 119. Tyrannosaurus rex (left) and Triceratops horridus (right), from a painting by Charles R. Knight. Based on specimens from Hell Creek Basin, Montana.

AMERICAN MUSEUM OF NATURAL HISTORY.

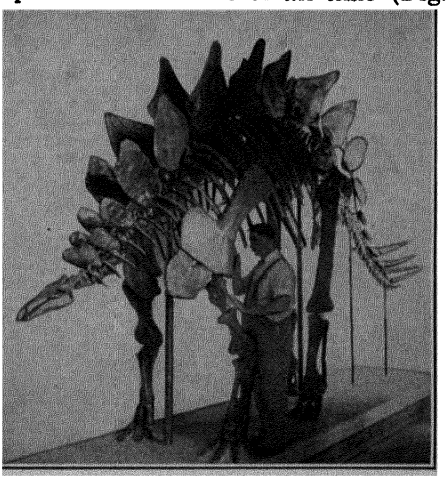
Fig. 120. Trachodon mirabilis, a duck-billed dinosaur, from a painting by Charles R. Knight. Based on specimens from Converse County, Wyoming. Such animals were about 29 feet long from nose to tip of tail.

AMERICAN MUSEUM OF NATURAL HISTORY.



derous bodies, long necks and tails, and four pillar-like limbs. These giants are best known from the Late Jurassic (Fig. 74, p. 116) and have been found in abundance in Wyoming, Utah, and Colorado. Great skeletons much like the American forms are also common in East Africa. Recently sauropod dinosaurs have been found in Lower Cretaceous beds in Wyoming and in the late Cretaceous of New Mexico, Utah, and Texas. A discovery made in the Rio Grande Valley in 1940 included parts of eleven skeletons pertaining to sauropods, duckbills, and horned dinosaurs.

The *carnivorous dinosaurs* were bipedal, and had clawed toes and large, tearing teeth. In the Triassic they were comparatively small and slender. In the Jurassic some attained a length of more than 30 feet, although many were smaller and one, found in Germany, was only 2½ feet in length over all and must have been no larger than a small kangaroo. The greatest size was attained in late Cretaceous time by *Tyrannosaurus rex*, the most powerful carnivore of all time (Fig. 119). Strangely, some of the carnivorous dinosaurs lost their teeth during the latter part of the Cretaceous, developing a beak much like that of an ostrich.



Yale Peabody Museum.

FIG. 121. Skeleton of the armored dinosaur, *Stegosaurus ungulatus*, from the Morrison formation at Como Bluff, Wyoming.

The *bird-footed dinosaurs* constitute another bipedal tribe, superficially resembling the carnivores, but adapted for plant food. Their toes had blunt nails instead of claws, and their teeth, arranged in batteries in the back part of the jaw, were adapted for chewing plant food, the front of the mouth being without teeth. They roughly paralleled the carnivores in size. Among them the *duckbills* are striking types (Fig. 120). Like the carnivores, they lived until almost the close of the era before suffering extinction.

The *armored dinosaurs* appeared in the Jurassic in bizarre forms such as *Stegosaurus* (Fig. 121), with its puny head and diminutive brain — a monument of stupidity. Its back was protected by bony plates elevated into high keels, and its powerful spiked tail afforded a mighty weapon of defense. This type is known only from the Jurassic, but

probable descendants in the Cretaceous have a lower, broader body almost completely covered by thick, bony plates.

Last of the race to appear were the *horned dinosaurs*, represented by *Triceratops* (Fig. 119). They developed in early Cretaceous time and were especially common in the late Cretaceous of western United States, their remains being preserved in nonmarine sandstone formed along the western border of the Rocky Mountain geosyncline, and in the Laramie beds of the Plains. The only other known occurrence of the horned dinosaurs outside of North America is in Mongolia. Skeletons representing all stages of growth have been found there, along with several nests of eggs, presumably belonging to the same dinosaur (Fig. 122).



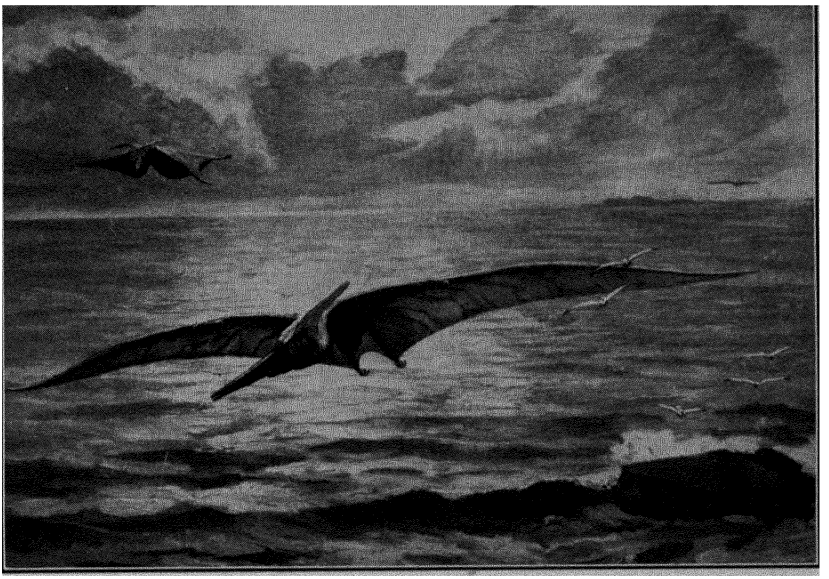
American Museum of Natural History.

FIG. 122. Nest of fossil eggs of the dinosaur, *Protoceratops*. Gobi Desert of Mongolia. These eggs were about 4½ inches long.

This early form was not over 5 feet long when mature, but the late Cretaceous of western United States had species as long as 20 feet and more than twice as bulky as a large rhinoceros, which they resembled superficially.

Winged Dragons. Perhaps the most bizarre animals of the Mesozoic were the pterodactyls or winged reptiles which " laid claim to the empire of the air in those medieval times." With leathern wings and naked bodies, they must have presented a batlike appearance, though the structure of the wings shows how false this resemblance was. The

bat is a warm-blooded animal allied to the other mammals, but the pterodactyl was a reptile. The bat has all but the first of its digits extended to bear a weblike wing membrane, whereas the pterodactyl had only the "little finger" greatly extended to support the wing, leaving the other digits free to serve as claws.



U. S. National Museum.

FIG. 123. *Pteranodon*, the greatest of the pterodactyls. A reconstruction made under the direction of F. A. Lucas for S. P. Langley, pioneer in aviation studies. The wing-spread of this creature was between 23 and 25 feet.

The pterodactyls may be represented in Triassic rocks of Europe by rare and fragmentary remains. They are abundantly preserved in the Jurassic of Europe, with species ranging in size from that of a sparrow to a wing-spread of 3 or 4 feet. Some of them had long tails with a fluke that doubtless served as a rudder in flight, but others were tailless. The Jurassic forms all had teeth, and front and hind legs were not greatly disproportionate in size. They could doubtless walk on all fours when on the ground.

In the Cretaceous, some of them increased greatly in size and became remarkably specialized for sustained flight, probably soaring over the sea in search of fish, as does the albatross, and seldom coming to rest. Of these *Pteranodon* (Fig. 123), whose remains are found in the Niobrara chalk of Kansas, had a wing-spread of about 24 feet, and so ranks as the greatest flying creature of all time. It had a birdlike,

toothless bill, and its hind limbs were dwarfed and degenerate. In spite of its great wings, the body was only about the size of that of a wild goose. In these grotesque reptiles everything had been sacrificed to flight, and it is not surprising that such extreme specialization led to their extinction before the close of the Cretaceous.

Reptiles that Went down to the Sea. The reptiles had hardly established their dominion over the lands, when certain groups began to invade the sea.

Of these, the *ichthyosaurs* (Gr. *ichthus*, fish, + *sauros*, reptile) were dolphin-like in appearance and streamlined for fast swimming (Fig. 124). The tail was gradually expanded into a broad, vertical fin, the tip of the spine being flexed down to serve as an axis for the lower fluke. The reason for this curious bend in the backbone was a puzzle until specimens were found with a trace of the flesh preserved as a carbonaceous film (Fig. 23, p. 40). The limbs, originally five-toed, were gradually modified into flippers like those of a seal or a sea turtle. They were undoubtedly fast swimmers, able to capture fish and the squidlike belemnites as well as ammonites. Indeed, the presence of some two hundred belemnite shells within the rib case of one Jurassic specimen bears witness to their insatiable appetite.

The ichthyosaurs were fully adapted to life in the sea and were already of large size in Triassic time, but they reached their zenith during the Jurassic when they varied in length from 5 to about 25 feet. They declined to extinction during the Cretaceous.

More like a mythical sea serpent were the *plesiosaurs* (Gr. *plesios*, almost, + *sauros*, reptile), which had a broad turtle-like body, a long neck, and long flippers (Fig. 124). Unlike the ichthyosaurs they were clumsy and slow, paddling their way like marine turtles. The long, agile neck partly made up for the clumsiness, however, permitting the plesiosaur to dart out his head to unexpected distances and seize fish or other prey.

Plesiosaurs appeared in the Triassic but were most common in the Jurassic. The largest ones lived in the Cretaceous seas, one of them having a length of 40 to 50 feet.

The *mosasaurs* were streamlined reptiles of the Cretaceous seas, not to be mistaken for ichthyosaurs, for their skin was scaled and their jaw structure shows that they were closely related to the lizards and snakes. Their tails were not fluked like those of the ichthyosaur. Their large conical teeth indicate that they were rapacious carnivores (Fig. 124).

The *turtles* constitute the fourth group of reptiles that went back to

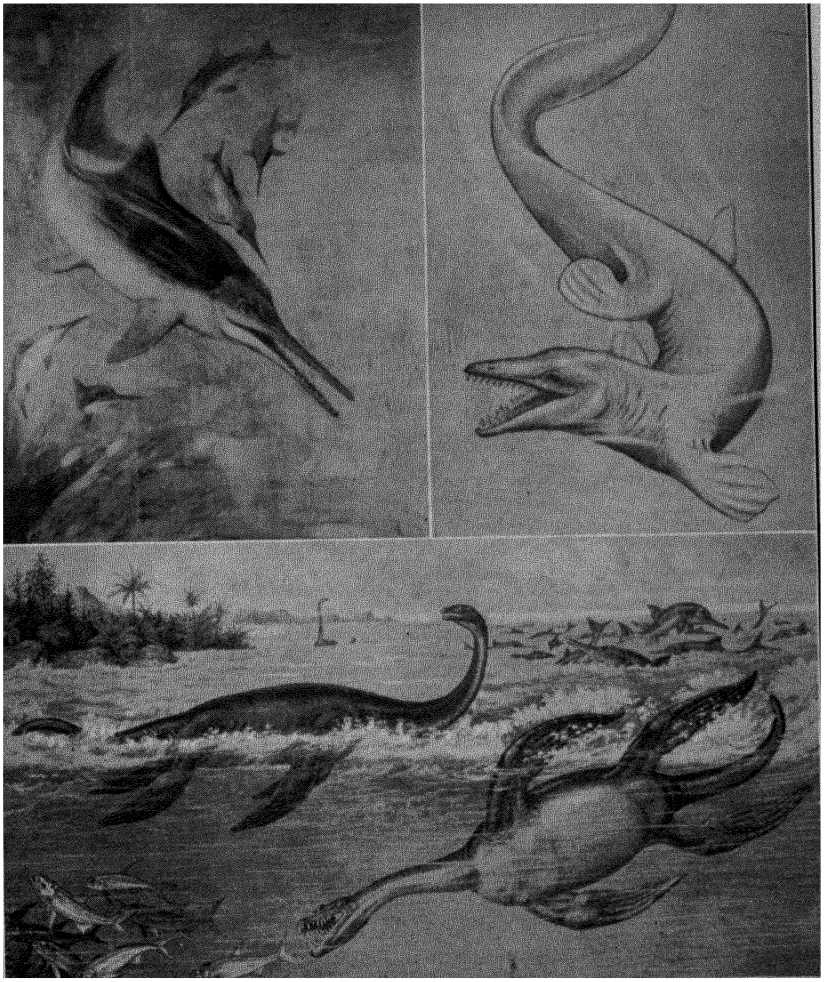


FIG. 124. Marine reptiles. Upper left, ichthyosaur with brood of young. From a painting by Charles R. Knight, in the American Museum of Natural History. Upper right, mosasaur from the Upper Cretaceous. After Williston. Below, plesiosaurs in the foreground, ichthyosaurs in the distance. After Fraas, from a painting in the Stuttgart Museum.

the sea and the only one that survived the close of the Mesozoic (Fig. 125).

TOOTHED BIRDS

Birds appear as fossils for the first time in Upper Jurassic rocks and represent one of the most remarkable advances that the life of

this period has to show. As yet only three specimens are known, and these are from the famous lithographic stone quarries about Solenhofen, Bavaria. Two of these are fine skeletons with impressions of the feathers. The third specimen is the impression of a single feather. The two skeletons seem to represent different genera and species, though both are about alike in size and general features.

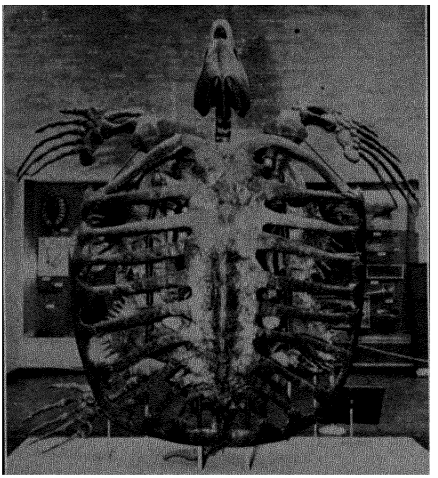


FIG. 125. Giant marine turtle, *Archelon*, from the Upper Cretaceous of Wyoming.

To the first-discovered bird was given the appropriate name *Archæopteryx* (Gr. *archaios*, ancient, + *pteron*, wing). It was a strange creature, more reptile than bird, and yet because of its feathers distinctly to be classed as a bird. It would be difficult to find a more perfect "connecting link" between two groups of animals, or more cogent proof of the reptilian ancestry of the birds.

Archæopteryx (Fig. 126) was about the size of a crow. Three remarkable features strike one at the first glance: (1) The jaws were set with a row of small teeth. These were not mere serrations on a horny beak but true conical teeth set in individual sockets like those of many reptiles. (2) In the wings the digits were not completely fused, and the first three still functioned as claws. (3) The tail was long and slender, with feathers diverging pinnately from its axis, not fanwise as in modern birds. The plumage was thoroughly birdlike, but the teeth, clawed wings, and long tail betray reptilian affinities.

In the Cretaceous, birds of three very distinct types are known, nearly all from the Niobrara chalk of Kansas. Two of these, like the Jurassic birds, had teeth. One (*Ichthyornis*) was a small shore bird about the size of a jack-snipe, having powerful wings; another was the large diving bird (*Hesperornis*) of which many skeletons have been found and several have been articulated into free mounts (Fig. 127). This remarkable bird, like the living penguin, was so perfectly adapted to life in the water that it had lost the power to fly and had only internal vestiges of wings. It reached a length

of nearly 6 feet, standing about 4½ feet high (if, indeed, it could stand at all).

It is obvious that these two highly specialized marine types do not fairly represent the bird faunas of the time. The land-living birds are still unknown except for a recently discovered toothless jaw. Their rarity is not surprising, because the bones of the bird skeleton are hollow and air-filled, and therefore so fragile as to require especially favorable conditions for preservation; as the birds die they fall upon the ground and are eaten by scavenging animals. Even in near-Recent deposits, birds are generally the rarest of fossils.

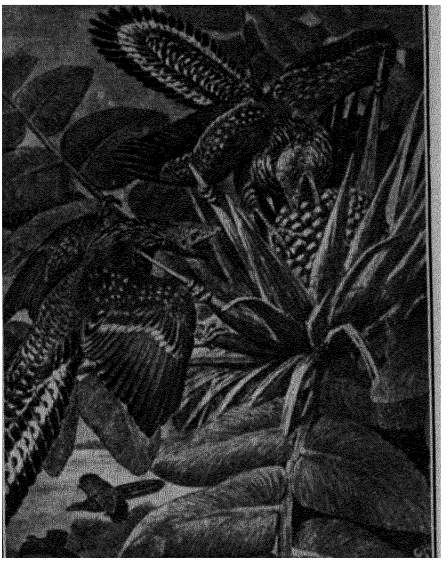
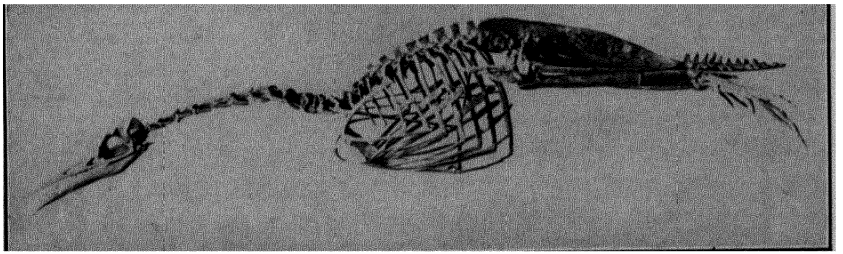


FIG. 126. The oldest known bird, *Archæopteryx*. Although here restored (by G. Heilmann) as feeding on fruit of the cycad, it was probably carnivorous. Upper Jurassic of Solenhofen, Germany. The bird was about the size of a crow.

THE FIRST MAMMALS

True mammals appeared just before the close of the Triassic period, but they were small, insignificant creatures, and their remains are among the rarest of all fossils. A few small jaw teeth from the



Yale Peabody Museum.

FIG. 127. The great diving bird, *Hesperornis regalis*, from the Niobrara chalk of Kansas, mounted in diving posture. Note long tail and vestigial wings. Over-all length about 4½ feet.

highest Triassic beds of Germany and England and a fragment of a small skull from South Africa embrace all that are known. They represent an extinct order.

Other types appeared in the Jurassic (Fig. 128), but none was larger than a very small dog and their remains are fragmentary, consisting mostly of jaws, isolated teeth, and pieces of limb bones. Nevertheless, they are represented in North America, Europe, and Africa and probably ranged over all the continents except Australia. So far as our knowledge of fossils permits of present judgment, it appears that

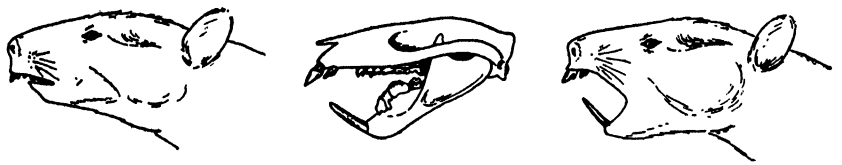


FIG. 128. A Mesozoic mammal, *Ctenacodon*, from the latest Jurassic of Wyoming, as restored by G. G. Simpson. Natural size.

Africa, and more especially South Africa, was the main seat of mammal origin. Most of the fossil remains have been found in association with dinosaurs. All the American forms have come from the Late Jurassic, and most of them from a famous dinosaur quarry at Como Bluff, Wyoming. The rest have been recovered mostly from Middle and Late Jurassic beds in England. Although small and unimpressive at the time, they represent the early development of the warm-blooded animals which now dominate the Earth, and the group to which man himself belongs.

In spite of their small size, these early mammals already showed marked specialization in their teeth, suggesting a wide variation in habits of life. Among the Jurassic species, four orders can be recognized, all originating in theriodont reptiles. All four of these early mammalian stocks are now extinct, but one of them appears to have given rise, during the Cretaceous, to the modern marsupials and placentals; the others died out without descendants. Although, on theoretical grounds, the obscure little egg-laying mammals (monotremes), now living in Australia and Tasmania, would seem to represent the most primitive possible stage of mammalian development, there appears to be no basis for the inference that the Jurassic mammals were also egg-laying. The monotremes may have developed independently of the other mammals out of ancient reptiles. Their geologic history is completely unknown.

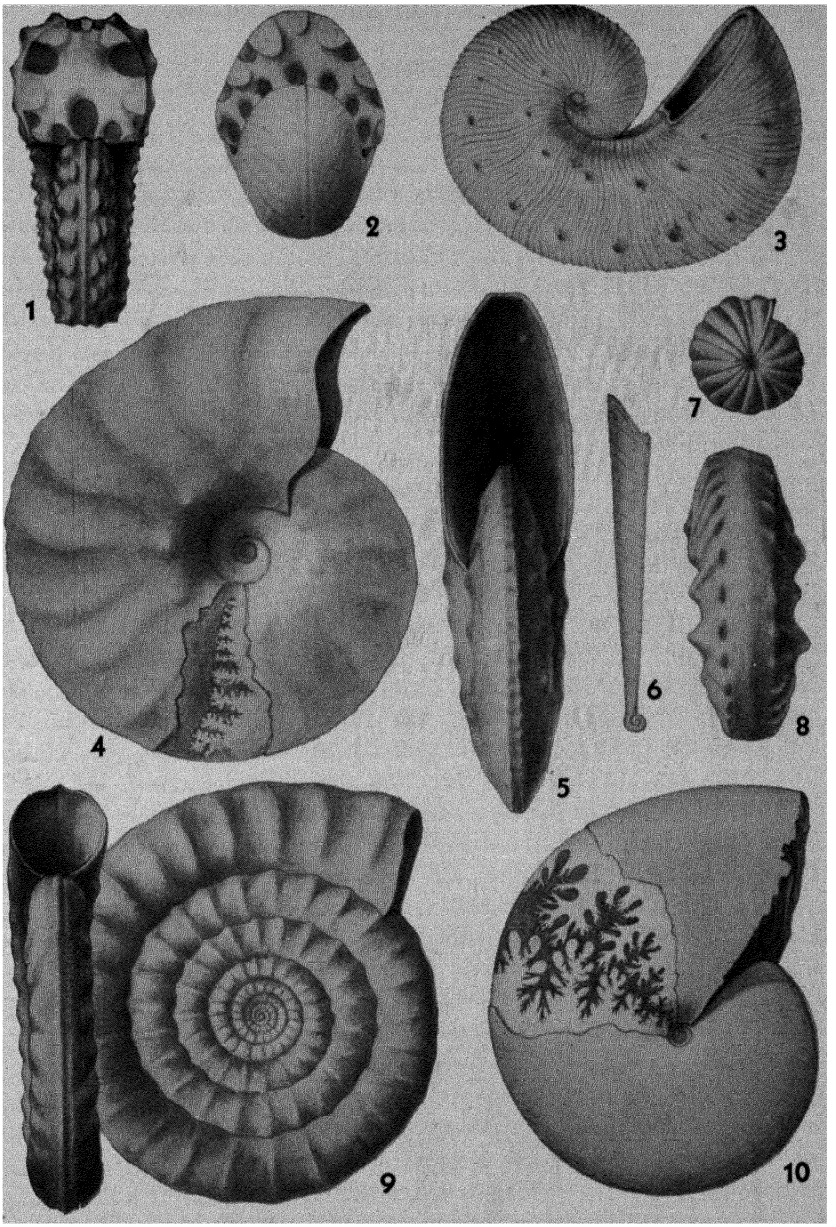


Plate 5. Mesozoic Ammonites.

Fig. 1, *Mortoniceras texanum*, × ½, edge view of a shell with living chamber broken away revealing last septum, Upper Cretaceous. 2, *Paratropites arnoldi*, Triassic. 3, *Scaphites nodosus*, 4, 5, *Placenticeras lenticulare*, × ½, lateral and edge views, and 6, *Baculites compressus*, a very young straightened ammonite, × 3, showing initial coiled stage, all of the Upper Cretaceous. 7, *Leconticeras californicum*, and 8, *Ceratites spinifer*, both Triassic. 9, *Echioceras raricostatoides*, and 10, *Phylloceras heterophyllum*, × ½, Jurassic. All natural size except as otherwise stated. Drawn by L. S. Douglass.

So long as the dinosaurs held their own, and the grasses, cereals, and fruits had not become generally distributed, the primitive mammals could only bide their time. Only one of the four Jurassic orders persisted into the Cretaceous, and it is represented at a number of places in the Rocky Mountain region by small unimpressive jaws and teeth.

During the Cretaceous, the *marsupials* (pouch-bearing mammals) and the *insectivores* (primitive placental mammals) were both present. The former were represented by forms remarkably like the living opossum, and the latter by several small forms like the shrew and the hedgehog. While the dinosaurs were still in their heyday late in the Cretaceous, other and still larger primitive mammals evolved in increasing abundance. Many of these types lived on into earliest Cenozoic time.

Invertebrate Life

Insects. Whether for good or ill, the insects play an important role in the modern world. As carriers of disease they make some parts of the earth dangerous for human habitation and impossible for certain of the domestic animals. They may in the past have played an unsuspected part in the extinction of large animals by transporting diseases like the sleeping sickness and malaria. But their presence is not by any means wholly obnoxious. As carriers of pollen, many insects are quite indispensable for the successful fruiting of some of the higher plants. The history of the insects is therefore not without interest.

Rapid changes were being made in the Triassic, and we see the rise of orders that undergo a metamorphosis while hibernating in a pupa or chrysalis stage. The Triassic record, however, is limited to a few isolated localities. From the Jurassic rocks about a thousand different kinds are known, and among these we note representatives of most of the modern orders: caddis-flies, scorpion-flies, dragon-flies, and beetles were common; grasshoppers, cockroaches, and termites also were present; and moths and flies made their appearance at this time.

In the Cretaceous rocks insects are not common fossils simply because suitable deposits have not been found, but from what is known it is certain that the chief modern types were then in existence and that insect evolution had been essentially completed by the end of the Mesozoic. Probably during the Cretaceous they adapted themselves to feeding upon the nectar of flowers and thus assumed their important role in the pollination of plants.

Shellfish. In many respects the marine invertebrates were essentially modern, even in the early part of the Mesozoic. Small lobsters appeared, for example, in the Triassic, and shrimps in considerable

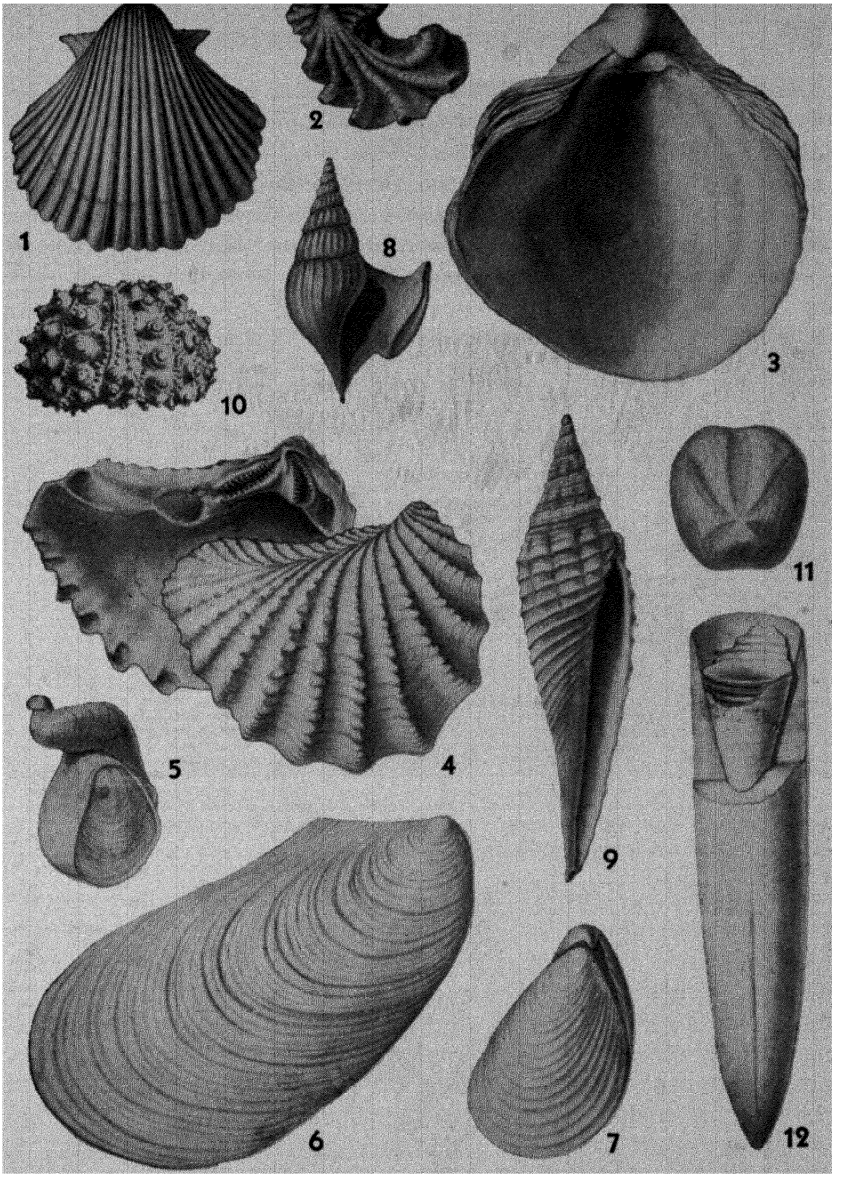


Plate 6. Mesozoic Invertebrates.

PELECYPODS: Fig. 1, *Pecten* (*Neithea*) *quinquecostata*, and 2, *Alectryonia placenta*, a ribbed oyster, both from the Upper Cretaceous; 3, the Lower Cretaceous *Gryphæa tucumcari*; 4, *Trigonia thoracica* (valves parted to show interior), of the Upper Cretaceous; 5, *Exogyra arietina*, of the Lower Cretaceous; 6, a characteristic form of the Upper Cretaceous, *Inoceramus labiatus*, × ½. 7, *Aucella piochii*, of the Jurassic. GASTROPODS: 8, *Anchura lobata*, and 9, *Volutoderma appressa*, both Upper Cretaceous in age. ECHINOIDS: 10, *Hemicidaris intermedia* of the Jurassic; 11, the Lower Cretaceous *Heteraster texanus*. BELEMNITE: 12, *Belemnites densus*, broken to show internal chambered shell, Jurassic in age. All natural size, except Fig. 6. Drawn by L. S. Douglass.

variety were added in the Jurassic. Crabs first became common in the Cretaceous. Corals of the modern families appeared in the Upper Triassic and were extensive reefmakers from the Jurassic onward. Clams and snails in great variety also closely resembled modern types (Pl. 6, Figs. 1–7). The distinctive character of the Mesozoic marine faunas, however, lies in the presence of two great groups now extinct, namely, the ammonites and the belemnites.

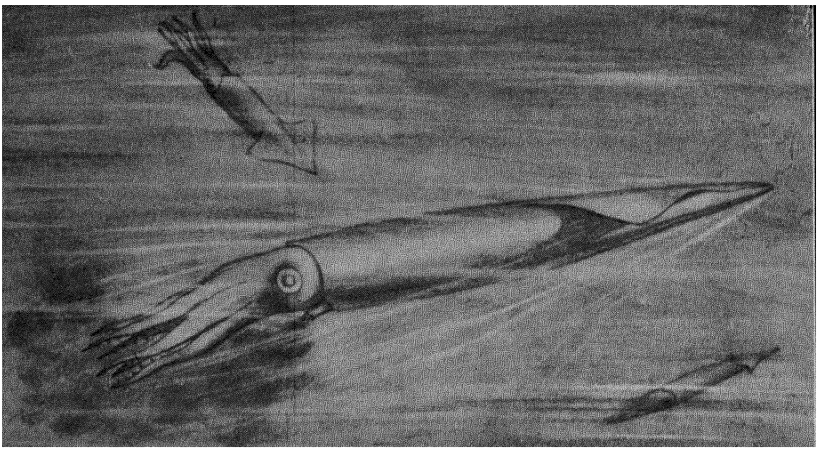


FIG. 129. Reconstruction of a belemnite, darting backward and discharging a smoke-screen of ink. Such animals ranged from a few inches to 5 or 6 feet in length. The internal shell of a belemnite is shown in Pl. 6, Fig. 12.

The *ammonites* (Pl. 5) were at once the most abundant and the most characteristic shellfish of the Mesozoic. Having descended from Late Paleozoic ancestors, they evolved rapidly in the Triassic, then declined suddenly at its close and multiplied enormously again in the Jurassic. Their thin and graceful pearly shells were commonly ornamented with ribs and nodes or spines, and were doubtless brightly colored in life, rare fossils preserving the color pattern. The fluting of the margins of the septa between the chambers in their shells underwent every possible variation and is the chief basis for the separation of many genera. Although normally neatly coiled like the shell of a pearly nautilus, several of the late Cretaceous types became partly uncoiled or spirally twisted like snail shells. All died out at the close of the Mesozoic.

The *belemnites* were squidlike animals with an internal shell of which the solid part is commonly preserved (Pl. 6, Fig. 12; Fig. 129); it is somewhat the shape of a cigar but has a deep, conical depression in one

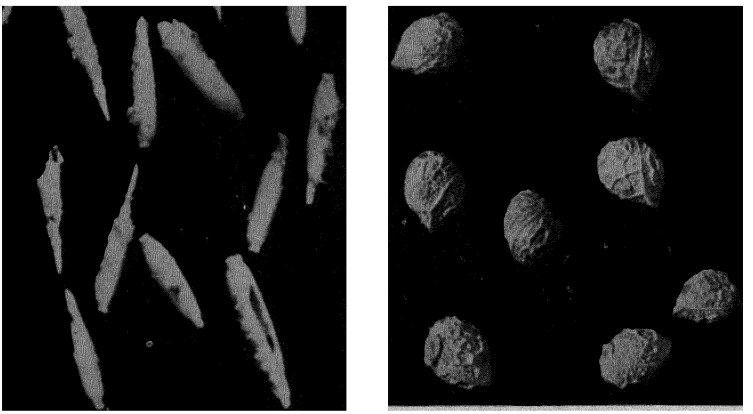
end. Rare specimens found in black shales of Lower Jurassic age in Europe show the form of the entire body and the arms, preserved as a carbonized film about the shells. They possessed an ink-sac like the modern squids and were, indeed, cousins of the true squids, which were evolving at the same time. Belemnites appeared in the Triassic, attained their greatest development in the Jurassic, and died out at the close of the Cretaceous.

CHAPTER 12

MAMMALS INHERIT THE EARTH

SPREAD OF THE PRAIRIES

The forests were essentially modern at the beginning of the Cenozoic era. Most of the genera of hardwood trees were represented in the Cretaceous, and subsequent evolution has been in the main a matter of specific details. Little is known, however, of the small, herbaceous plants.



M. K. Elias.

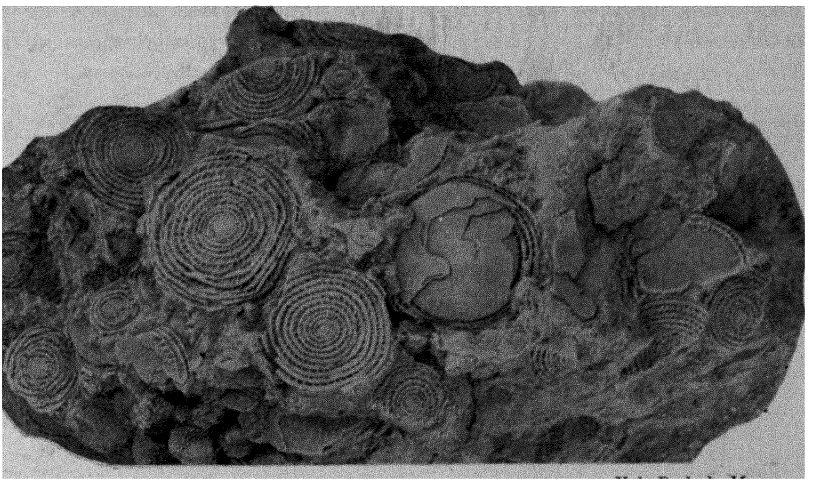
FIG. 130. Seeds of grasses and other herbs. Left, the spear grass, *Stipidium commune*, from the Pliocene (Valentine formation) near Wray, Colorado; right, the borage herb, *Biorbia fossilia*, from the Pliocene (Ash Hollow formation) near Castle Rock, Kansas.

Until recently the history of the prairies was known only from inference. Prairie grass is harsh food and tends to wear down the grinding teeth of animals that feed upon it. To make up for this, modern grazing animals, like horses and cattle, have high-crowned teeth (Fig. 135, p. 215) that grow out to replace the wear. But their Eocene and Oligocene ancestors, like all other early Cenozoic mammals, had low-crowned teeth. The rapid change from low- to high-crowned molars in many Miocene mammals has long been inferred to reflect the first spread of the grasses.

Within the last decade wonderfully preserved grass seeds (Fig. 130) have been found in the sands of middle and late Miocene and Pliocene

deposits of the High Plains, and now about thirty species are known. Since none have yet been found in lower beds of the same region, the fossil record now seems to confirm the inference drawn years ago from the adaptation seen in mammalian teeth, namely, that the grasses first spread over the plains in Miocene time.

It would be difficult to overestimate the importance of this step in the history of life. The tribe of the grasses includes not only the forage plants but the cereals and grains, such as oats and rice and corn and wheat, which form the basic food supply for the modern world.



Yale Peabody Museum.

FIG. 131. A chunk of nummulitic limestone from one of the pyramids of Egypt. Herodotus (about 450 B.C.) alluded to this stone as an instance of petrified animals. Natural size.

MODERNIZATION OF THE INVERTEBRATES

The invertebrate animals, like the plants, had practically accomplished their present evolution before Cenozoic time. A few of the modern species were already living in the Eocene epoch and many were extant in the Miocene.

Special note should be made, however, of the *nummulites*, a family of very large Foraminifera that formed discus-shaped, or coin-shaped, multichambered shells. These were extraordinarily abundant in the Eocene and Oligocene seas, and their shells contributed largely to the nummulite limestones that are widely distributed in southern Europe, northern Africa, and the Himalayan region. In the Mediterranean countries, the Eocene is still commonly spoken of as the Nummulitic period.

Decline of the Reptiles

With the extinctions at the close of the Mesozoic, the reptile dynasty collapsed. Turtles, crocodiles, and lizards lived on through the Cenozoic about as they are today, except that large land turtles and alligators were more widely distributed during the warmer times. Large land turtles are abundant fossils in the badlands formations of Oligocene and Miocene age. Enormous species, much like the modern Galapagos turtles, but large enough to stand waist-high to a man, were common in Florida in Pleistocene time. As noted before, alligators occur frequently in the Eocene and Oligocene deposits as far north as Wyoming and the Dakotas. Snakes are first recorded in the Late Cretaceous and therefore existed throughout the Cenozoic, but, because of their retiring habits and their delicate skeletons, they are always rare fossils. An Eocene species estimated to be 35 feet long was found recently in Patagonia. It is related to the modern boa constrictor.

Birds

Modern types of birds, all toothless, appeared in the Eocene, and even at that early date most of the modern orders were represented. Such, for example, were the eagles, vultures, pelicans, quail, and various shore birds. The many kinds of birds persisted through the Cenozoic, though fossil remains are, in general, rare because of the fragile nature of the bird skeleton.



Fig. 132. *Phororhacos*, a giant flightless bird of the Miocene of Patagonia. Painting by Charles R. Knight. From Lucas, *Animals of the Past*.

Nearly all the continents at one time or another during the Cenozoic had large, flightless, ostrich-like birds. One of these (*Diatryma*), known from the early Eocene beds of Wyoming, stood nearly 7 feet high and had a very stout neck and a head almost as large as that of a horse. Another (*Phororhacos*), found in the Miocene of the Argentinian pampas, stood 7 to 8 feet high and had a skull 23 inches long (Fig. 132). It had a strongly hooked beak and was undoubtedly the

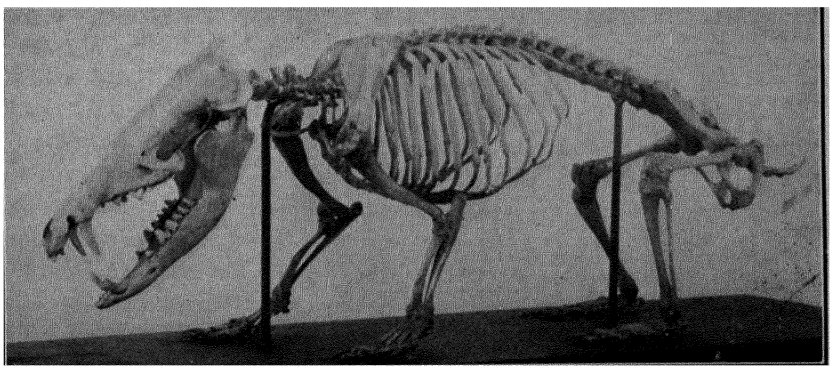
greatest of all birds of prey. The largest of all birds, however, was *Dinornis*, one of the moas, which lived into historic time in New Zealand and was exterminated by the Maoris only a few centuries ago. This enormous bird stood about 10 feet high and was therefore more than 2 feet taller than the greatest living ostrich. Still another giant (*Æpyornis*) of Madagascar laid the largest known eggs, measuring 13 inches long and 9 inches across. Discovery of the eggs of this bird by early navigators inspired the thrilling tales of the roc related by Sindbad the Sailor in the *Arabian Nights*.

MAMMALS COME INTO THEIR OWN

Immediately upon the extinction of the dinosaurs, the lowly mammals swept into dominance over all the world. At first they were small and rather feeble creatures, but their spectacular evolution soon eclipsed all other forms of life and made the Cenozoic the *Age of Mammals*.

Symbols of Progress

The first and most primitive mammals without a doubt resembled the modern hedgehog (Fig. 133) in the following essential respects: (1) they were small; (2) they were short-legged and flat-footed, walking



Yale Peabody Museum.

Fig. 133. Skeleton of the modern tenrec, a primitive and generalized mammal closely allied to the hedgehog. About 2/5 natural size.

on the soles instead of the ball of the toes; (3) they had five toes on each foot; (4) they had 44 teeth, of which all but the canines were low-crowned; (5) their brains were small and their intelligence of a low order; and (6) they were long-faced, because the jaws exceeded the brain

case in size. From ancestors of this sort all the varied mammals of the modern world have evolved. In this development four major trends can be detected in nearly every group:

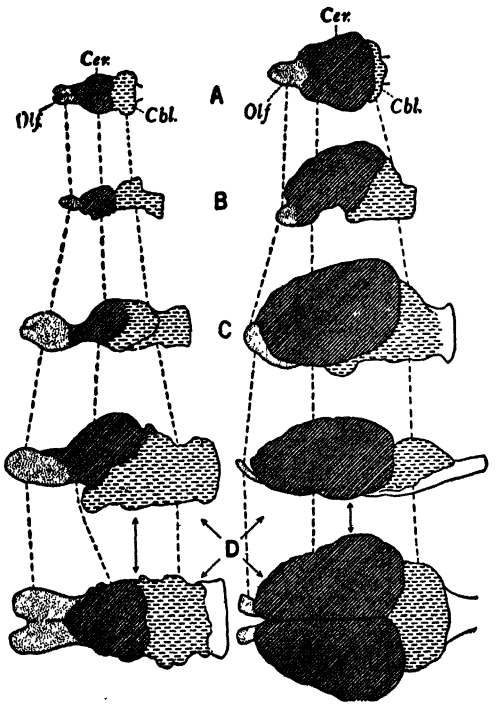


FIG. 134. Brains of archaic mammals (left) and modern mammals (right), paired so that the brains of animals having equal body size are side by side. Note that in each instance the brain of the modern mammals is the larger, and that the difference is due mostly to the greater size of the cerebrum which is the seat of memory and reason. The olfactory lobes are stippled, the cerebrum obliquely lined, and the cerebellum marked by broken lines. A, *Arctocyon* (left) and *Canis* (the dog); B, *Phenacodus* (left) and *Sus* (the swine); C, *Coryphodon* (left) and *Rhinoceros;* D, *Uintatherium* (left) and *Hippopotamus*, lateral and dorsal views. After H. F. Osborn.

(1) *Increase in size* was marked in every order. The ancestor of the horse was no larger than a fox, the earliest elephant was not waist-high to a man, the first primates were smaller than an organ-grinder's monkey; in short, every group of the large animals started small and increased gradually to a maximum stature.

(2) *Increase in brain power* has been achieved by every surviving stock of mammals. This involves an increase in size of brain that is not only actual but relative to the bodily weight. Fig. 134 shows graphically the relative sizes of brain in several Early and Late Cenozoic animals that would compare closely by pairs in bodily form and size. The change is, moreover, more than one of size. In the primitive mammals the bulk of the brain is formed of those parts that have to do with the purely physical senses, whereas in modern and highly specialized types these parts of the brain are secondary to the cerebrum or upper brain in which lie the centers of memory and intellect.

(3) *Specialization of the teeth* according to feeding habits has been great in those groups that use special types of food. The primitive mammalian jaw tooth was small and low-crowned (Fig. 135, *a* and *b*), its full growth being attained in a short time. Omnivorous animals

like the bear, swine, and man retain the short crown and have low, blunt cusps. Carnivores, on the contrary, have developed fangs for tearing, and shearing teeth in the jaws for efficient cutting of flesh. The most remarkable specializations are seen, however, in the grazing (grass-feeding) animals of the prairies. In these the enamel became deeply infolded and the crown high and prismatic, as growth continued throughout life to replace the wear at the surface (Fig. 135, *c* and *d*). Efficiency was attained by developing deeper crowns, greater grinding surface, and more elaborate infolding of the enamel. It is remarkable that the fundamental pattern of the infolding enamel differed in the main stocks of mammals and yet persisted in each line, so that it is almost as easy to identify the family by a single jaw tooth as by all the rest of the skeleton.

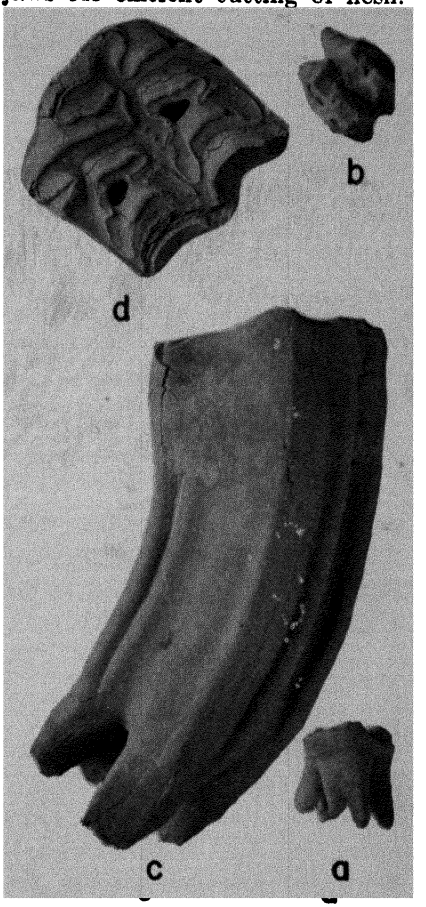


FIG. 135. Low- and high-crowned molar teeth. *a,b*, oblique-lateral and crown views of a left upper molar of a swine; *c,d*, same views of a comparable molar of a horse. The crown is much shorter than the roots in the swine, but many times as high in the horse. Natural size.

(4) *Specialization of the feet* has been great in those stocks that use the feet for highly specialized functions. In tree-dwelling types like the monkeys and squirrels, prehensile hands and feet have been developed. In many of the carnivores, sharp, curved claws have been produced to aid in the capture and holding of prey. But again, the highest specialization is shown by the hoofed mammals of the plains in which locomotion is the only function of the limbs, and fleetness of foot commonly the greatest safeguard of life. These animals have sacrificed everything else for the ability to run.

In swift running almost all animals rise on the toes, for this gives a longer stride. Animals adapted to running thus stand permanently up on the ball of the foot (as does a dog) or even on the very ends of

the toes (as do all hoofed mammals). Concomitantly, the foot tends to lengthen and the powerful leg muscles to concentrate near the body where they can manipulate the limbs without sharing fully in their motion. The graceful limb of a horse or a deer shows the acme of this developmen' and presents a striking contrast to that of a bear, which has specialized almost not at all (Fig. 136).

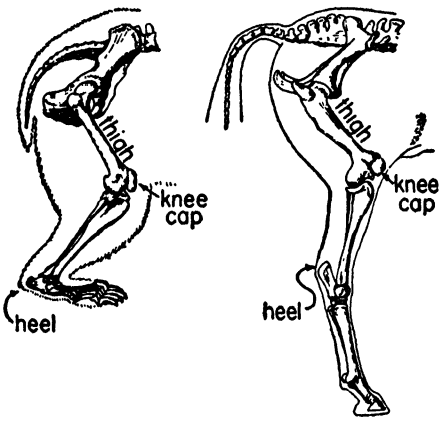


FIG. 136. Hind limb of bear (left) and horse, showing correspondence of parts.

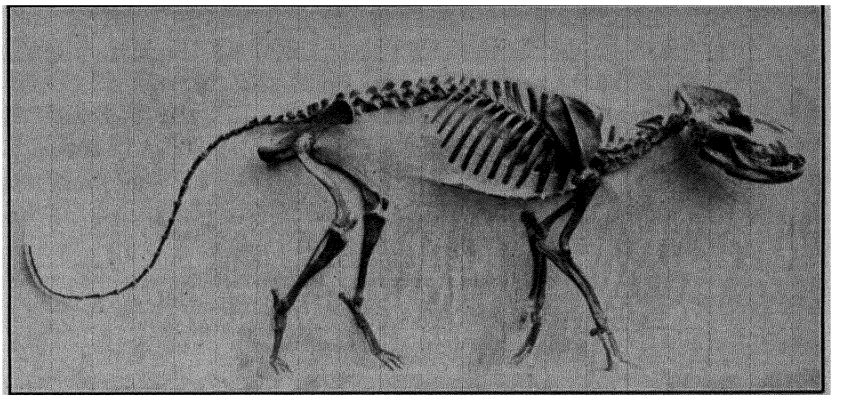
The rise to the end of the toes led in turn to the degeneracy and loss of the side toes, for the middle digits are naturally and primitively longer than the others and thus bear the weight when the animal rises on its toes in flight. The Cenozoic record of the evolving mammals shows the most convincing evidence of the gradual reduction and loss of the outer digits in the several families of hoofed mammals. The reduction from five toes to one toe in the horse is a classic and well-known illustration (Figs. 139, 141).

THE PALEOCENE VANGUARD

With the coming of the Cenozoic, the mammals expanded like a race delivered from bondage. In the Paleocene seven distinct orders were represented, the marsupials, insectivores, primates, rodents, creodonts, amblypods, and condylarths. It is notable that all these were small, the largest not exceeding the size of a large hog.

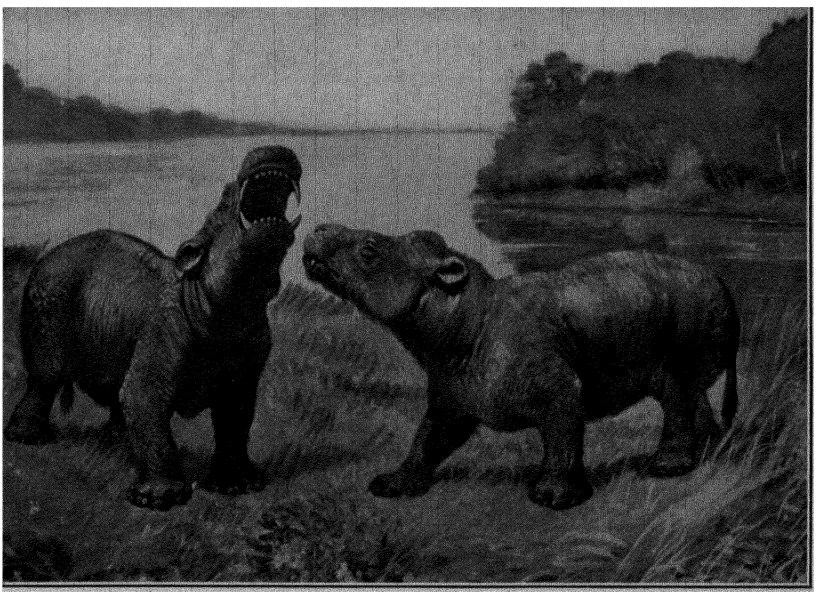
The *marsupials* were essentially like the modern opossum and at this time were possibly worldwide, reaching even the continent of Australia, where they later developed into the amazing and highly varied Australian fauna of pouch-bearing mammals, including the kangaroo. Outside of Australia the marsupials have never competed successfully with more progressive types and have never risen above the modest and retiring role played by the living opossum.

Insectivores are likewise small and unprogressive mammals with limited capabilities for evolution. They appeared in the Cretaceous and persisted through the Cenozoic as small, retiring, and altogether unimpressive creatures such as the moles, shrews, and hedgehogs.



Yale Peabody Museum.

FIG. 137. Skeleton of a creodont, *Dromocyon vorax*, from the Eocene (Bridger) of Henrys Fork, Wyoming. Animal about the size of a large dog.



American Museum of Natural History.

FIG. 138. Restoration of *Coryphodon*, an amblypod from the lower Eocene of Wyoming. From a painting by Charles R. Knight.

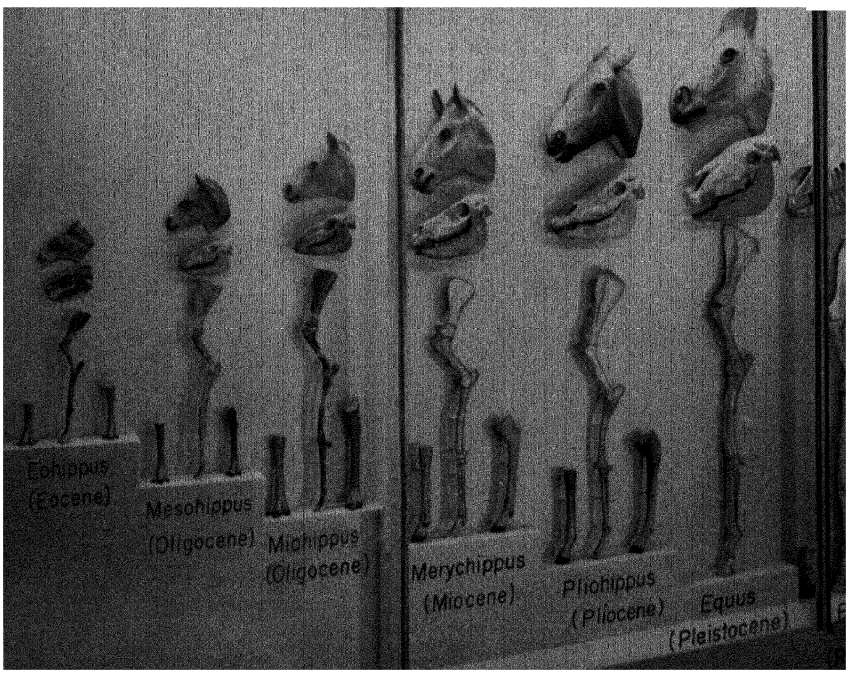
The *primates* are represented in the Paleocene by small and very rare lemurs. *Rodents* are also rare, but one small squirrel-like form was recently discovered.

The dominant mammals of the Paleocene, and all the larger forms, belong to three groups that are now extinct. The first of these were the *creodonts* (Fig. 137), the precursors of the true carnivores. Although differentiated into catlike and wolflike types, some had strangely blunt, inefficient teeth and blunt toes lacking claws. Their brains, moreover, were less than half the size seen in modern carnivores of corresponding stature. They must have been stupid brutes, and it is not surprising that nearly all of them perished before the close of the Eocene. One small progressive group, however, later evolved into the modern carnivores, giving rise to the cats and dogs. Most of the creodonts were not larger than wolves and all were small in the Paleocene, but in the Oligocene of Mongolia there was a giant (*Andrewsarchus*) the skull of which was about 2½ feet in length.

The two remaining groups were herbivorous animals, the *amblypods* being heavy-bodied like the modern pachyderms, the hippopotamus and the rhinoceros. They were represented in the Paleocene by small creatures not larger than a sheep. They persisted into the true Eocene,

YALE PEABODY MUSEUM.

Fig. 139. Evolution of the horse, as shown by limbs and skulls recovered from successive horizons in the Cenozoic rocks.



where they were represented by *Coryphodon* (Fig. 138), thick-bodied animals as much as waist-high to a man; and in the late Eocene they developed into the *uintatheres*, the largest land animals of their time, rivaling an average circus elephant in bulk. Even the last and greatest of these amblypods were defective in having relatively small, short cheek teeth, stubby feet, and very inferior brains. They died out without descendants about the close of the Eocene epoch.

The remaining order, the *condylarths*, were lighter-bodied herbivores less easily characterized than the amblypods, which they resembled in having small brains, poor teeth, and inadaptive feet. This tribe died out about the middle of the Eocene epoch.

The Modernized Mammals Arrive

At the base of the Eocene, in both the United States and Europe, the ancestors of the horse, the rhinoceros, and other modern stocks of mammals made a sudden appearance, soon overwhelming the archaic types of the Paleocene and relegating them to a place of inferiority. This sudden advent implies that the modernized stocks had been evolving somewhere in the northern land masses and at this time migrated into Europe and North America. Their development from this stage on constitutes one of the most fascinating chapters in the history of life.



American Museum of Natural History.

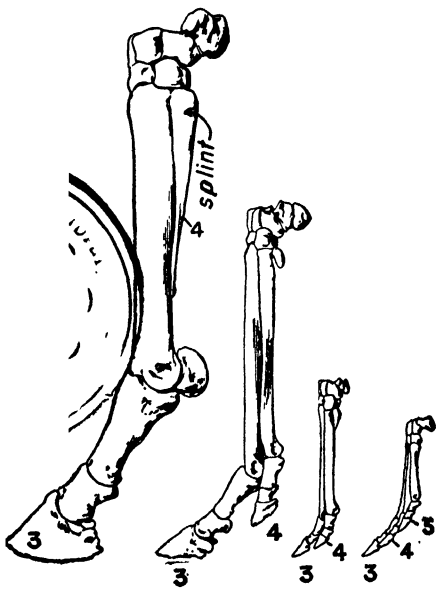
Fig. 140. *Eohippus*, the "dawn horse," from the Eocene (Wind River). Restoration by Charles R. Knight. This horse was about a foot high at the shoulders.

Eohippus, the Dawn Horse, and His Progeny. The horse was a native of North America from early Eocene time onward and underwent most of its development here, spreading in Miocene time to other continents. Skeletons assembled from successive horizons show a record of gradual evolution in teeth, limbs, feet, and size hardly equaled for any other stock of animals. The record is graphically shown in Fig. 139.

Eohippus, the "dawn horse," oldest member of the race, was a small, graceful animal, scarcely a foot high, with a slender face, arched back, and long tail (Fig. 140). Its hind feet had three toes, and its front

feet four toes. Vestiges of still other toes indicate clearly that its Cretaceous ancestor possessed five toes all around, though no five-toed horse has yet been discovered.

The evolution that followed was long and complicated, but it may be epitomized by noting three intermediate stages between *Eohippus* and the modern horse, *Equus*. *Mesohippus* of the Oligocene was about the size of a sheep. It had three toes on each foot, and these all touched the ground, sharing equally in the animal's weight. The teeth were still short and simple. *Merychippus* of the Miocene grew to the size of a small pony. Although it still possessed three toes on each foot, the middle toe was much heavier than the others, which dangled like the "dew-claws" of cattle, failing to touch the ground. The jaws had now lengthened and deepened appreciably, and the molar teeth were becoming deep and prismatic, to provide for wear by the harsh grasses on which it fed. *Pliohippus* of Pliocene time was the first one-toed horse. It attained the height of a pony and had high-crowned teeth and long jaws like a modern horse. The side toes were represented only by a pair of splint bones lying alongside the cannon bone, but the lateral toes had completely disappeared externally. The modern horse, *Equus*, appeared about the close of the Pliocene epoch and during the Pleistocene was represented in America by no fewer than 10 species, one of which fully equaled in size the greatest modern draught horse, while another was as small as the Shetland pony. These wild horses roamed the American plains in great herds until late in the Pleistocene and then, for some reason unknown (possibly an epidemic like the modern hoof-and-mouth disease or the African sleeping sickness, they became extinct. Fortunately, however, the horses had found a Miocene land bridge (probably via Alaska and Siberia) into the Old World, where they



American Museum of Natural History.

FIG. 141. Lower fore limbs of fossil and modern horses, illustrating four stages in the evolution of the one-toed limb. The numbers indicate the correspondence of the digits. From right to left: *Eohippus* of the Eocene epoch, *Mesohippus* of the Oligocene, *Merychippus* of the Miocene, and *Equus* of the Recent.

survived to become a servant and friend of man. The present American wild horses are descendants of those brought over by the Spaniards.

Rhinoceroses. The rhinoceros is also primarily of North American stock. The group first appeared near the beginning of the Eocene and by early Oligocene time had become numerous and varied and had specialized into three tribes: the *running rhinoceroses,* which were small, light-bodied, and fleet-footed; the *amphibious rhinoceroses,* which anticipated the habits of the hippopotamus and became thick-bodied and very short-legged; and the *true rhinoceroses,* which developed gradually into modern types (Fig. 142). The first two stocks died out in the Oligocene, but true rhinoceroses were very common in the Great Plains region in Miocene time, declining to extinction in the Pliocene. Only those which had passed into the Old World survived.

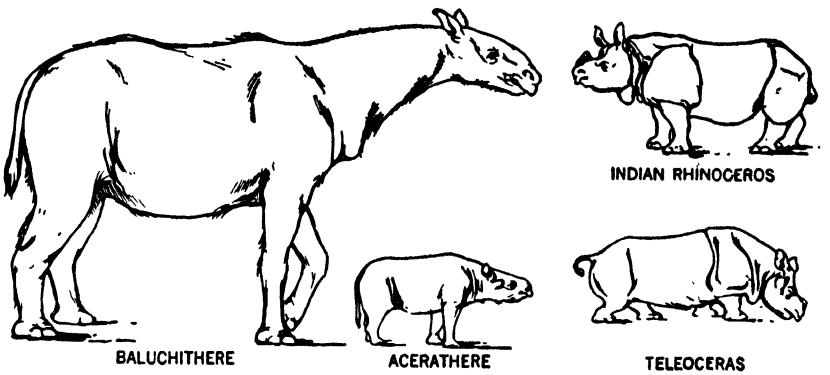


FIG. 142. Rhinoceroses, restored to scale, to compare certain fossil types (facing right) with the modern Indian rhinoceros. *Aceratherium* was a primitive, hornless type, of Oligocene date; *Teleoceras* was a short-legged type from the Miocene; and *Baluchitherium* was a giant from the Miocene (possibly Oligocene) of Asia. Adapted from H. F. Osborn.

It is significant that the early rhinoceroses were small and hornless. The Oligocene species were not larger than a modern tapir, i.e., less than waist-high to a man. In America few of the Cenozoic forms attained the size of a large modern species, but in southern Asia a Miocene or Oligocene rhinoceros (*Baluchitherium*) reached the incredible height of 13 feet and a length of 25 feet, possessing a skull about 5 feet long. It was apparently the greatest land mammal of all time (Fig. 142).

Titanotheres. These constituted a magnificent tribe of Early Cenozoic mammals remotely related to the rhinoceroses and the horses. Like the former, they were ponderous beasts with very large heads bearing nasal horns. Unlike the rhinoceroses, however, whose horns are made of agglutinated hair, the titanothere had horns that were

laterally paired bony processes from the skull. The earliest titanotheres, like *Eotitanops* of the early Eocene, were small animals hardly larger than a big hog, and they were hornless. The tribe advanced rapidly in size, however, attaining a spectacular development during the early Oligocene in the Great Plains region just before their sudden extinction. One of the latest and largest of them, *Brontotherium* (Fig. 143), stood about 8 feet high at the shoulders and far outbulked the largest living rhinoceros. During early Oligocene time this was one of the largest types of land animal.

The titanotheres are known only from the United States, Mongolia, and Europe. They left no descendants, either collateral or direct. Their front feet bore four toes and their hind feet three, further reduction being inhibited by their great weight.

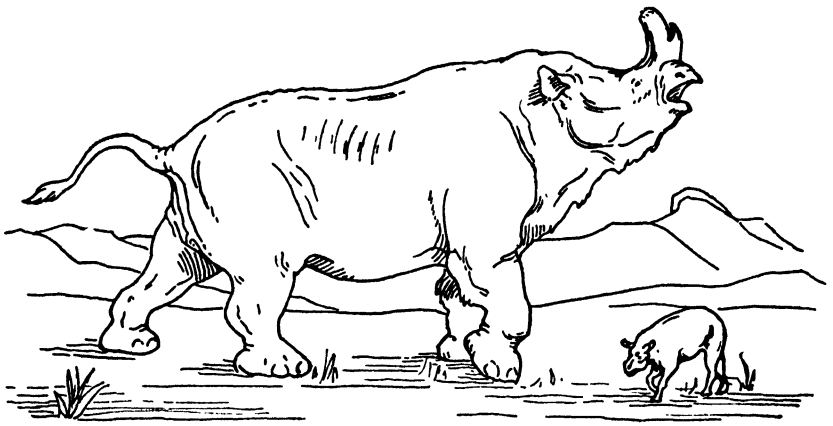
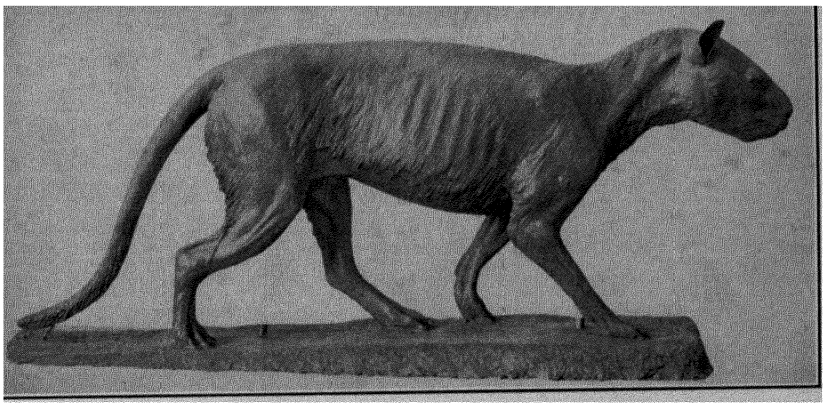


FIG. 143. First and last of the titanotheres. Right, *Eotitanops*, of the Eocene; left, *Brontotherium*, of the Oligocene. The latter stood about 8 feet high at the shoulders.

Camels. Of the even-toed or "cloven-hoofed" mammals (Artiodactyla) the Cenozoic had several great tribes such as camels, oreodonts, giant pigs, and deer.

Camels appeared as early as the Eocene and in their long evolution ran a course remarkably paralleling that of the horse. One of the earliest genera was a slender little four-toed creature, scarcely larger than a jack-rabbit, associated with *Eohippus* in the late Eocene of the Cordilleran region. By Oligocene time there were camels as large as sheep associated with *Mesohippus*. These already displayed their true relationship by the peculiar carriage of the head and by the enamel pattern of the teeth. The toes were then reduced to two on each foot, but they were still free.

In Miocene time, camels underwent a spectacular diversification, one race becoming very tall and long-necked, like the giraffe, while some remained small and graceful and others resembled the modern dromedary. By this time the upper toe bones had become greatly elongated and fused to form the cannon bone. The teeth were fast becoming prismatic and high-crowned, and the skull had taken on a typical cameloid contour. Cameloids persisted in this country until the close of the Pleistocene, and a skull of an extinct species, found, with dried flesh still preserved, in a cave in a postglacial lava flow in Utah, seems to imply the persistence of wild camels until the Recent epoch, though none were extant within historic time.



Yale Peabody Museum.

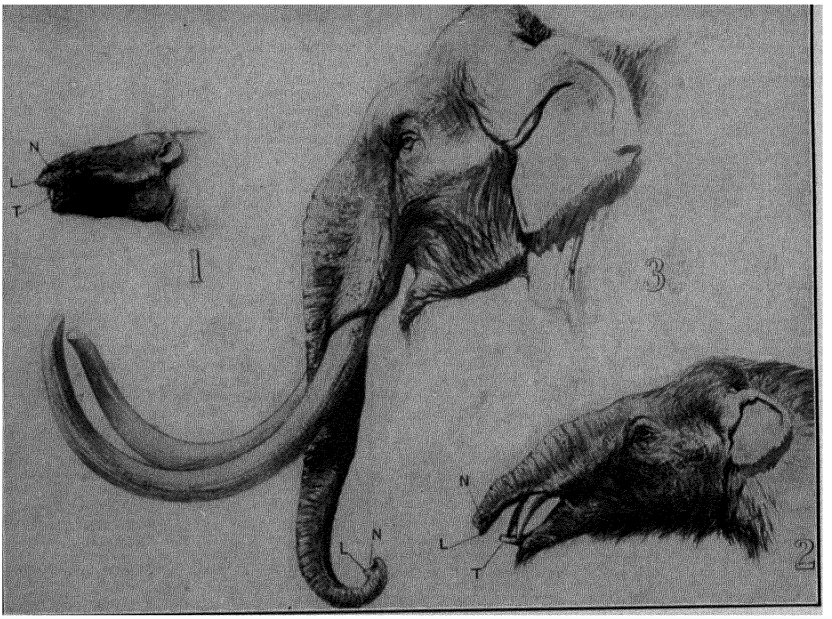
FIG. 144. An oreodont, *Merycoidodon gracilis*. Model by Richard S. Lull, based on a skeleton from the Oligocene (White River beds) of Sioux County, Nebraska. The animal was about as tall as a sheep.

Oreodonts, a Lost Tribe of the Plains. One of the most abundant and most characteristic mammals of the Early Cenozoic epochs in western America was the oreodont (Fig. 144). These were small creatures not closely allied to any living types and therefore difficult to characterize in nontechnical terms. They were four or five-toed, short-legged and generally long-bodied animals of somewhat the proportions of swine, but their teeth and skulls belie this superficial resemblance. They were grazers and cud-chewers, and, if we may judge by the remarkable abundance of their remains, they roamed the prairies in vast herds.

Although they persisted from late Eocene to early Pliocene time, the oreodonts were in many respects the least progressive of the great groups of mammals. For example, they remained four-toed

and short-footed, none of them became larger than a hog, and none showed marked tooth specialization. Apparently they were confined to North America.

Deer and Cattle. Unfortunately, it is not yet possible to present a connected account of the geologic history of the deer and cattle. Apparently their evolution was largely accomplished in parts of the Old World that have not been adequately studied. Certain types of deer



American Museum of Natural History.

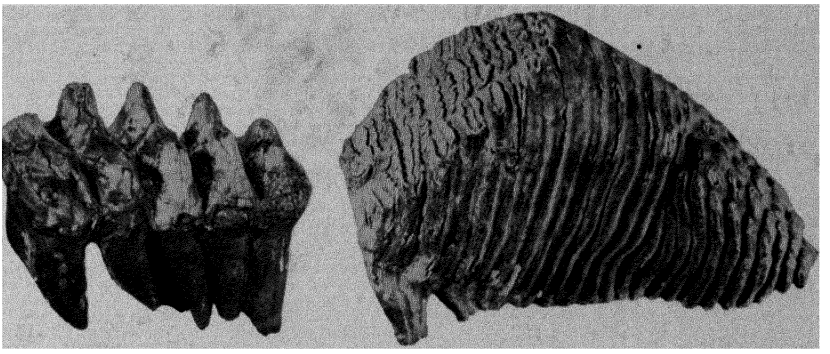
FIG. 145. Reconstruction of proboscidean heads showing stages in the development of tusks and trunk. 1, *Mœritherium* (early Oligocene); 2, *Phiomia*, a mastodon (Oligocene); 3, *Elephas* (Recent). *T*, incisor teeth; *L*, upper lip; *N*, nostrils. After a drawing by Charles R. Knight.

are represented in the American Cenozoic, but the record is not impressive. Musk-ox and buffalo were present in Pleistocene time but apparently both were migrants from the Old World.

Elephants and Their Kin. The modern elephants represent an order of mammals characterized by the possession of a proboscis or "trunk." Powerful and keenly intelligent as they are, the elephants migrated widely during the Cenozoic and adapted themselves to a great variety of habits and conditions, evolving into more than a dozen well-defined stocks. Since the race is now verging on extinction, it is difficult to realize that they were not only one of the most spectacular groups of Cenozoic mammals but also one of the most abundant and most diversified.

The elephants made their first appearance in America among the Miocene immigrants from the Old World. The oldest fossils are found in the Fayûm Desert of Egypt, and that now appears to have been their ancestral home. The Eocene and Oligocene beds of the Fayûm are delta deposits of the ancient Nile, formed at a time when the climate was humid and the region timbered.

The oldest and most primitive proboscidians known were small, squatty, partly amphibious animals that lived on the Nile delta during late Eocene and early Oligocene time. The typical genus, *Mœritherium* (Fig. 145), grew to a height of 2 or 3 feet and possessed neither tusks nor trunk. It was long-faced, had numerous molar teeth, and undoubtedly looked more like a tapir than an elephant. The second



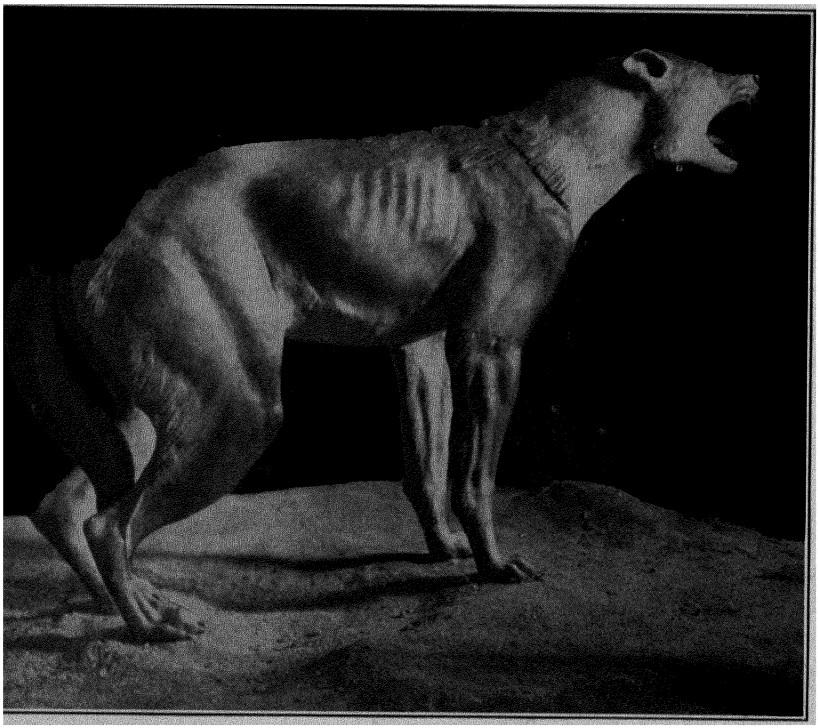
Yale Peabody Museum.

FIG. 146. Mastodon tooth (left) and mammoth or elephant tooth (right). About ¼ natural size.

pair of incisors, however, had a band of enamel on the front side and were considerably extended; these are the teeth that developed into the tusks of all later proboscidians. Moreover, the molars of the mœritheres had an enamel pattern that betrays their relation to the next younger proboscidians.

The *mastodons* constitute another race that may have sprung from the mœritheres and in turn gave rise to the true elephants. They are characterized by molar teeth with relatively few conical or nipple-shaped cusps (Fig. 146), whence the name (Gr. *mastos,* breast, + *odous,* tooth). Of these, the oldest known, *Palæomastodon,* lived on the Nile delta in later Oligocene time. Although it had the proportions of a small elephant, it was scarcely more than shoulder-high to a man and, unlike the modern elephant, had a long face and a short trunk. Moreover, its jaw teeth were all functional at once whereas in the elephant they succeed one another in order so that only one at a time is normally functional in each half of the jaw.

This small mastodon was the first of the elephants to migrate into Eurasia. During Miocene time its descendants became larger and developed a longer trunk and larger but fewer jaw teeth. At this time they migrated over Europe and Asia and crossed by the Siberia-Alaska land bridge into America (Fig. 150). They persisted in the forests until the very close of the Pleistocene in North America and in Europe as well. *Mastodon americanus* must have been fully as common in the eastern United States during the Pleistocene epoch as the modern elephant is in India or East Africa (Fig. 151).



Yale Peabody Museum.

FIG. 147. The dire wolf, *Canis dirus*, a common species in the asphalt pits at Rancho La Brea, near Los Angeles, California. Size about that of a modern timber wolf. Pleistocene. Modeled by R. S. Lull.

The *true elephants* are distinguished from the mastodons by the plate-like folds of the enamel in the molar teeth (Fig. 146). This makes a more efficient grinding surface and is especially characteristic of the elephants that assumed a grazing habit. The true elephants developed out of mastodons in the Pliocene and with the latter migrated widely, increasing in size during the Pliocene and Pleistocene epochs until they commonly reached the stature of an average circus elephant.

Meanwhile the trunk was perfected and elongated, the tusks greatly enlarged, and the molar teeth reduced in number but individually enlarged. The climax of their evolution was attained only in Pleistocene time, when elephants were fully as common in North America and Eurasia as they are now in East Africa, and their habits far more di-

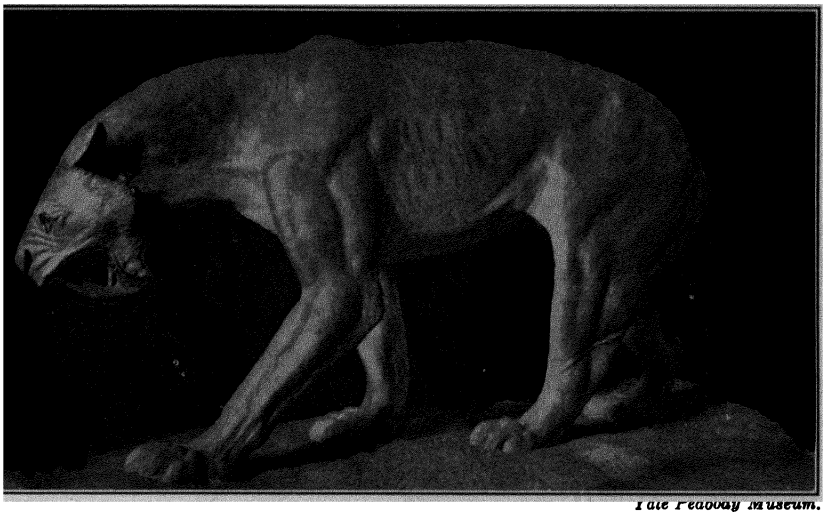


FIG. 148. The great saber-toothed tiger, *Smilodon*, also common in the asphalt pits at Rancho La Brea, near Los Angeles, California. Height about 3 feet. Pleistocene. Modeled by R. S. Lull.

versified. At this time, for example, the *imperial mammoth* was at home on the arid plains of western Texas, while the *woolly mammoth*, protected by a thick coat of brownish wool, was roaming about and in front of the ice sheets in North America and Europe and was particularly common in the bleak tundra of the Arctic. This is the species of which frozen carcasses have been found in Siberia (Fig. 17, p. 35). The imperial mammoth was the tallest of all elephants, standing 13 to 14 feet high. It also bore the noblest of all tusks, which reached the exceptional length of 13 feet and must have weighed several hundred pounds apiece; a pair of tusks of this species in the Yale Peabody Museum weigh, in their fossilized state, almost half a ton.

Carnivores. A flesh-feeding animal must make almost daily kills, and therefore must be greatly outnumbered in any region by its prey. This is one of the reasons why the geologic record of the carnivores is so scanty in comparison with that of the herbivores. A further cause is the fact that flesh-feeders hunt in pairs or in small packs and usually die singly. Finally, they are wary and alert enough to escape common catastrophes such as miring and drowning. Hence their remains are relatively scarce and commonly occur as isolated skeletons.

The Eocene history of the carnivores is still very imperfectly known, but by Oligocene time catlike and doglike forms were well differentiated though still small. From this time on the dogs specialized for a running pursuit of their prey, which they cut down by slashing and snapping. The cats, on the contrary, adopted the habit of lying in ambush and then springing upon their prey to hold and kill it by crushing. Hence the cats developed retractile claws and short, powerful jaws, while the dogs retained simpler, blunter claws and developed longer limbs and long jaws. Traced back toward the Early Cenozoic, the dogs and cats converge toward a common ancestry.

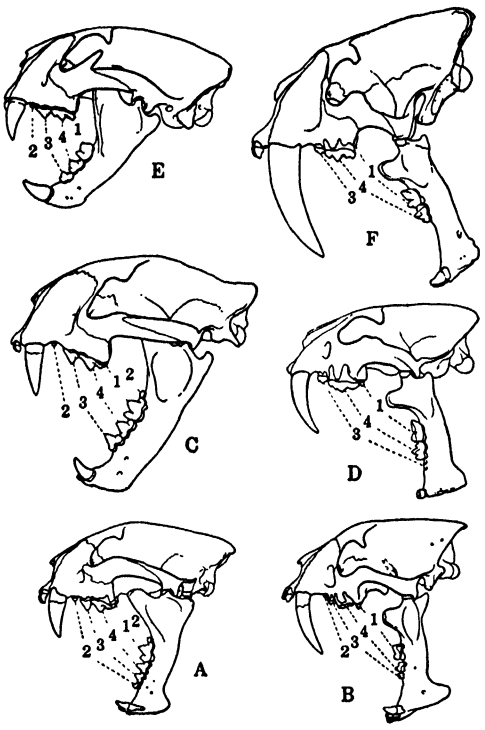


FIG. 149. Skulls of biting cats (left) and stabbing cats (right) arranged in pairs of equivalent geologic date to show parallel development in these two tribes. *A*, *Dinictis*, and *B*, *Hoplophoneus*, of the Oligocene; *C*, *Nimravus*, and *D*, *Machærodus*, of the Miocene; *E*, *Felis*, and *F*, *Smilodon*, of the Pleistocene. After W. D. Matthew.

The plains of western United States appear to have been one of the chief arenas for the development of the *dogs*. Springing from a small but progressive creodont in the Eocene, they attained the size of a small coyote in the Oligocene. In the Miocene epoch they branched out into a great diversity of types, some leading up to the true dogs and wolves, some to foxes, others to bears, still others to raccoons. In the western Pliocene formations of the United States, several species of wolves are represented, some large and some small, and by Pleistocene time the species were very close to the modern ones. One of the largest of the Pleistocene forms was the "dire wolf," *Canis dirus*, whose remains are common in the asphalt pits of Rancho La Brea near Los Angeles (Fig. 147).

The *cats* also underwent a long and complex evolution in America. Their Eocene history is little known, and they may have developed

first in the Old World. By Oligocene time, however, two great tribes were well represented in the western United States (Fig. 149).

The *true cats* (or *biting cats*) were specialized for killing their prey by biting and crushing. They were represented in the late Oligocene by several species ranging from the size of a lynx to that of a small leopard. By Miocene time they had developed into a variety of great cats that led up to the tigers, lions, pumas, leopards, and lesser cats of the Pleistocene and Recent. The true lion, *Felis leo*, ranged over Europe during parts of the Pleistocene epoch.

The *saber-toothed* or *stabbing* cats paralleled the true cats in their evolution but differed in habits. In the former the upper canine teeth were greatly elongated but the lower canines were small and the lower jaw relatively weak; they made their kill by stabbing and tearing with the saber-like upper canine and thus bled their prey to death. The saber-toothed cats were represented in the Oligocene by several species scarcely larger than a lynx. In succeeding epochs, they increased gradually in size and in the specialization of their stabbing teeth until they culminated in *Smilodon* (Fig. 148), the great saber-tooth of the tar pits of Los Angeles. This species was very heavy and muscular and short-tailed. None of the stabbing cats survived the Pleistocene epoch in any part of the world.

The history of the *bears* (Family Ursidæ) is less well known, and it seems probable that they evolved in the Old World. Fragmentary remains as old as the Miocene are believed to be bears, and their descent from early canids seems probable. It is not certain that they reached America before Pleistocene time.

Man's Family Tree. The lemurs, monkeys, gibbons, apes, and man constitute a well-defined order of mammals whose history begins about the close of the Cretaceous and rises to a climax in the ascendancy of man during the Recent epoch. Like the carnivores, however, the primates have left a rather scanty geologic record. The reason for this is, first of all, their forest-dwelling habit, the leaf mold on the forest floor destroying bone so readily that we have only a fragmentary record of the forest life of any age. Living in the trees, they easily escaped miring or drowning, and their exceptional intelligence enabled them to avoid almost every natural death trap. Most of them therefore sooner or later fell prey to some carnivore that scattered the bones after devouring the flesh. Primate remains as a consequence consist generally of jaws, skulls, and incomplete skeletons, found as rare and isolated occurrences. Because of their exceptional human interest, however, especial attention has been given to primate fossils, and the general features of the evolution of this group can now be confidently presented.

The primate ancestry can be carried back to small "half-apes" (lemuroids) of the Paleocene. These ran, squirrel-like, along the branches instead of climbing like true monkeys, and had a smaller brain and a longer muzzle, thus resembling their probable ancestors, the insectivores. Even in the Paleocene there were two groups of these "half-apes," the lemurs proper and the tarsioids. The tarsioids — so named from the living tarsier of Madagascar — already showed an excessive enlargement of the brain, a forward direction of the eyes, and other specializations, indicating that they were the immediate ancestors of the true monkeys.

Small tarsioids and lemuroids appeared in western North America near the beginning of the Cenozoic, and their scattered remains are found in both the Paleocene and lower Eocene strata. Before the close of the Oligocene, however, they had become extinct in this country and there were no primates apparently in all North America from the Oligocene extinction until the arrival of man in modern times. Some of the American monkeys migrated into South America and persisted there throughout the Cenozoic, but they contributed nothing to the evolution of the great apes and man.

The higher primate history is then continued in Eurasia and Africa. In the last-named continent, in early Oligocene time, lived ancestral primates that gave rise to Old World monkeys and the gibbons, the latter being probably the central stock from which the great apes arose.

Recapitulation

Paleocene Faunas. "The most dramatic and in many respects the most puzzling event in the history of life on the earth . . . is the change from the Mesozoic, Age of Reptiles, to the Tertiary, Age of Mammals. It is as if the curtain were rung down suddenly on a stage where all the leading roles were taken by reptiles, especially dinosaurs, in great numbers and bewildering variety, and rose again immediately to reveal the same setting but an entirely new cast, a cast in which the dinosaurs do not appear at all, other reptiles are mere supernumeraries, and the leading parts are all played by mammals of sorts barely hinted at in the preceding acts" (G. G. Simpson).

Clearly, these Paleocene mammals came for the most part as migrants from some region (probably northern Asia) where they had been developing even before the close of the Mesozoic. Among them are a few holdovers of Mesozoic types (multituberculates). The dominant groups were three orders now extinct and commonly referred to as the "archaic" mammals because of their primitive and inadaptive teeth and feet and their small brains. These were the creodonts, amblypods,

and condylarths. Although they lived on into the Eocene and some of them attained considerable size, the Paleocene species were small, the largest scarcely bigger than a hog or a small bear.

With these archaic types were the forerunners of groups still extant, notably the marsupials, insectivores, rodents, and primates. These, however, were small and primitive.

Nearly all the Paleocene mammals had long narrow heads with small brain cases and long slender muzzles. They were quadrupedal, with fore and hind legs nearly equal in length. All had five toes, and the earliest known examples of each stock walked on the sole of the foot. The distinction between the marsupials and all the rest was already so complete as to suggest that the placental mammals were not direct descendants of the marsupials, but cousins descended from a common Mesozoic ancestor.

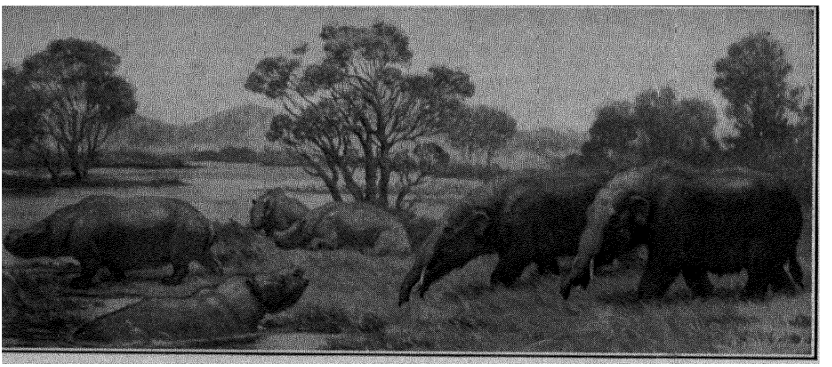
Eocene Faunas. The most striking feature of the life of the early Eocene was the appearance in considerable numbers of progressive forms ancestral to the modern orders of mammals. Among the Eocene types were diminutive *horses* (*Eohippus*), small hornless *rhinoceroses*, equally small *titanotheres*, tiny *camels*, the first *oreodonts*, squirrel-like *rodents*, and small *monkeys*. None of these attained a considerable size, and the largest would hardly have stood waist-high to a man.

With these were associated the " archaic " mammals, some of which attained a far greater size. Insectivores and opossum-like marsupials were common and widely distributed but small. *Creodonts* were the carnivores of that time, and of these some were doglike, some hyenalike, and others more catlike. Common American types reached a maximum size only about that of a modern timber wolf, though one of the latest Eocene types was as large as a great bear. The greatest of all Eocene carnivores, however, was the Mongolian *Andrewsarchus*, with a skull about 2½ feet long. The *condylarths* were common during the early half of the epoch but died out before its close. The great animals of this time were the ponderous *amblypods*, which increased gradually to their maximum bulk in *Uintatherium* of the late Eocene.

In the later Eocene occurred the first mammal adaptation to a marine life, in the form of whalelike animals, whose fossil bones occur abundantly in parts of our Southern States, in Egypt, and in Europe. One of these, *Basilosaurus*, must have been the " sea serpent " of its time, with 4 feet of head, 10 feet of body, and 40 feet of tail! But even a mammal of this size met its match in the great sharks of those seas, the gaping jaws of one of which were about 6 feet across.

Recently a nearly complete skeleton of a bat was found in the Eocene beds of Utah.

Oligocene Faunas. By Oligocene time, the modernized types comprised nearly the entire mammalian fauna. In western America the *oreodonts* roamed in vast herds over the plains. Three-toed horses scarcely larger than sheep were common. *Rhinoceroses* of several kinds were present, the largest of them being amphibious, though not related to the hippopotamus. Probably all the Oligocene species were hornless. The *titanotheres* displayed a meteoric evolution, becoming the largest land animals of this time and then dying out with remarkable rapidity about the middle of the epoch. Small camels were present, and so were peccaries and tapirs. The rodents were represented by beavers, squirrels, rabbits, and mice. Among the carnivores there were many small *dogs* as well as both *biting* and *stabbing cats.*



Field Museum of Natural History.

FIG. 150. Late Miocene landscape in Nebraska, showing at the left a group of short-legged rhinoceroses, and at the right a pair of four-tusked, long-jawed mastodons. From a painting by Charles R. Knight.

In the Old World the elephants were beginning their career, being represented by the first mastodons only about 5½ feet high. Monkeys had become extinct in North America, and the oldest known great ape was represented in Europe by a small type most nearly akin to the gibbon.

Miocene Faunas. The Miocene was the "Golden Age" of mammals. The spread of the prairies and the change to more arid climate led to rapid evolution of the grazing stocks, and the formation of a Bering land bridge permitted intermigration between North America and Eurasia.

Within the groups of animals already present there was a rapid expansion into new genera and species and an increase in size in many stocks. The habit of feeding on the harsh prairie grasses resulted in a remarkable change in the teeth of many groups, whereby the jaw teeth

became long and prismatic and continued to grow throughout life, thus counteracting the rapid wear at the crowns. *Horses* now attained the size of small ponies, but the many species all had dangling side toes. *Camels* were especially abundant and varied, some being little larger than sheep while others rivaled the modern giraffe in height. *Oreodonts* were still very common. *Rhinoceroses* of several kinds were abundant, a small, twin-horned type occurring in great multitudes in Nebraska. Of *carnivores* there were numerous wolflike dogs as well as biting and stabbing cats. There were no North American primates, but in the Old World a great ape (*Dryopithecus*), somewhat related to the gorilla, ranged over Europe and southern Asia.

Pliocene Faunas. The Pliocene faunas of North America are still imperfectly known because the terrestrial formations of this age are so sparsely preserved. At this time there was further immigration from the Old World, bringing us more *mastodons*. *Horses* continued their rapid evolution and were represented in America by several genera among which appeared the first single-toed horse, *Pliohippus*. *Rhinoceroses* were still very abundant. *Camels* continued to be among the most common animals of the plains. The last straggling survivors of the oreodonts were extinct before the close of the epoch.

Pleistocene Faunas. Throughout the Pleistocene epoch North America and Europe were both inhabited by great game animals fully as varied and impressive as those of modern East Africa. In the United States the *elephants* were perhaps the most impressive, for there were at least four species, two of which exceeded modern elephants in size. The tall, rangy imperial mammoth of the southern Great Plains stood nearly 14 feet high at the shoulders. Another species was at home even in the arid basins of Arizona and Nevada. Numerous remains of two tall, rangy species have been found in the uppermost beds of glacial Lake Bonneville, and these elephants must have been common in the Great Basin region until after the last of the glacial ages. Throughout the forests the last of the mastodons (*Mastodon americanus*) browsed in great herds; their remains are common in the peat bogs of the eastern states, no fewer than 217 individuals having been discovered in the bogs of New York State alone. In Florida, New York, and elsewhere the remains of this species are associated with human artifacts in such a way as to indicate that mastodons survived the Ice Age and may have lived until within the last several thousand years. The woolly mammoths ranged widely over the glaciated areas, extending northward into Alaska and eastward across Siberia where their skeletons and tusks are still incredibly numerous in the frozen soil, about half the present ivory of commerce being derived from this

source. Siberian ivory was imported into China as early as the fourth century B.C., and began to be extensively transported into Europe early in the nineteenth century. Between 1800 and 1850 the annual sale of tusks at the trading center of Yakutsk averaged about 18 tons, and to date not less than 46,750 pairs of tusks have been recovered in Siberia.

Horses were still common, and at least 10 species are known from North America. Most of these were of the size of small ponies but one fully equaled the greatest modern draught horse. *Buffaloes* roamed the plains in great herds as they did when the white man first reached



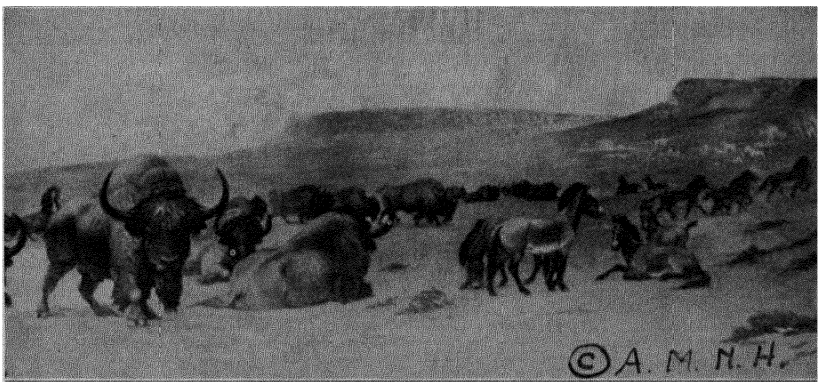
FIG. 151. Scene in the Mississippi Valley during Pleistocene time. Left, the
From a mural by

America. There were at least seven Pleistocene species, and one of these was a colossal beast with a horn-spread of fully 6 feet. *Camels* also were common. *Wild pigs* (peccaries), now confined to Texas, Mexico, and Central America, then ranged over the United States.

Carnivores were abundant and varied, including species of such modern types as the wolves, foxes, pumas, lynxes, raccoons, badgers, otters, skunks, and weasels. In addition, there were extinct types of which the great saber-tooth (*Smilodon*) was perhaps the most striking (Fig. 148). Another great cat, also known from the tar pits of Rancho La Brea, was very much like the modern lion in form and size. The great wolf (Fig. 147) which was so common in southern California exceeded in size any modern American canines. True bears apparently made their appearance in America at this time as immigrants from the Old World.

One of the most striking features of the Pleistocene fauna was the immigration from South America of the *giant armadillos* and the great

ground-sloths. These both reached Texas in the Pliocene, and the latter spread over the United States in the Pleistocene. The ground-sloths (Fig. 28, p. 45) were clumsy beasts with the bulk of an elephant, but they were short-legged and curiously club-footed as a result of the fact that their ancestors had lived so long in the trees and had developed such long, curved claws that it was impossible for them to walk on the bottoms of the feet when they became too heavy to live longer off the ground. These creatures are common fossils in the tar pits of southern California, and one genus at least ranged eastward to the Atlantic States. A claw of this form was discovered in a cave in Virginia by



American Museum of Natural History.

American mastodon; center, the Royal bison; right, the wild horse, *Equus scotti.* Charles R. Knight.

President Jefferson, who was the first to describe and name the genus but thought it to be a mighty lion.

North and South America were separated throughout Cenozoic time until they became united by the present Isthmus of Panama in the late Pliocene. Just before this connection, South America had 29 families of mammals and North America 27, but with 2 doubtful exceptions they had no families in common. Shortly afterward, in the Pleistocene, they had 22 families in common, 7 of South American origin, 14 of North American origin and one doubtful. Those emigrating to South America included the mastodons, horses, tapirs, camels, and peccaries; those coming in the opposite direction included the ground-sloths, armadillos, and glyptodonts.

Another striking element of the Pleistocene faunas was supplied by the arctic animals that migrated southward during the glacial ages. For examples, the musk-ox is recorded as far south as Arkansas and Utah, while in Europe the reindeer, the woolly rhinoceros, the

woolly mammoth, and the arctic fox ranged southward into France and Poland.

There were no primates in North America until primitive man reached here from the Old World. Although evidence of the presence of Pleistocene man in America has been claimed repeatedly, it is still very scanty. On the other hand, savage races were present in Europe and in eastern Asia and northern Africa throughout much if not all of the epoch. The history of Pleistocene man is reserved, however, for a special chapter.

In Europe, the Pleistocene fauna of the warm interglacial ages included most of the types of great game animals now found in Africa. Such, for example, were the lion, the rhinoceros, the hippopotamus, the elephants, antelopes, and lesser animals.

Chapter 13

THE COMING OF MAN

Prehistoric Documents

Artifacts. The American pioneers found the Indians using stone implements instead of metal. Flint provided tips for their arrows and blades for their tomahawks, and stone mortars served as mills for the grinding of maize. To these early settlers there was no mystery attached to the finding of such carefully shaped stones where the Indians had once pitched their camps.

Similar stone implements found in western Europe, however, were regarded with strange superstition throughout the Middle Ages, and were commonly thought to be thunderbolts. The civilized world at that time had little contact with primitive peoples, and moreover, it was completely dominated by the belief in a Special Creation that left no place for extinct races of men antedating the present civilization. Yet stone implements are abundant in parts of Europe and were commonly collected as curios after the Renaissance, and we find Olaf Worm, a Danish authority on such objects, writing in 1655 that "they are commonly supposed to fall with the lightening from the sky," though "opinions differ as to their origin, since some believe they are not thunderstones but petrefied iron implements, seeing they resemble the latter in shape so closely." And as late as 1802, Thorlacius, writing of stone artifacts discovered in burial mounds, concluded that "the objects found in the mounds are nothing else than symbols of the weapons employed by the Gods of Thunder in chasing and destroying evil spirits and dangerous giants. They could not be ordinary tools and weapons as these have been made of metal since the earliest times."

It now seems strange that a belief so fantastic could have persisted for 300 years after Europeans had encountered the American Indians and other aborigines still using stone implements; it sprang from the assumption that such savages were pre-Noachian degenerates who had wandered far from the original center of civilization and had lost the art of working metal. Occasional thinkers, far ahead of their time, had, indeed, realized the true meaning of archeological remains since before the beginning of the Christian era, but it was not until within the last century that these remains were generally accepted as evidence of

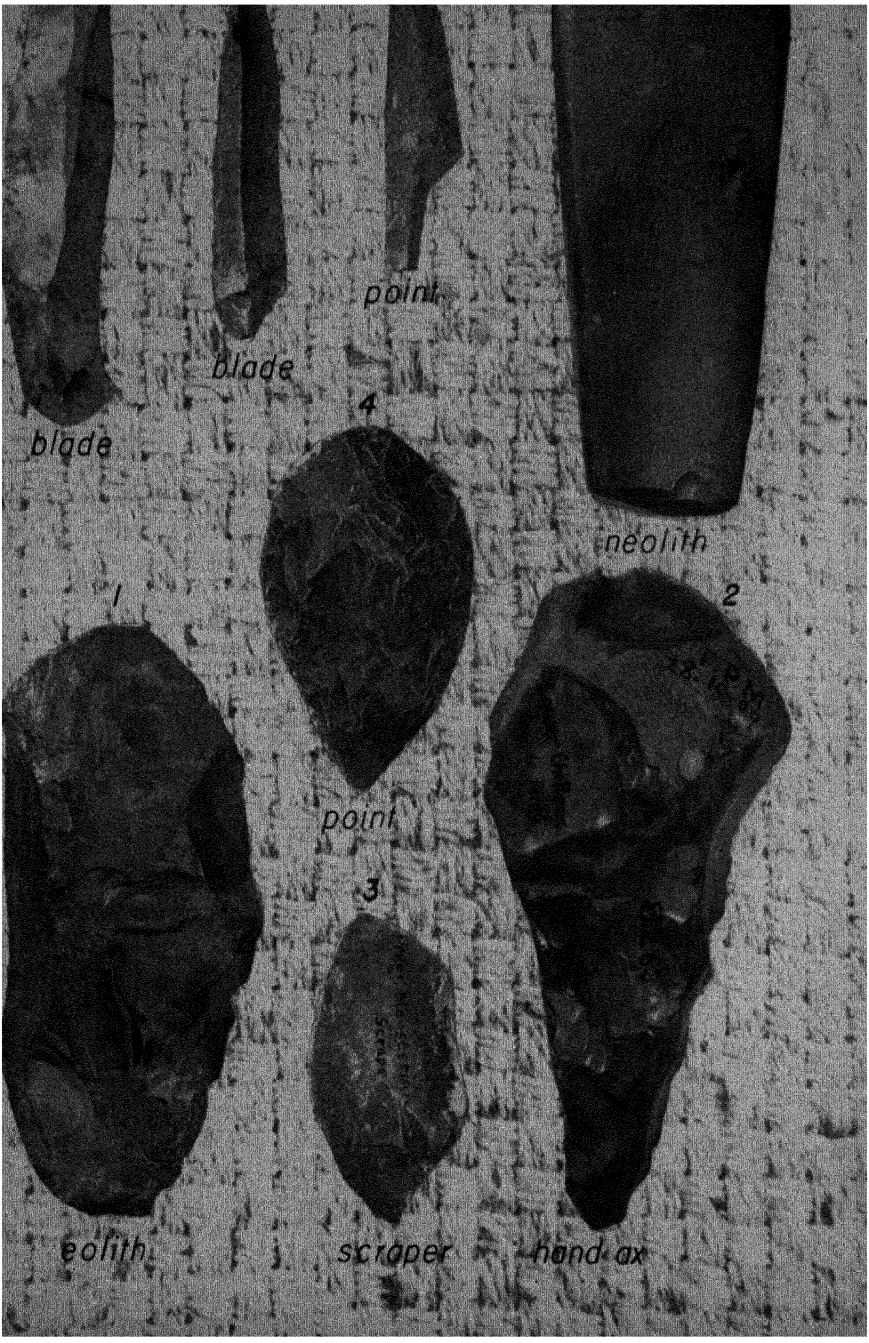


Fig. 152. Stone implements. No. 1 is an eolith, 2–7 are paleoliths, and 8 is a neolith. No. 1 represents a pre-Chellean culture (from Reutelier); 2, a Chellean culture from France; 3 and 4, Mousterian cultures; 5 and 7, Solutrean cultures; 6, Aurignacian culture; 8, a Neolithic culture from Denmark.

prehistoric races. Even then, no one considered the possibility that they might represent the work of extinct *species* of man until after Darwin's *Origin of Species* had paved the way for a belief in the gradual evolution of man from the lower animals.

The appreciation of the true meaning of stone artifacts was first established in Scandinavia 100 years ago. It began with the creation by the Danish Government of a scientific commission to study the refuse heaps and shell mounds that had already attracted attention in that region. As a result of this project, there were assembled at the Royal Museum in Copenhagen extensive collections that had been studied with respect to their stratigraphic occurrence in the mounds. On this basis, Thomsen, the director of the Museum, in 1837 proposed a chronology of human culture that was at once accepted in Scandinavia and later was recognized the world over. It was he who divided human prehistory into the *Stone Age*, the *Bronze Age*, and the *Age of Iron*.

The assemblage of tools and other implements used by a particular people represents its *culture*. The style of workmanship changed with time during the Stone Age, just as it does in the modern world; and as it is easy to distinguish the relative ages of a collection of colonial flintlocks and one of modern high-power rifles, so it is also possible to distinguish different cultures of stone implements. Accordingly, other workers, following Thomsen, further subdivided the Stone Age into three stages, Eolithic, Paleolithic, and Neolithic, based on the type of workmanship displayed.

The first tools used by man were doubtless those accidentally shaped by nature to fit his hand, such as sharp-edged chips of flint that he could use to scrape skins or fashion wooden tools. Such stones, which he picked up and used without modification, are known as *eoliths* (Gr. *eos*, dawn, + *lithos*, stone). Showing evidence of wear but not of conscious shaping, they represent the lowest stage of human culture and are found in formations as old as the late Pliocene (Fig. 152).

Eventually man learned to flake off pieces of stone and to shape them, by chipping, into scrapers, hand axes, spear heads, and other useful tools. This was an art slowly acquired through countless generations of trial and experiment by primitive peoples whose lives often depended on the quality of their weapons. Such artifacts, shaped by chipping alone, are known as *paleoliths* (Gr. *palaios*, ancient, + *lithos*, stone), and cultures represented by such implements characterized the *Paleolithic* age, which endured in Eurasia through most of the Pleistocene.

In Europe some of the prehistoric peoples advanced a stage farther in the making of stone implements whch they shaped and sharpened by grinding and polishing against natural abrasive stones. Such objects,

known as *neoliths* (Gr. *neos*, recent, + *lithos*, stone), are found only in deposits younger than the last glacial till in northern Europe and mark the highest Stone Age culture, attained shortly before the discovery of the use of copper.

Metals were first used about 5000 B.C., copper and bronze (alloy of copper) being employed sooner than iron because easier to smelt. Copper was used in Egypt about 5000 B.C. and in Chaldea as early as 4500 B.C., but its first known use in Europe dates from about 1500 B.C. Iron was used in Egypt as early as 3000 B.C., and iron swords were in use in Greece between 1400 and 1300 B.C., but the iron industry did not spread to central Europe until about 800 B.C.

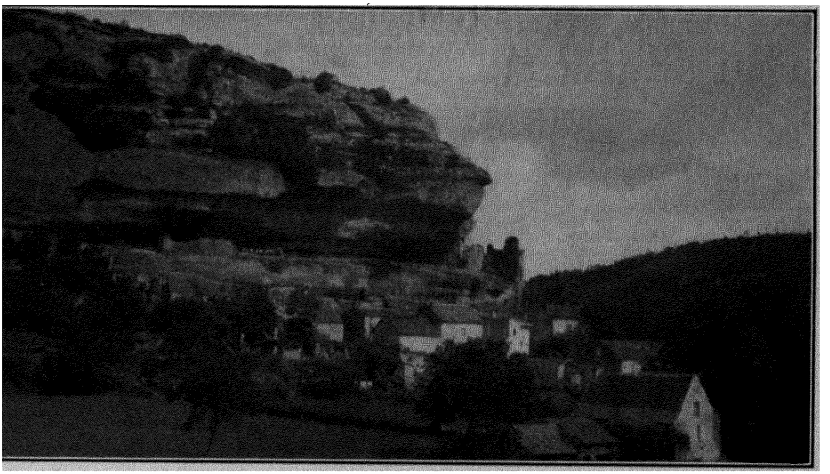
TABLE OF HUMAN CHRONOLOGY

Geologic Age			Estimated Date in Years	Cultural Stages		Fossil Men	
American Units		European Units					
Recent epoch		Recent epoch		Iron		*Homo sapiens*	Modern
				Bronze			
				Neolithic			
Pleistocene epoch	Wisconsin glacial age	Würm glacial age	25,000 B.C.	Paleolithic	Magdalenian Solutrean Aurignacian		*Cro-Magnon*
	Third interglacial age	Riss-Würm interglacial age	150,000		Mousterian		*Neandertal*
	Illinoian glacial age	Riss glacial age	250,000		Acheulian		
	Second interglacial age	Mindel-Riss interglacial age	350,000		Chellean		*Peking Man** *Pithecanthropus*
	Kansan glacial age	Mindel glacial age	650,000		Pre-Chellean		
	First interglacial age	Günz-Mindel interglacial age	750,000				*Piltdown*
	Nebraskan glacial age	Günz glacial age	950,000				
Pliocene epoch			1,000,000	Eolithic			

* Sir Arthur Keith (*Nature*, vol. 147, 1941, p. 473) maintains that the consensus of opinion favors an early Pleistocene instead of a mid-Pleistocene date for both *Pithecanthropus* and Peking man.

The succession of cultures is shown in the table of human prehistory above.

Human Fossils. Prehistoric human remains are, for obvious reasons, among the rarest of fossils. With his superior intelligence, man generally avoided such common catastrophes as miring and drowning. Of course this did not reduce the number who died, but it lessened their chances for burial where preservation would be likely. Furthermore, the funeral rites, observed by man since very remote times, commonly insured the destruction of the remains, whether the funerals involved cremation, elevation on scaffolds, or burial in shallow graves. Even burial generally did not favor fossilization, since the graves were made on elevated mounds where both weathering and erosion are active.



G. G. MacCurdy.

FIG. 153. Rock shelter of Les Eyzies, Dordogne, France. The re-entrant in the middle of the cliff was occupied by Paleolithic man.

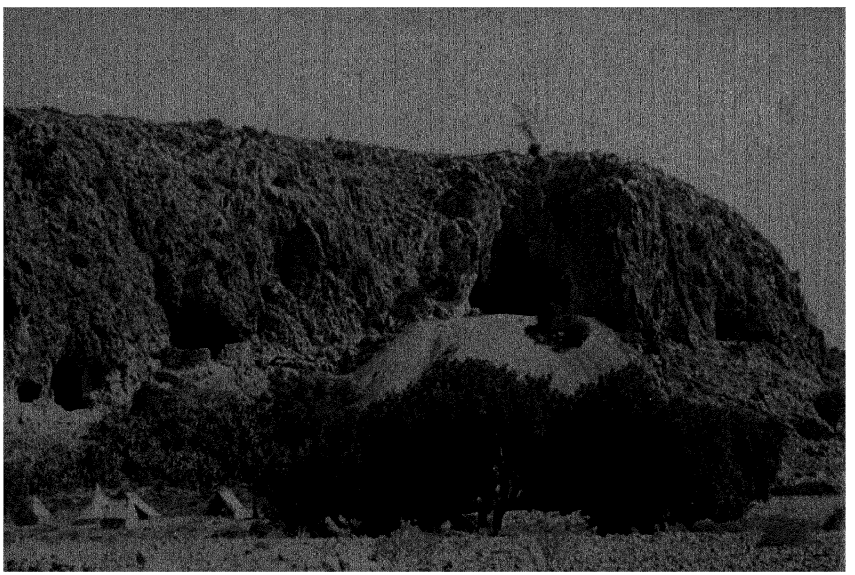
A fortunate exception was provided by the cave dwellers, who took refuge in caverns or overhanging shelters along the river bluffs of Europe and parts of Asia during the late Pleistocene, finding there a shelter from the inclement weather and a refuge from the powerful carnivores of the time. These peoples commonly buried their dead in the caverns where they also would be safe from the ravages of wild beasts — and, fortunately for us, they surrounded them with food and weapons intended for use in the future life. Such cave burials therefore give us not only the physical characters but also the culture which was actually used by the individual preserved. Thus we find a tie-up between the human fossils, which are rare, and the definite cultures of stone implements, which are widely scattered and almost indestructible. Such burials also commonly include two or more individuals, thus giving us a record of both sexes and of the young as well as the old.

Until it was admitted that extinct races had preceded the present inhabitants of Europe, human fossils were not recognized as such and if observed were considered merely the remains of buried dead. But in 1857 there was found in the Neander Valley near Düsseldorf, Germany, a type of skull obviously unlike modern man in many characteristics. After the publication of Darwin's *Origin of Species* in 1859, this discovery was soon appreciated as the record of an extinct species far more apelike than any living men, and it became the type of the Neandertal race (Fig. 157). During recent years, the present interest in human antiquity has led to increasingly numerous discoveries, until approximately 100 localities have now yielded human fossils. The majority of these are associated with caves and rock shelters, but several are in river terraces or lake deposits and record accidental deaths and natural burial.

Dating the Record. Paleolithic man was a hunter, procuring both food and clothing from the game he could kill. His weapons were adapted to this end, and his camp sites were surrounded with the bones of his prey. As he lived through the Ice Age in Europe, his environment changed greatly with the advance and retreat of the glaciers. In addition to the climatic differences between glacial and interglacial ages, he experienced great changes in his food supply. During the

G. G. MAC CURDY, AMERICAN SCHOOL OF PREHISTORIC RESEARCH.

Fig. 154. Cave of the Kids in the Valley of the Caves (Wady el Mughara) in Palestine. Before this group of caves there is stratified refuse about 70 feet thick, with eleven distinct prehistoric cultures superposed, ranging from the pre-Acheulian to the Bronze Age.



last glaciation, for example, an arctic fauna ranged southward to the Mediterranean, including the arctic fox, the woolly mammoth, and vast herds of reindeer. The last named became at that time the chief source of human food and clothing. But during the preceding interglacial age the reindeer had been restricted to the Arctic, and temperate and subtropical game had spread northward over Europe, including, among other creatures, the lion, the hippopotamus, the elephant, and great herds of wild horses. At that time the horse was the chief object of the chase.

Thus throughout the million years or so represented by the Stone Age, the steady evolution of the mammalian faunas was accentuated in Europe by extensive north and south migrations induced by the glaciation. Accordingly, the different stages of the Pleistocene, represented south of the limits of glaciation by outwash and terrace gravels, contain quite distinctive mammalian faunas. The succession of faunas, worked out from many occurrences, provides the key to the dating of the human records.

Fortunately for us, primitive man had little notion of sanitation, and camp refuse was thrown away to accumulate over the slope below many shelters that were long inhabited. Of course it included broken or discarded artifacts as well as the bones of game. The most-favored camp sites were used in succession by different peoples throughout much of Paleolithic time, and the refuse of each in turn accumulated to form a roughly stratified deposit. One of the thickest and most complete records known is that about the Cave of the Kids in the Valley of the Caves in Palestine (Fig. 154) where stratified refuse about 70 feet thick includes distinct layers representing eleven distinct cultures ranging from early Paleolithic time to the Bronze Age.

In dating actual human fossils, it is always necessary to make sure that the bones have not been artificially buried in layers of sediment of much older date, for of course a modern skeleton might be buried in river gravel that encloses an extinct Pleistocene fauna.

Men of the Old Stone Age

Flint Workers of England. The most ancient relics of mankind are found in England. Near the city of Ipswich, about 65 miles northeast of London, the upper Pliocene beds include three layers that have yielded abundant eoliths, now accepted by archeologists as the implements of primitive man. About 50 years ago there was also found here a stiletto made of a deer horn. The locality has particular

interest because the flint implements lie under a fossiliferous marine bed that proves conclusively the Pliocene age of the deposit.

Slightly younger deposits (early Pleistocene) of similar nature are found at Foxhall, a few miles northeast of Ipswich, and here the flints are associated with charred wood, suggesting that the ancient flint workers had already discovered the use of fire. At Cromer, still farther northeast of London, there is another bed (the Cromer Forest bed) of early Pleistocene age from which large but crudely chipped flint implements have been recovered. In none of these localities have any skeletal remains been found, but the crude implements indicate clearly the presence of man in England at the close of the Pliocene and early in Pleistocene time.

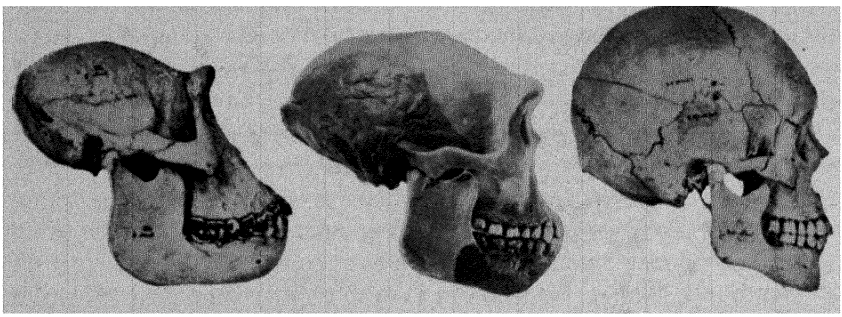


FIG. 155. Skull of modern gorilla (left), *Pithecanthropus* (center), and modern man (right). The apelike characters of *Pithecanthropus* may be seen in the low forehead, heavy brow ridges, protruding jaws, and chinless profile. After F. Weidenreich in *Natural History*.

Pithecanthropus. The most discussed of all human fossils was discovered in 1891 by Eugene Dubois, a Dutch army surgeon quartered on the island of Java. He had opened an excavation in the bank of Solo River to collect vertebrate fossils which are abundant in a 3-foot layer of ancient river gravel. There he came upon fragments of a human skeleton — a skull cap, a left femur, fragments of nasal bones, and three teeth.

The skull cap was remarkably thick, the brow ridge very massive, and the forehead so low that the individual was at once hailed as a "missing link" between man and the apes, and was named *Pithecanthropus* (Gr. *pithecos*, ape, + *anthropos*, man) (Figs. 155, 157).

The brain capacity, now estimated at 900 c.c., stands intermediate between the maximum ever measured in an ape (600 c.c.) and the average for the lowest type of living man (1240 c.c.). Moreover, the areas of attachment of the great neck muscles at the base of the skull

clearly imply that the head was carried forward as in the apes and not balanced on the neck as in modern man.

The thigh bone, found about 50 feet from the skull, is remarkably straight, and implies an erect posture. There is now serious doubt whether this limb bone and two of the teeth belonged to the same type as the skull, but we have indirect confirmation (in Peking man) that *Pithecanthropus* did walk upright, nevertheless, and was distinctly human, even though far more apelike than late human fossils.

At the time of discovery, skeptics argued that *Pithecanthropus* was an abnormal individual, perhaps an idiot, and no fair representative of a race of men; but trained students never doubted his significance, which is now abundantly justified by the discovery of three additional skulls, one in 1936, one in 1938, and another in 1939. The last, and most important, of these supplements the original skull in that it includes the upper jaw, part of the lower jaw, and several teeth, along with the posterior and basal part of the brain case (Fig. 155). It is somewhat larger and more massive than the first skull and is believed to be that of a male whereas the original find was a female, but the skull bones are even thicker and the brain capacity apparently no greater than that of Mrs. Pithecanthropus.

Both skull and jaws indicate a chinless face with a protruding mouth, giving an apelike profile that was accentuated by the heavy brow ridges and the low forehead (Fig. 155). Yet the tooth line is even, the canines relatively small, and the dentition in all respects human rather than simian.

The geologic date of *Pithecanthropus* was at first thought to be late Pliocene or early Pleistocene but is now thought by some students to be about mid-Pleistocene. Since Java is far from the glaciated regions, the correlation of the deposits on Solo River with those of a definite glacial or interglacial age can not be precise; but a large fauna of mammals has now been recovered from the gravel bed which yielded the human fossils and it clearly indicates a date in the early half of the Pleistocene (see note accompanying table on p. 240).

It is now known that there are at least six faunal zones in the Pleistocene deposits of Java. All the remains of *Pithecanthropus* came from one of these, the so-called Trinil horizon. Other human remains of younger type are found in some of the higher zones.

Peking Man. A series of discoveries in 1928 and 1929 near Peking, China, brought to light another race closely allied to *Pithecanthropus* and representing the same stage of human evolution. The remains were found amidst cave deposits at Chicken Bone Hill (Chou Kou Tien) about 30 miles south of Peking. At the time of habitation the

site was a spacious limestone cavern, but it has since been filled with debris fallen from the walls or washed in from above and cemented in part with travertine. The race has been named *Sinanthropus pekingensis* (Gr. *Sinos*, China).

Once the great significance of this primitive human race was perceived, systematic exploration of the deposits was undertaken with the joint support of the Geological Survey of China and the Rockefeller



FIG. 156. Model of the skull of Peking man, by Franz Weidenreich. Note the low forehead, the heavy brow ridges, the protruding mouth, and the receding chin. About ½ natural size.

Foundation, and for more than a decade from 50 to 100 technicians and laborers have worked continuously at the excavation. As a result, about 40 individuals have now been recovered, including men and women and children. In addition, a large fauna of contemporaneous mammals has been found, many of them representing the prey which Peking man brought home from the chase.

The human remains are nearly all skulls and lower jaws, though a few limb bones have now been found. The absence or rarity of other skeletal parts, as well as evidences that each skull had been crushed

by a blow before burial, suggests that these are the remains of cannibalistic rites.

As in *Pithecanthropus*, the chin is receding, the forehead very low, the brow ridges over the orbits massive, and the jaws protruding. All these features, and many other technical details, are decidedly apelike characteristics and indicate plainly that Peking man was much closer to our simian ancestors than any modern races. The limb bones prove, nevertheless, that he walked erect. The capacity of the brain case ranges from 850 to 1220 c.c., but in the three best preserved skulls is about 1000 c.c. (Fig. 156).

Associated with the skeletons have been found charred animal bones and superposed layers with charcoal debris, ranging through a thickness of 20 feet of deposits. It is therefore clear that these people used fire. There have also been found with them more than 2000 crude artifacts of the Chellean cultural type, made from greenstones and vein quartz. These stone implements include choppers, scrapers, gravers, and awls. Some of them were evidently used also for fashioning weapons from animal bones, such as the daggers made from deer antlers. In other words, *Sinanthropus* was already man, and was able to organize his life so as to select intelligently the materials useful for fuel, weapons, and tools, besides being a successful hunter of animals.

Associated mammal fossils indicate an age in the early half of the Pleistocene epoch (see note accompanying table on p. 240).

Neandertal Man. Best known of all the extinct species of man is *Homo neandertalensis*, who inhabited the caverns of western Europe during the latter part of the Pleistocene epoch. The original discovery of the remains of this race was made in the Neander Valley near Düsseldorf, Germany, whence the name. Although discovered the previous year, this remarkable skeleton was first described in 1858, the year before the publication of Darwin's *Origin of Species*. The striking characteristics of the race, and the timeliness of the discovery, led to an immediate appreciation of the significance of the Neandertals as a species far more apelike than any living men.

Since 1858, several entire skeletons have been recovered, and incomplete remains of many men, women, and children of the Neanderta! race have been found in the caves and rock shelters of Belgium, France, Italy, Spain, Croatia, Crimea, and Palestine. Their stone implements (the Mousterian culture), moreover, are found scattered throughout western Europe and farther eastward in Asia Minor, North Africa, Syria, northern Arabia, Iraq, and even in China. Among the striking Neandertaloid discoveries of the last few years may be mentioned the skeleton at Broken Hill, Rhodesia; that near Galilee in



Field Museum of Natural History.

FIG. 157. Restoration of Neandertal man. From a group by Frederick Blaschke.

Palestine; and others at the Cave of the Kids near Mount Carmel, Palestine. From these abundant remains it is possible to present an adequate picture of the racial characteristics and the culture of these interesting people.

The Neandertals were stocky and short of stature, rarely exceeding 5 feet 4 inches (Fig. 157). Although they stood upright, the carriage

was more like that of a great ape than is that of living man, because the spine lacked the fourth or cervical curvature and the thigh bones were sigmoidally curved in compensation. The head accordingly was carried far forward and the body had a slouched appearance (Figs. 157, 158). Both hands and feet were large, and the great toe was offset against the rest as in the great apes.

The head differed from that of modern man in the very low forehead, heavy brow ridges, and receding chin (Fig. 159). The face was undoubtedly big-featured and brutal. Nevertheless the brain was approximately equal in size to that of modern man (1400 to 1600 c.c.), the brain case being low in front but large in the back and lower part. It has been inferred from the proportions of the brain that the species was deficient in the higher qualities of reasoning and association, and probably less capable than modern man in social organization. It must be remembered, however, that Neandertal man dominated all Europe during the last interglacial age and the early part of the last glacial age, a period estimated to exceed 100,000 years.

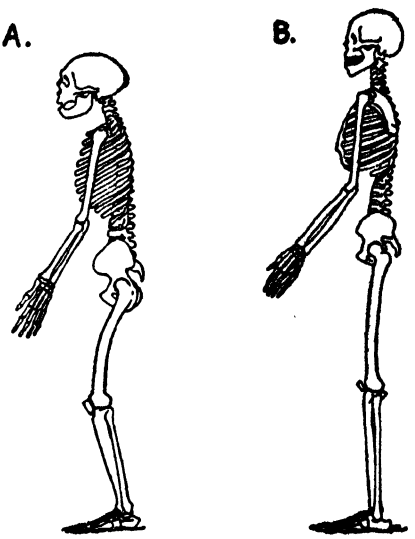


FIG. 158. Skeleton of Neandertal man (left) and that of a living Australian, showing contrast in posture. After Boule, from Woodward, British Museum *Guide to Fossil Man.*

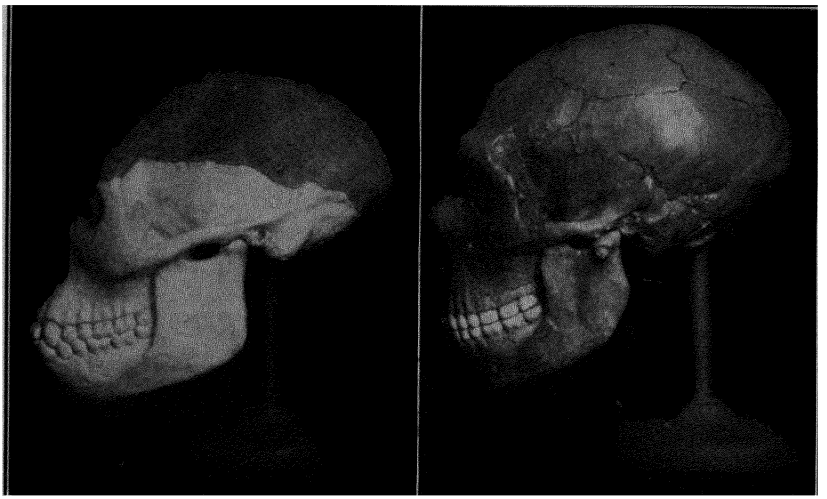
The Neandertals made fairly good stone implements, and they also knew how to kindle a fire, for hearths have been found in their cave abodes. In at least two instances the skeletons have been found in their original burial places, where they had been laid away with implements, paints, and food, indicating that the race held a belief in immortality, and buried the dead with ceremonial rites.

Among the stone implements of these people, the hand ax, scraper, and point are most characteristic. Flint-tipped spears were used, but there is no evidence that Neandertal man used the bow and arrow. In view of his relatively feeble weapons, it is remarkable that he was a successful hunter of big game, including the bison, cave bear, horse, reindeer, and mammoth, all of which inhabited Europe during his reign.

In his physical make-up, Neandertal man, like the species of the

earlier Pleistocene, retained many primitive characteristics pointing clearly to his simian ancestry. He was replaced with relative suddenness by the modern species, *Homo sapiens*, about the middle of the last glacial age, and may have perished without contributing to the modern races of mankind, though it is possible that some existing stocks, like the aboriginal bushmen of Australia, still carry a mingling of Neandertaloid blood.

Piltdown Man. In 1911 and 1913 there was discovered at Piltdown, south of London, a remarkable skull of a race somewhat older than the Neandertals, yet more progressive. It may represent the remote ances-



American Museum of Natural History.

FIG. 159. Skulls of *Pithecanthropus* (left) and Neandertal man. White portions restored. From models by J. H. McGregor. The *Pithecanthropus* restoration was based on the original skull cap and may be compared with Fig. 155, which is based on a more complete skull recently found.

tors of modern types of man. The fragments originally discovered are parts of a single skull broken by the tools used in the gravel quarry, where it was uncovered. There were nine fragments of the skull, nearly half a lower jaw, and a loose tooth. Subsequently, fragments of another skull were found in the same gravel bed about 2 miles from the original locality.

After much labor and discussion, the pieces of the first skull were fitted together to permit a fairly satisfactory reconstruction of the whole head (Fig. 160). The skull bones — probably those of a female — were much thicker than in moderns, but the forehead was high, the brow ridges not especially prominent, and the brain (with a capacity

now estimated at 1400 c.c.) somewhat larger than the average for modern European women. In spite of this evidence, the skull showed a receding chin and a prognathous (protruding) jaw. Unfortunately, nothing is known as yet of the limb bones.

Crude stone implements of a Pre-Chellean culture (see table, p. 240) occur in the gravel bed with Piltdown man, and the associated mammal fossils fix the date as First Interglacial. The large size of the brain indicates a progressive race, and the high forehead and feeble brow ridges point to a head far less apelike than the other fossil men we have considered.



American Museum of Natural History.

FIG. 160. Skulls of Piltdown man (left) and Cro-Magnon man, from models by J. H. McGregor.

These finds make it evident that during early Pleistocene time a large-brained, progressive type of man inhabited western Europe even though a very different type, represented by *Pithecanthropus* and *Sinanthropus,* occupied the Orient at the same time or even later. The Neandertals were clearly successors to the low-browed group and migrated into Europe during the last interglacial age.

The Cro-Magnons. Some time during the last glacial age, a very superior race of men appeared in southern Europe, quickly replacing the Neandertals. These men had high foreheads, well-defined chins, and large brains, and clearly belong to the modern species, *Homo sapiens.* They have been called the Cro-Magnon race for the original discovery of five skeletons at the rock shelter of Cro-Magnon in the French village of Les Eyzies (Dordogne).

The original find included the skeletons of an old man, two young men, a woman, and a child. Numerous other remains have since come to light, so that the race is now known from many skeletons and associated stone implements and other evidences of culture and art. Among the notable occurrences is that at Předmost, Moravia, which was a mass burial including 14 complete skeletons and fragments of others. The ancient camp site at Solutré, France, has also yielded several skeletons besides abundant artifacts and vast numbers of skeletons of the wild animals, chiefly horses, upon which these people fed after the reindeer was gone from southern Europe. The caverns of the Dordogne Valley and those about Grimaldi on the Italian frontier have likewise yielded numerous skeletons in burial position, with associated artifacts.

Unlike the Neandertaloids, the Cro-Magnons were tall and straight, with relatively long legs, straight thigh bones, and the complete double curvature of the spine that permitted the balance of the head as in modern man. The chin was prominent, the jaws not protruding, the forehead high, and the brain fully as large as in modern races. In physical development they were essentially modern (Fig. 160).

In mental development, also, they were superior, for they had abundant and well-formed implements of both stone and bone. They used bone for awls and ivory for skewers and ornaments; they made spears and bows and arrows; and they dressed themselves in fur. Their bodies they ornamented with marine snail shells, derived from the Mediterranean and Atlantic coasts, with fossil shells from places far inland, with the teeth of mammals, and even with those of human beings. Toward the close of the Pleistocene they made beads and bracelets and other objects of shell and ivory.

Armed with better weapons of the chase than any of their predecessors, and with a fuller knowledge of their use, the Cro-Magnons were able to take better advantage of their environment. Thus, they had more ease and time for reflection, and we witness in them the development of an art and culture that excite the wonder and admiration of all anthropologists. Besides personal adornment and the use of clothing, this artistic development was expressed in picture writing on the walls of their caves, in sculpture upon fragments of stone or bone implements, and finally in polychrome paintings like those preserved on the walls of certain of the caverns in France and Spain.

The Cro-Magnons were the last of the Paleolithic races in Europe. They appeared during the last glacial age and persisted until the ice sheet had largely wasted away. Their history is divisible into three cultural stages, the Aurignacian, the Solutrean, and the Magdalenian, each characterized by the development of certain types of flint work-

manship. The race was not exterminated like the older human species, for the Cro-Magnon stock is the direct ancestor of living races of southern Europeans.

Neolithic Peoples and the Beginning of Civilization

As the last ice sheet disappeared from Europe, the climate moderated and became moister. The reindeer, which had been the chief source of food and clothing for Cro-Magnon man, vanished from all southern Europe. These changes in climate and food were accompanied by human migrations, as man spread northward in the wake of the vanishing ice. About this time the art of finishing stone implements by grinding and polishing was developed in southern Europe, and a new culture, the Neolithic, spread quickly over the continent. This modern development, shortly after the beginning of the Recent epoch, was accompanied by the development of the art of making pottery, the domestication of animals, and the adoption of habits of communal life. Later on, permanent habitations in the form of stone or wooden huts or tents of skins became general, and agriculture was pursued. In order to secure protection, villages were commonly built on piles over lake shores, swamps, or streams.

With the spread of Neolithic culture, civilization had truly begun, replacing the barbarism and savagery of Paleolithic peoples. There is evidence of this change in human affairs as early as 18,000 B.C. in Asia Minor, Arabia, and Persia. Probably the oldest center of Neolithic culture yet known is the ancient city of Susa in Persia, which is said to date from at least 20,000 B.C. The culture had spread to the island of Crete by 14,000 B.C. and to Denmark by about 12,000 B.C.

Early Man in North America

It will be noted that all the Paleolithic races described above lived in the Old World. It is generally accepted that man evolved in that hemisphere, for no remains of the higher primates are known in America. The date of man's first migration to this continent has been a controversial question for many years. Although human remains have been found on numerous occasions during the past 50 years in geologic associations that led their discoverers to assert that they were thousands of years old, if not actually of Pleistocene date, a feeling of skepticism has prevailed and most of these assertions have been discredited. Evidences of man's antiquity in North America keep coming to light, however, and within the last few years there has ap-

peared convincing evidence of the presence of man here before the close of the Pleistocene.

In 1916, human remains were found along with bits of pottery and charcoal at Vero on the Atlantic coast of Florida. Since then much more human material and many additional artifacts have been discovered here and 40 miles to the north at Melbourne. The associated plants, though of living species, appear to indicate that the man of Vero may be but a few thousands of years old. The associated mammal bones are all of extinct Pleistocene forms (including two species of elephant), and presumably they are of a warm climate. The association of man and the Pleistocene elephant here seems certain, but whether this means that man was present in the Pleistocene or that the elephant lived into post-Pleistocene time in Florida is not clear.

At Colorado, Texas, beneath 18 feet of Pleistocene gravels, was found an extinct buffalo of the Asiatic type, and beneath the skeleton were three stone implements of the chase. In the same layer occur other extinct Pleistocene mammals. Similar finds have been made in stream-gravel terraces in Oklahoma, and others in Kansas.

The most abundant and widespread evidence of early man in America is the *Folsom culture*, so called because of its type locality near Folsom, New Mexico. It was discovered in 1925 when crude stone implements were found associated with an extinct species of bison. Later excavation revealed an arrow point between two bison ribs and finally the remains of some 40 or 50 specimens of the extinct bison, representing a kill and barbecue. Among these bones were 16 arrow points of a distinctive type of workmanship now recognized as the *Folsom point*. In recent years this type of stone implement has been found widely distributed in southwestern United States and in several places it is associated with extinct mammals. A notable example is the Lindenmeier site north of Fort Collins, Colorado, where, at a depth of 14 or 15 feet below the present surface, the Folsom culture is found associated with a "bison kill" similar to that at Folsom. Here the remains of an extinct camel were found with the bison. From this ancient camp site some 2000 stone implements have been recovered, including scrapers, drills, gravers, blades, etc. Folsom points have also been reported recently from southwestern Virginia.

Thus we have clear evidence of a race of men using stone implements of a distinctive culture, contemporaneous with an extinct bison, camel, and mastodon, but their physical characteristics are entirely unknown, since no skeletal remains have as yet been found.

In the Holloman sand quarry a mile north of Frederick, Oklahoma, have been found during the past few years more than a dozen flint

implements, associated with at least thirteen genera of extinct mammals. Among these animals are a camel, horse, elephant, mastodon, and three genera of the extinct ground-sloth. These sands, bones, and implements are found in the highest stream terrace, about 100 feet above the adjacent Red River. Since their deposition, therefore, sufficient time has elapsed to allow the stream to deepen its valley by at last 100 feet. This process has probably required more than postglacial time, and if so, we have evidence here of Pleistocene man in North America.

In 1931 a skeleton of a young woman was found at a depth of 9 feet, 9 inches in laminated, glacial lake clays near Pelican Rapids in central-western Minnesota. Workmen who exhumed the skeleton assert that the lamination in the clay extended unbroken above the skeleton, disproving artificial burial. If this be true, the woman apparently drowned in a lake that bordered the ice sheet during late Pleistocene time. The deposits are inferred to be probably 20,000 years old.

Although the last occurrence needs further confirmation, we apparently now have sufficient evidence to justify the belief that man was present in North America, not only all through Recent time but during the last of the Pleistocene as well.

APPENDIX

AN INTRODUCTION TO ANIMALS AND PLANTS

Scientific Names. The beginner in natural history is usually dismayed by the scientific names of unfamiliar types of animals and plants, and is inclined to wonder why common names are not used instead. The answer to this is very simple: a name is common only because it is familiar. Such words as *boa constrictor*, *gila monster*, and *rhinoceros* are common, but a small child finds them fully as difficult as *Homo sapiens* (man), or *Equus caballus* (the horse). Moreover, only a few thousand kinds of animals are at all commonly known, and the rest, already exceeding 825,000 kinds, can therefore have no really " common " names.

Furthermore, so long as we have a diversity of languages, there can be no really common names of general and worldwide usage. To the Germans, the common name of the horse is *Pferd;* to the French, *cheval;* to the Italians, *cavallo*, etc. Moreover, a common name such as *bear* has many different meanings; to a New Englander it implies one species, to a Montanan another, and to an Alaskan a quite different kind of bear. Therefore, if naturalists of all countries are to share in scientific studies, it is obviously necessary that each species should bear a name that applies to one kind alone and is recognized in all languages. For such names, naturalists have wisely turned to the classical languages, Greek and Latin.

The early naturalists did, indeed, give each kind of animal but a single name. Thus, in the Roman Empire the cat bore the name *felis* and the horse was called *equus*. This scheme sufficed so long as only a few hundred kinds of animals were known and the scholars of the civilized world all lived in a relatively small area about the Mediterranean. But as culture spread during the Middle Ages, and animals from other regions were studied, it became necessary to accompany each name with a short diagnosis or description in order to distinguish it from some similar, previously known kind. Latin scholars at first used the name *felis* for the domestic cat, but they later became acquainted with the great tawny cat of Africa, as well as the spotted cat of the tropics.

When it became necessary to accompany the common name with sufficient adjectives or descriptive phrases to indicate clearly which kind

was meant, the great Swedish naturalist, Linnæus, devised the plan of giving each species a double name, the first representing the group (genus), the second a special or specific name for that particular kind. The latter is generally a descriptive or qualifying adjective standing in place of a descriptive paragraph, and, and in harmony with the Latin custom, it follows the word which it modifies. Thus, the house cat became *Felis domestica*, and the great spotted cat, *Felis leopardalis* (Lat. *pardalis*, spotted). The scientific name is, therefore, in reality a nickname, or an abbreviation of the longer diagnosis that would otherwise be required. The generic name is capitalized and the specific name is not.

Classification of Animals and Plants. In dealing with any large or complex group of objects, some scheme of classification or orderly grouping is required. To appreciate this fact, we need only contemplate an army of individuals without organization, a great library with the books placed at random on the shelves, or a dictionary with the words arranged by chance! Nowhere is the need for organization more keenly felt than in the study of the enormously varied forms of animal and plant life. Here, obviously, the most useful basis of classification is that of blood kinship, and a *biologic classification* has therefore been adopted which aims to group creatures according to their degree of actual relationship, regardless of superficial resemblances or differences.

In this biologic scheme, the animal and plant kingdoms are divided, first, into *phyla* (Gr. *phylon*, stock or race), each phylum including organisms that are alike in some fundamental anatomical characters. For example, animals with backbones form the phylum *Vertebrata* (Lat. *vertebratus*, having a backbone); those with jointed legs and bodies, such as insects, spiders, and crabs, form the phylum *Arthropoda* (Gr. *arthron*, joint, + *pous*, foot).

Each phylum in turn is divisible into classes, within which the resemblances are still closer. For example, among the vertebrates the fishes constitute one class, birds another, and mammals a third. Classes are further subdivided into *orders*. Thus, the class Mammalia includes the orders *Ungulata* (hoofed animals), *Carnivora* (flesh-eating types), *Rodentia* (gnawers like rats and squirrels), etc. Orders are divisible into *families*, and these in turn into *genera*, each genus including one or several kinds (*species*) of animals that are very closely related and structurally alike. For example, the cats form the genus *Felis*, and the dogs and wolves the genus *Canis*. The species is the next smallest unit, including individuals very closely alike.

ANIMALS

The following table presents in simple form the major subdivisions of the animal kingdom, groups that are wholly extinct being italicized.

A Simple Classification of the Animal Kingdom

Phylum **Protozoa** — single-celled, generally microscopic animals. Ex.: amœba, foraminifera, radiolaria, and many disease germs.
Phylum **Porifera** — sponges.
Phylum **Cœlenterata** — coral-like animals, lacking viscera.
  Class **Hydrozoa** — hydroids, *graptolites.*
  Class **Anthozoa** — corals and sea anemones, *tetracorals,* hexacorals, *honeycomb corals.*
Phylum **Platyhelminthes** — flatworms (never fossil).
Phylum **Nemathelminthes** — threadworms (never fossil).
Phylum **Trochhelminthes** — rotifers, all microscopic (never fossil).
Phylum **Brachiopoda** — brachiopods.
Phylum **Bryozoa** — " moss corals."
Phylum **Echinodermata** — echinoderms.
  Class **Asteroidea** — starfish.
  Class **Echinoidea** — sea urchins, heart urchins, sand dollars.
  Class **Crinoidea** — sea lilies or feather stars.
  Class **Blastoidea** — *sea buds* or *blastoids.*
  Class **Cystoidea** — *cystoids.*
Phylum **Mollusca** — molluscs.
  Class **Pelecypoda** — clams, oysters, scallops.
  Class **Gastropoda** — snails, conchs, etc.
  Class **Cephalopoda** — squids, devilfish, nautiloids, *ammonites,* and *belemnites.*
Phylum **Annelida** — segmented worms, earthworms, beach worms, etc.
Phylum **Arthropoda** — invertebrate animals with jointed legs.
  Class **Crustacea** — lobsters, crabs, *trilobites.*
  Class **Myriapoda** — centipedes, millipeds, etc.
  Class **Arachnida** — spiders, scorpions, *eurypterids.*
  Class **Insecta** — insects.
Phylum **Vertebrata** (Chordata) — animals with backbones.
  Class **Pisces** — fishes.
  Class **Amphibia** — salamanders, frogs, *stegocephalians.*
  Class **Reptilia** — crocodiles, turtles, *dinosaurs, ichthyosaurs, plesiosaurs, mosasaurs, pterodactyls,* snakes.
  Class **Aves** — birds.
  Class **Mammalia** — milk-feeding, warm-blooded animals (including man).

Phylum Protozoa

Single-celled animals constitute the phylum *Protozoa* (Gr. *protos,* first, + *zoön,* animal), so called on the assumption that it includes the most primitive types of animal life. Although widely distributed and extremely numerous, protozoans are nearly all microscopic and therefore seldom seen.

Each protozoan is a tiny droplet of fluid living matter inclosed in a membranous cell wall. Unlike higher animals, it has no special visceral organs for digestion, circulation, reproduction, etc. Food consists of other microscopic creatures, commonly plants, which are swallowed whole. Lacking a mouth, the little animal takes its food through a temporary rupture in its cell wall, and later voids the indigestible residue by the same means. Once in the body, the food particle is attacked by fluids that digest it, and the single-celled animal assimilates this food without the need of a circulatory system. When fully grown, the

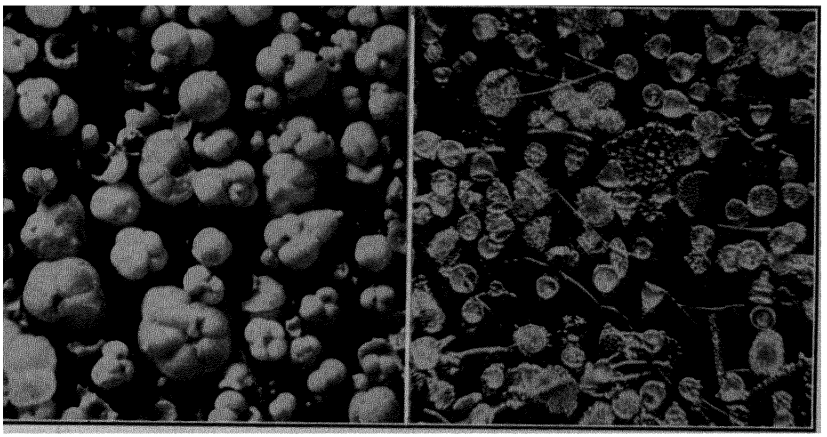


FIG. 161. Protozoan shells. Left, globigerina ooze, × 10, dredged from a depth of 2898 feet about 100 miles west of Martinique, West Indies. Right, radiolarian ooze, × 35, from the Miocene beds of the island of Barbados, West Indies.

tiny animal reproduces by simply splitting into two or more daughter cells, each of which is like the parent but smaller. Since the parent passes completely into its offspring, *there is no death* in the normal course of events for these simple creatures. Individuals may be killed, of course, by unfavorable environment or by other animals; this, however, may be considered accidental, for death is not the inevitable fate of each individual as it is with all higher animals.

Although protozoans probably exceed all other types of animal life combined, both in number of individuals and in total bulk, the vast majority are soft-tissued and incapable of fossilization. There are, however, two prolific groups of them that form delicate shells of calcium carbonate or silica, and have left an imposing record. These are the orders Foraminifera and Radiolaria.

The *Foraminifera* build tiny chambered shells, commonly of calcium carbonate. They inhabit all the oceans but are rarely found in fresh

waters. The majority live on the bottom or cling to seaweeds, but about 20 kinds float near the surface of the open oceans, whence their shells, abandoned at time of reproduction, rain down like a snowfall to cover the sea floor. The commonest of these is *Globigerina*, and the soft, fine-grained, limy deposit made mainly by its shells is known as *globigerina ooze* (Fig. 161). Approximately 50,000,000 square miles of the sea floor are now covered to an unknown depth by these deposits. At various times in the geologic past, foraminiferal shells have accumulated in shallow water to form extensive beds of chalk or limestone. The pyramids of Gizeh, for example, are made of a limestone that is widely spread in the Mediterranean region and is largely made of coin-shaped shells known as *nummulites* (Fig. 131, p. 211). Still older limestones of the late Paleozoic are formed of *fusulines*, a tribe having shells about the size and shape of wheat grains (Pl. 4, Figs. 4, 5, p. 175).

The *Radiolaria* (Fig. 161) make their shells of silica. Differing from the capsule-like shell of the foraminifer, these are of a loose, open texture, like a delicate glass sieve. They form deposits of radiolarian ooze on parts of the deep-sea floor.

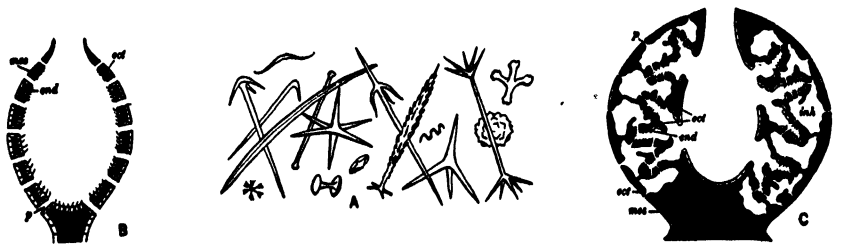


FIG. 162. Sponges. *B*, diagrammatic vertical section of a very simple sponge. *C*, similar section of a more complex sponge. *A*, various types of sponge spicules, greatly enlarged. *ect*, ectoderm; *end*, endoderm; *inh*, inhalant canal; *mes*, mesoglea; *p*, wall pore. From Brooklyn Museum of Natural History.

PHYLUM PORIFERA

The Porifera or sponges are multicellular animals in which there is little specialization of tissues. The "bath sponge" is but the silken skeleton of one highly specialized type. The essential features of the group are better displayed by a very simple sponge (Fig. 162, *B*). Such an individual has the form of a slender vase; there is nothing to it but a living *wall* surrounding a large hollow space. This wall is made up of three layers like a jelly sandwich, the outer layer being formed of protective cells (ectoderm), the inner of feeding cells (endoderm), and

the middle layer of a noncellular jelly-like substance (mesoglea). The endodermal cells feed as do protozoans, each capturing and swallowing other microscopic organisms; the ectodermal cells do not take food but absorb what is needed from the nearby endodermal cells. Thus no digestive or circulatory organs are required.

To strengthen this delicate wall, either mineral spicules or threadlike fibers of spongin, an organic substance allied to silk, are formed in the gelatinous layer. These are secreted by specialized cells and are united to form a loose meshwork. In the bath sponge the spicules are all made of spongin, but in many sponges the spicules are of silica or calcium carbonate (Fig. 162, *A*). The mineral spicules are commonly preserved, and some of these, found in the Pre-Cambrian rocks of the Grand Canyon, are among the oldest records of life on the Earth.

Phylum Cœlenterata

The third phylum of animals includes the *hydroids*, *corals*, and *jellyfish*. These, like the sponge, consist essentially of a body wall, lacking any internal organs, whence the name Cœlenterata (Gr. *koilos*, hollow, + *enteron*, inside cavity).

Hydroids. *Hydra* is a simple representative of the phylum, and particularly of the class *Hydrozoa*. A vertical section through its slender subcylindrical body (Fig. 163, *B*) shows a wall of three layers, as in the sponge. But in three respects it is vastly ahead of the sponge. First, it has muscular tissue that permits change of shape and even locomotion, and makes possible a circlet of muscular tentacles about the mouth with which to capture food; second, in the inner (endodermal) layer are special gland cells that excrete digestive juices into the central cavity; and, third, it bears stinging cells like those of the jellyfish, which can paralyze other animals that come in contact with it. The hydroid is thus able to capture, swallow, and digest animals almost as large as itself (Fig. 163, *A*).

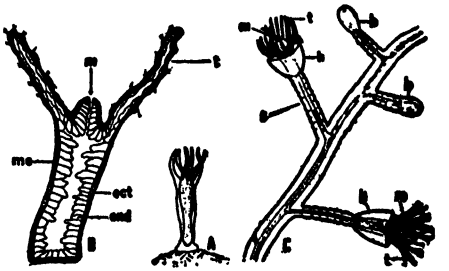


Fig. 163. Hydroids. *A*, *Hydra* devouring a young trout, × 2. *B*, diagrammatic vertical section of *Hydra*, much enlarged. *C*, a colonial hydroid, *Obelia*, with two adult individuals and two young buds. In *Obelia* a chitinous sheath covers the stem and expands into a bell-like chamber (*h*) about each individual; *b*, budding young individual; *ect*, ectoderm; *end*, endoderm; *h*, hydrotheca or sheath about the animal; *m*, mouth; *me*, mesoglea; *s*, stem; *t*, tentacles.

Hydras live as solitary individuals, but many hydroids reproduce by budding and thus form colonies of individuals organically united (Fig. 163, *C*). Many of these secrete a bell-like or vase-like sheath (hydrotheca) about their body as a protection. These sheaths are formed of chitin, a substance similar to finger nails.

The *graptolites*, commonly considered an order of hydroids,* lived in early Paleozoic time, forming slender colonies in which individuals were closely ranked along a common axis. They are generally preserved in dark shales where they are pressed flat and reduced to a film

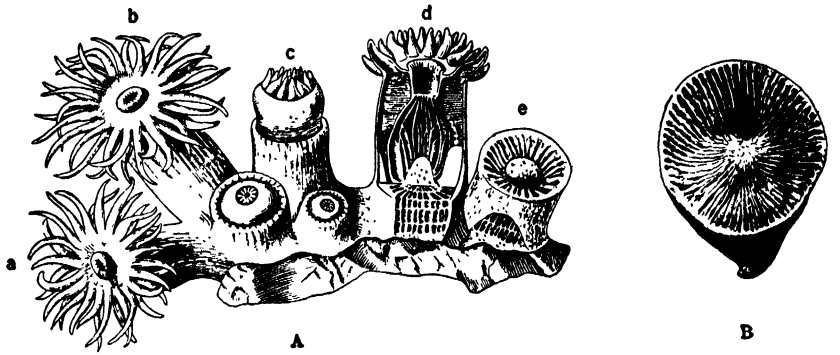


FIG. 164. Corals. *A*, portion of colony of a modern coral, showing relation of living polyps (*a–d*) to stony skeleton (*e*). *B*, a horn coral, showing bilateral symmetry characteristic of the Tetracoralla.

of carbon superficially resembling heavy pencil marks on the stone, whence their name (Gr. *graptos*, written, + *lithos*, stone) (Pl. 4, Figs. 6, 7, p. 175).

Corals. The corals and sea anemones form another class of this phylum, the *Anthozoa* (Gr. *anthos*, flower, + *zoön*, animal), so named because of their bright colors and flower-like symmetry (Fig. 164). The coral animal resembles *Hydra* in essentials, but with the addition of thin radial partitions (mesenteries) that extend from the wall into the central cavity, subdividing it into a series of alcoves.

The coral animal secretes about its side and base an external skeleton of calcium carbonate. The animal is correctly termed a *polyp*, and its skeleton, *coral*.

For some unknown reason the base of the coral polyp is invariably marked by radial infoldings, like the pleats in a skirt, which alternate in position with the internal mesenteries. The skeleton secreted against this base is marked by radial ridges or plates known as *septa*. Coral

*Kozlowski has advanced arguments for placing the graptolites with the hemichordates, lowly relatives of the vertebrates.

polyps may live singly, but many kinds reproduce by budding new polyps from the margins of the older and thus develop colonies in which many individuals co-operate to build a complex stony skeleton.

The skeleton of a solitary coral may be cushion-shaped or horn-shaped or subcylindrical, and usually has a cuplike depression at the summit in which the base of the polyp is housed. In colonial forms the skeleton is commonly branching or massive, with depressions for the bases of the individual polyps. *The radiating septa are absolutely distinctive of the coral skeleton and serve to distinguish it from all other types of shells.*

It is well known that corals thrive and make reefs in the sea, but only where it is warm and shallow. Accordingly, the coral reefs in the rocks of past geologic ages are regarded as evidence of mild temperature and of shallow water. Corals have been important agents in rock formation at various times in the past. At present, coral reefs occupy an area of about half a million square miles of the shallow seas, and their limy debris spreads over a vastly greater area.

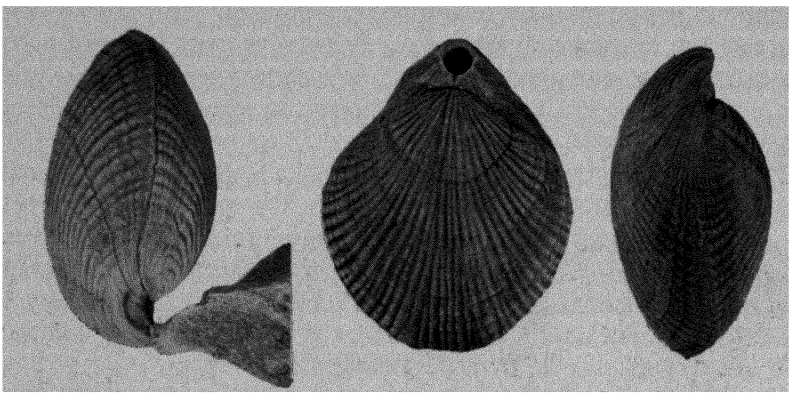
Nearly all modern corals belong to the subclass *Hexacoralla*. In these the radial symmetry is nearly perfect and the septa are multiples of six. This group has been the dominant one since the beginning of Mesozoic time. The subclass *Tetracoralla* (Fig. 164, *B*), on the contrary, which was dominant in the Paleozoic era, shows more or less conspicuous bilateral symmetry, with septa introduced in multiples of four.

Phylum Brachiopoda

The brachiopods constitute a phylum of rather small marine animals that invariably bear an external shell of two pieces (known as valves) (Fig. 165).

The body is much more complex than that of the coral, having a digestive system, kidneys, a nervous system, reproductive organs, and well-developed muscles. In life, the animal is attached to the bottom by a fleshy stalk (pedicle) at the posterior end, its mouth facing upward. The two valves of the shell are hinged together at the posterior end of the body and can be opened more or less widely at the front. They are borne on the back and ventral surfaces of the body (not on the sides), and thus a plane of symmetry passes through the middle of each valve. Special muscles open and close the shell, and a pair of interlocking teeth and sockets at the posterior end form a hinge. A hole (pedicle foramen) for the passage of the stalk is usually present near the apex of the ventral valve.

In so far as the brachiopod shell consists of two valves, it resembles the shell of a clam, but the likeness is purely superficial. The structure of body is quite unlike that of a clam, and the shell valves are borne in a wholly different position. In the clam, the valves are on the *sides* of the body and hinged *along the back;* in the brachiopod, they are



Yale Peabody Museum.

FIG. 165. A brachiopod, *Terebratulina*. Left, lateral view of shell in normal position of growth, attached to a piece of stone by a short, fleshy stalk; center and right, ventral and lateral views of the same shell in inverted position. The pedicle foramen is shown in the middle view.

borne on the *back* and *ventral* surfaces and hinged *across the posterior end.* As a result, the symmetry of the shell is dissimilar in these two groups, the brachiopod shell having unequal valves, each of which is *equilateral,* each half being a mirror reflection of the other, like the left and right sides of a coat. The valves of the clam shell are normally equal, right and left valves being mirror reflections of one another (except in deformed types like the oyster), but each valve is *inequilateral,* the front and hind ends being normally different in shape.

Brachiopod shells vary greatly in shape, some being strongly biconvex, others plano-convex, and others concavo-convex, the space between the valves in the last type being so thin that the animal must have had the proportions of a flatworm (Pl. 4, Figs. 17–24, p. 175). In many the hinge is short and the posterior end of the shell pointed or "beaked" as in Fig. 165; in others, it is long and straight and the shell is "square-shouldered." Some shells are smooth, many are ribbed, and some are spinose. In spite of the diversity of form, the brachiopod shell is easily recognized by the symmetry indicated above.

Brachiopods are rather small animals, the average length of shell

being between 1 and 2 inches. A few attained a diameter of 3 or 4 inches, and the largest that ever lived had a breadth of about 1 foot.

Phylum Bryozoa

The Bryozoa or "moss corals" form another important phylum little known to the general public, in spite of the fact that living forms are commonly attached to the rocks and seaweeds everywhere along the sea coast (Fig. 166). Anatomically the bryozoan is very simple and in many respects more like a brachiopod than other animals, but, unlike the brachiopod, it is invariably minute and always grows in colonies.

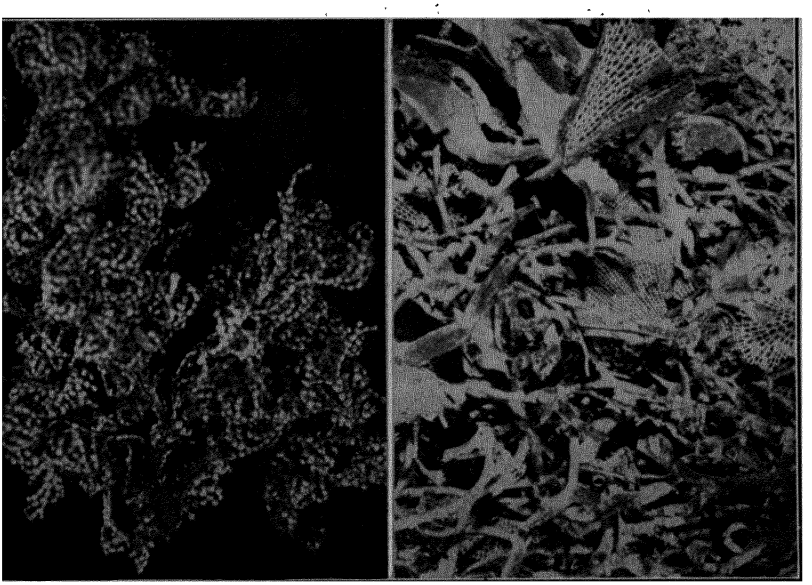


Fig. 166. Bryozoa. Left, a living colony of mosslike form, *Menipea;* right, fossil bryozoans of many kinds, weathering from a piece of Lower Devonian limestone. Natural size.

The individuals rarely attain a diameter much greater than that of a period on this page, but thousands of them living together may form a colony some inches across. Locally they combine to make reef limestones.

The form of the colonial skeleton varies enormously with different species. It may be branching and mosslike, whence the name (Gr. *bryon,* moss), or stemlike, leaflike, massive, or incrusting. In spite of all this diversity, the bryozoan skeleton is easily recognized because it is made up of minute tubules or cells.

Phylum Echinodermata

The *echinoderms* are peculiarly different from all other animals. This great phylum includes the starfishes, echinoids, crinoids, blastoids, and cystoids. Their bodies are short and commonly globular. Almost all have a radial and five-rayed symmetry. Nearly all develop a shell in the form of limy plates that are secreted in the body wall and fit edge to edge like the pieces in a mosaic. The types enumerated above represent five distinct classes which will be discussed in order.

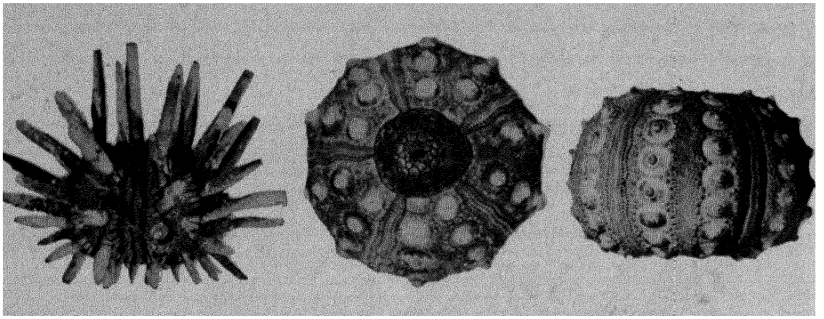


Fig. 167. *Cidaris*, a typical echinoid. Left, side view of young specimen with spines intact; center and right, top and lateral view of a larger shell with the spines removed so that the plates of the shell are visible. About ½ natural size.

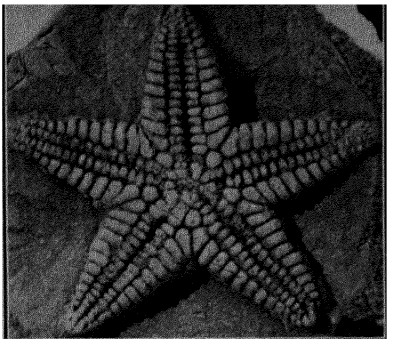
Echinoids or Sea Urchins. A typical echinoid (Fig. 167) has a globular or bun-shaped body bristling with slender, movable spines, whence the name (Gr. *echinos*, hedgehog). The mouth is at the center of the lower side, and the axis of the body is vertical. Stripping away the spines, we find the body wall of the animal to be a rigid, boxlike shell of polygonal plates arranged in twenty vertical columns. Upon these plates are scattered small rounded nubs, each of which was the pivot for a spine.

Radiating from the summit of the shell to the mouth are five paths along which the plates are thickly perforated with small double-barreled pores. These paths are the food grooves or *ambulacral areas*. In life each pair of pores bears a slender muscular organ known as a *tube-foot*. The tube-feet are part of a remarkable "*ambulacral system*," found only among the echinoderms, which serves for feeble locomotion, for the gathering of food, and for respiration. The body cavity is spacious and includes a well-developed digestive system, a nervous system, and reproductive organs.

We have described a typical sea urchin as a radially symmetrical animal, but there are some specialized types (heart urchins and sand dollars) in which a secondary bilateral symmetry has modified the

primitive, pentameral form. In all echinoids, however, a five-rayed symmetry is clearly evident even though somewhat irregular.

Starfishes. Next of kin to the echinoids, the starfishes are distinguished by their star-shaped form (Fig. 168), the body being depressed and extended at the sides into tapering rays. The skeleton is made of small limy plates, articulated by fleshy tissues so as to permit some flexibility as in a coat of chain-mail.



Yale Peabody Museum.

FIG. 168. A primitive starfish, *Devonaster eucharis*. Artificial cast from a natural mold in Middle Devonian sandstone of New York. Natural size.

Starfishes probably have been abundant since early Paleozoic time, but are rarely found as fossils, because their loosely joined plates fall apart with the decay of the flesh, and such small irregular plates are not easily recognized.

Crinoids. The crinoids or sea lilies (Fig. 169, *A*) look more plant-like than animal-like, for their globular bodies are supported by flexible stalks which anchor them to the sea floor, mouth upward. The animal consists of three chief parts, a *stem*, the *body* proper, and a series of branching *arms*.

In spite of its plant-like appearance, the crinoid is an animal, essentially comparable in its structure to a starfish, though in making this comparison we must turn the starfish with its mouth upward.

The body of the crinoid is covered by a series of limy plates which fit edge to edge like those of the echinoid. These plates are arranged in several horizontal rows, one above another, beginning at the upper end of the stem. Normally the plates in each cycle number five or some multiple of five so that five-rayed symmetry is the rule here as in the sea urchins and starfish. The stalk is strengthened by the secretion within it of a series of button-shaped limy plates which are superposed like buttons strung on a thread (Fig. 103, p. 177). These "stem joints" are united by muscular tissue so that the stem has flexibility enough to let the animal swing with the currents. The mouth is at the summit of the body, and from it the food grooves radiate on to the upper sides of the arms. Indeed, the arms are structures developed merely to extend the food grooves.

The living crinoids are brilliantly and beautifully colored with shades of lavender, purple, red, lemon-yellow, or brown, and it is small wonder

that the Greeks called them sea lilies. They tend to grow in patches on the sea floor and where present are commonly very abundant, so that they display much the appearance of submarine flower beds as they sway gracefully with the bottom currents. Upon the death of the animal its limy plates commonly fall apart.

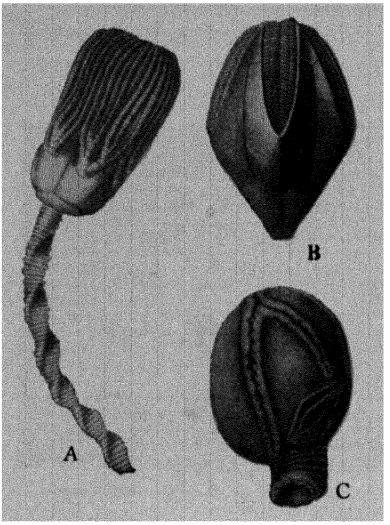


FIG. 169. Stalked echinoderms. *A*, a crinoid, *Platycrinus*, with part of its stem; *B*, a blastoid, *Pentremites*, without its stem; *C*, a cystoid, *Sphærocystites*, with most of its stem missing. Natural size. After Wachsmuth and Springer, Roemer, and Schuchert.

Blastoids. The blastoids or sea buds (Gr. *blastos*, bud) form another group of stalked echinoderms (Fig. 169, *B*). Their bodies are globular or bud-shaped and are incased in a shell of thirteen chief plates of which three form a basal cycle while two succeeding cycles have five plates each. There are no arms, the food grooves lying upon the surface of the body as they do in the echinoids. These food grooves are always simple, five in number, and arranged in perfect five-rayed symmetry about the mouth, which occupies the summit. The five ambulacral areas are submerged a little below the level of the chief body plates in such a fashion as to give the entire body a superficial resemblance to a flower bud in which the sepals are just beginning to part.

Blastoids are all extinct and are known only from Paleozoic rocks. They were very abundant during only one geologic period, namely, the Mississippian.

Cystoids. The cystoids (Gr. *cystis*, bladder) are primitive echinoderms with globular or almond-shaped bodies, but differ from both crinoids and blastoids in that their plates are irregularly arranged so that the body shows no definite symmetry (Fig. 169, *C*). They are extremely varied in details. Some had arms and others had none; many were stalked but some apparently were attached directly to the sea floor or were free. They were the most primitive echinoderms.

PHYLUM MOLLUSCA

This great phylum includes the clams, the snails, the devilfish, the squids, the pearly nautilus, and the extinct ammonites. These possess solid, limy, external shells, and they are commonly known as "shell-

fish." The phylum is an enormous one, with probably no fewer than 50,000 species now living.

Pelecypods. A typical clam has a laterally compressed body incased in a bivalved shell, the two halves of which lie on the sides of the body and are hinged along its back.

The body is generally elongated, and the mouth is at the front end but there is no distinctly marked head. Lining each valve there is a thin, fleshy extension of the body wall, the *mantle,* which hangs freely about the body like a loose garment. The most conspicuous organs are the great gills, which hang as a double pair of thin plates between the mantle and the sides of the body.

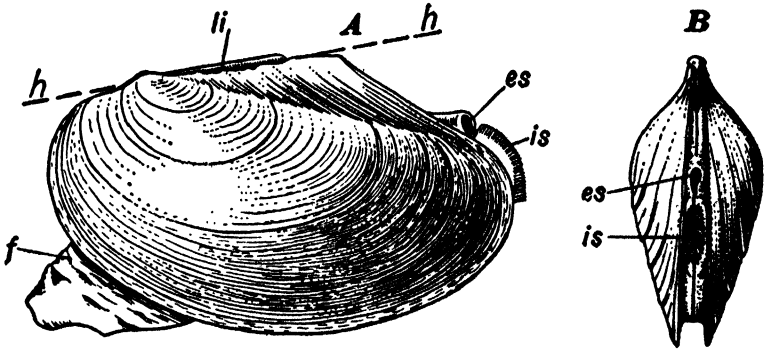


FIG. 170. Pelecypod. *A*, left side, and *B*, posterior end, of the fresh-water pearl clam, *Anodonta*. After Howes. *h–h* marks the hinge line of the shell, and *f* the muscular "foot" of the body. *is*, inhalant siphon; *es*, exhalant siphon; *li*, ligament.

The shell (Fig. 170) is opened by an elastic ligament at the hinge-line which is placed under tension (or in some cases under compression) when the valves are closed. The shell of most clams is closed by a pair of heavy transverse muscles which run through the animal's body from side to side. Normally one muscle is near the front and the other near the back end.

The typical clam is free to creep slowly about by thrusting out the ventral edge of its muscular body wall, which serves to draw the animal along. Secondarily, many clams have given up this freedom and lie on one side and adhere to the bottom as does the oyster, or attach themselves to the rocks by silken threads as does the blue clam. Still others burrow in the mud or even in hard rock.

The clam shell, like that of all other molluscs, consists of three layers. The outer one is a film of organic material to protect the limy part of the shell from solution. The second layer is of calcite and commonly

has a white, porcelain-like appearance, while the inner layer is made of aragonite or mother of pearl and has the iridescence of pearl. In fact, the precious pearl is a secretion formed between the mantle and the shell, usually in an attempt by the animal to protect itself against a parasite or other irritant.

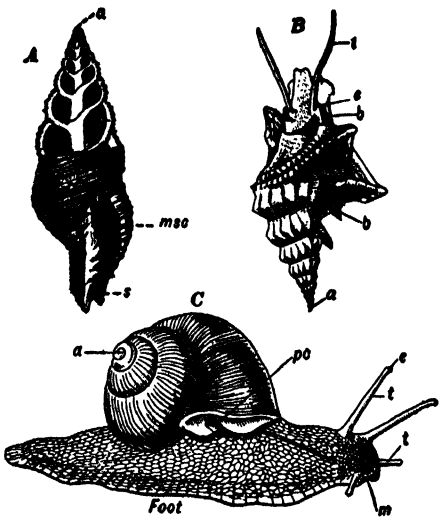


FIG. 171. Gastropods. *A*, empty shell with the front side of the spire cut away. *B*, another species with flaring aperture, showing the animal in creeping position, facing upward on the page. *C*, a land snail in creeping position, facing right. After Hatschek and Cori. *a*, apex of shell; *b*, creeping sole or "foot"; *e*, eye; *m*, mouth; *msc*, aperture of shell; *pc*, opening of cavity lung; *s*, siphonal canal.

Gastropods. Though fundamentally like the clam in many of its anatomical structures, the snail is in several ways more highly specialized. It has an elongate muscular body with a distinct head bearing a pair of eyes and a pair of tentacles or feelers. Its mouth is provided with a flexible rasping tongue whereby it can shred either plant or animal food; it is therefore not dependent on microscopic objects. As a result its gills are small and plume-like, since they are used only for respiration. Internal organs resemble those of the clam in most respects.

The shell of the snail is coiled spirally and consists of a single valve. As in the clam, the shell is secreted by a mantle so that the body may be measurably free.

When disturbed, the snail can withdraw completely into its shell, but normally it extends most of its body and creeps about, carrying the shell upon its back. The ventral surface of the body has developed into a muscular creeping sole, whence the group is known technically as the *Gastropoda* (Gr. *gaster*, stomach, + *pous*, foot) (Fig. 171).

Most commonly the gastropod shell is coiled in a helicoid (corkscrew-like) spiral, but many fossil forms are bilaterally symmetrical like a watch spring. Rapidly expanding shells have few volutions, but slowly expanding ones commonly have high, slender spires. The shell may be ornamented with spines, ribs, or nodes.

Cephalopods. The squids and devilfish represent a class of molluscs that has been abundant and important in all the seas since Paleozoic time. Unlike the sluggish snails and clams, they are active, alert, and

aggressive. With their keen eyesight and strong powers of swimming, they alone of all invertebrates are able to compete actively with the vertebrate animals of the seas. The living *giant squid* is the largest invertebrate animal of all time.

The name cephalopod (Gr. *cephale,* head, + *pous,* limb or foot) was suggested by the fact that all members of the class bear a circlet of fleshy limbs about the mouth which is at the front of the head.

The squid and devilfish are shell-less, but the pearly nautilus bears an external chambered shell, as did a host of forms known only as fossils. Here, then, are living examples of the two great subclasses of cephalopods. The first is represented by the squids, whose only shell is vestigial and internal; the second by the nautilus with its external, chambered shell. Obviously the shelled cephalopods are of chief interest to the geologist, since they alone are ordinarily preserved as fossils.

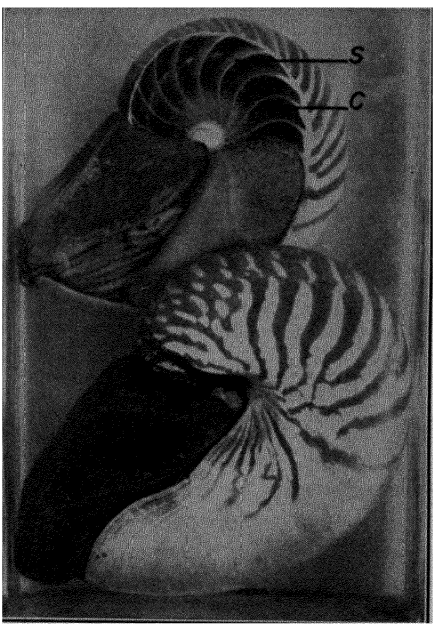


FIG. 172. Cephalopods. The pearly nautilus in its shell. The upper specimen has the left side of the shell cut away, revealing the gas chambers (*c*), separated by septa (*s*).

The cephalopod shell has essentially the form of a slender cone, which may be straight or coiled. If coiled, it is almost invariably in a flat spiral like a watch spring. The animal's body occupies only the larger end of the shell, the rest having been partitioned off into a series of chambers by transverse plates known as septa. In the living nautilus (Fig. 172) (and presumably in extinct types) the chambers are filled with gas and thus serve to buoy up the animal and its shell.

The chambers represent successive portions of the shell that were vacated as the growing body moved forward; and the partitions or *septa* are walls secreted against the bluntly rounded posterior end of the body to give it support after the animal has moved forward. These partitions are attached to the inner surface of the shell, and the line of junction is known as a *suture.* The form of the sutures and the course which they take in the shell are of great importance in the

classification of the cephalopods. Since the septa are formed within the shell the *suture is not visible externally, but in fossil forms where the chambers have been solidly filled with mineral matter and the outer shell then dissolved away, the sutures show clearly as sharp lines on the fossil* (Fig. 173). The animal retains connection with the abandoned chambers by a slender tube, the *siphuncle,* which runs back through all the septa. *Septa and a siphuncle are absolutely distinctive features of the cephalopod shell* and serve to distinguish it readily from that of the snail.

Nearly all the primitive cephalopods had straight shells (Fig. 102, p. 174), which, to an animal swimming backward, presented obvious disadvantages. Curved, loosely coiled, and tightly coiled shells were developed in order, and the forms with straight ones eventually became extinct. Besides being compact, the coiled shell brings the supporting gas chambers directly above the center of gravity, so that the animal can float at ease in the water.

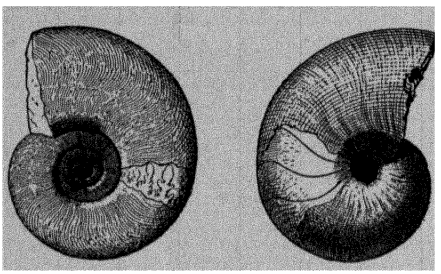


FIG. 173. Ammonite and nautiloid shells. Fossil cephalopods of comparable form, each having part of the shell removed to show the internal mold and the sutures. The simple form of the nautiloid suture (right) contrasts with the complexly flexed suture of the ammonite (left). After K. von Zittel.

Nautiloids. The shelled cephalopods are further divisible into two great orders. In the first the septa were simple, saucer-shaped plates secreted against the smoothly rounded posterior end of the animal's body. In these, of course, the sutures run directly around the shell as simple lines without marked flexures, as in the nautilus (Fig. 173). This order has been named, accordingly, the *Nautiloidea.* The pearly nautilus is their only living representative.

Ammonites. The ammonites, cousins of the nautiloids, also bore chambered shells; but in these the septa were fluted or ruffled near their edges, and as a result the sutures form highly irregular lines around the shell (Fig. 173). In the earliest ammonites the fluting of the septa was very slight and each suture showed only a few simple bends, but gradually the fluting became highly complex and the suture lines accordingly assumed a complicated form (Pl. 5, p. 205).

Belemnites. The belemnites (Fig. 129, p. 208) were squidlike cephalopods that lived only during the Mesozoic. They possessed a conical chambered shell like that of a primitive straight-shelled nautiloid, but it was internal, having been overgrown completely by flesh (Pl. 6, Fig. 12, p. 207).

Squids are closely related to the belemnites, but in the former the shell (also internal) is reduced to a mere vestige (the "pen").

Phylum Arthropoda

The insects represent a phylum of animals characterized by jointed walking legs, whence the name *Arthropoda* (Gr. *arthron,* joint). Other examples are the spiders, scorpions, lobsters, and crabs, and some important fossil groups such as the trilobites. All these have segmented bodies and jointed limbs. Their bodies are protected by a neatly fitting jointed armor made of chitin, an organic compound similar to our finger nails. In some, like the lobster and crab, this skeleton is strengthened by the addition of calcium carbonate. This is undoubtedly the largest and most diversified phylum in the animal kingdom.

Insecta. The insect possesses an elongate, bilaterally symmetrical body distinctly divided into head, thorax, and abdomen. The sharp constriction separating thorax and abdomen, as in the wasp, has suggested the group name (Lat. *insectus,* cut into). The abdomen is without limbs, but the thorax bears three pairs of walking legs and commonly two pairs (in one order, one pair) of wings. The head bears a pair of compound eyes and a pair of slender feelers or antennæ. The mouth is provided with specialized biting or sucking devices. The physical senses are rather highly developed.

Insects are too easily destroyed to be commonly preserved as fossils, but locally they are found as far back as the late Paleozoic (Fig. 114, p. 188).

Crustacea. The lobster and crab represent another great class of the arthropods, but, unlike the insects, these, and nearly all their kin, live in the water and breathe by means of gills. The name *Crustacea* (Lat. *crusta,* crust) refers to their hard, crustlike armor, but it must be confessed that many examples of the class do not have a hard shell.

In most Crustacea each of the segments of both thorax and abdomen bears a pair of jointed appendages (in some forms, part or all of the abdominal segments lack appendages). Commonly those on the thorax are walking legs (as in the lobster) and those on the abdomen are for swimming, but in many of the primitive Crustacea all the limbs are flattened swimming paddles. The gills are generally plumose and are borne as a branch of the legs.

Trilobites (Fig. 100, p. 169; Pl. 1, Figs. 8–15, p. 168) formed a primitive but exceedingly important group of Crustacea, now extinct and known only as Paleozoic fossils. In these the body was depressed and distinctly divisible into head, thorax, and tail. Head and tail

were each covered by an unsegmented shield, but the thorax was jointed. The entire body was longitudinally trilobed by reason of a pair of grooves that separated a rounded central axis from the lateral areas. *This trilobation is at once the most distinctive feature of the group* and the one which gave it the name *Trilobita.*

Like other Crustacea the trilobites usually possessed a pair of compound eyes and a pair of antennæ or feelers. Each body segment bore a pair of legs, and these were essentially alike from head to tail. Each leg consisted of two branches, the lower one of which was a jointed limb for crawling, while the upper and outer branch was a delicate, feather-like structure, commonly regarded as a gill.

Phylum Vertebrata

The most advanced of all animals are those possessing a vertebral column or backbone. So important is this phylum that it is often contrasted with all the other animals, which are known collectively as *invertebrates.* The vertebrates are characterized by the highly organized character of their nervous system, with the spinal cord running along the dorsal side of the body, and by many other important details, but *the possession of a backbone is the most obvious and distinctive character.* There are five distinct classes, as follows: *fishes, amphibians, reptiles, birds,* and *mammals.*

Fishes. Fishes are primitively aquatic vertebrates and therefore breathe by means of gills. They are cold-blooded. Normally they possess two pairs of lateral fins besides the unpaired dorsal and tail fins. In three of the four major groups of fishes, the skeleton is cartilaginous, and a true bony skeleton is present only in the last to appear geologically. Four of the great tribes of fishes deserve brief mention.

Sharks constitute the most primitive of these four groups. They are almost exclusively marine. The skeleton is entirely of cartilage, but the teeth and some of the fin spines are bony and are readily preserved as fossils. Sharks were exceedingly abundant in the middle and later Paleozoic seas and may have had much to do with the extinction of the trilobites, on which they probably fed.

The *dipnoans* (lungfish) constitute a tribe of fresh-water fishes that were common in later Paleozoic time but are now rare. Living representatives are confined to semiarid regions, such as southern Australia and central Africa. The structure and habits of these fishes are extraordinary. Their "swim-bladder" has a direct connection with the throat so that air can be drawn into it and expelled at will. Blood vessels in the walls of this delicate organ permit the absorption of

oxygen from the air within it, and thus the swim-bladder serves as a lung, supplementing the gills. *Protopterus* (Fig. 174), which lives in the Nile Valley, can thus gulp air when the water becomes foul. More than that, as the water gradually disappears, it wriggles down into the mud about a foot below the surface, and excavates for itself a small cavity which it lines with a mucous secretion to form a juglike chamber with but a small opening to the surface. Here the fish lies at rest like an animal in hibernation. Gradually the water disappears, the gills

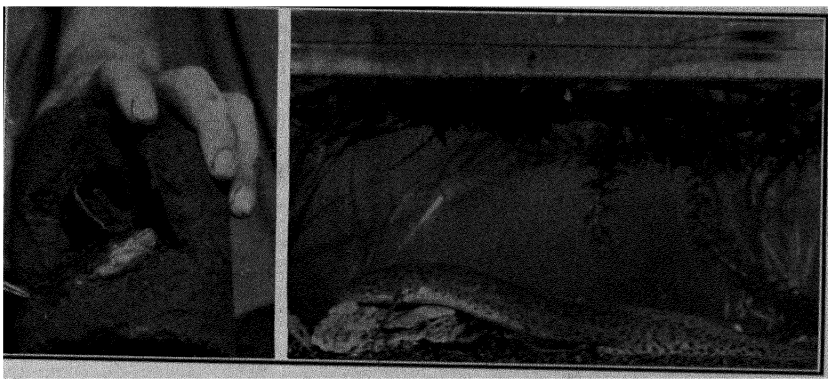


FIG. 174. The African lungfish, *Protopterus*. Left, the fish in its "cocoon" as it was shipped from Africa to Chicago in an open tin can. The shipment was in transit for more than six months, during which time the fish lived thus incased in dried mud. Right, the same after being placed in an aquarium. From *Turtox News*, through the courtesy of the General Biological Supply House, Inc.

become functionless, and the fish breathes wholly by means of its lung. After a period of three or four months, the water returns and the fish wriggles out of its retreat and swims about in the normal fashion.

The *ganoids* form another great tribe of fishes and one that completely dominated the Mesozoic seas. It is represented by the living "gar-pike" of the Mississippi River and its tributaries. The skeleton is cartilaginous. The swim-bladder has a definite connection with the throat, but in the gar-pike and in most other living types it does not permit air to be voluntarily inhaled and expelled. On the other hand, one group of the ganoids, represented by *Polypterus*, an inhabitant of certain African rivers, uses the swim-bladder as a lung precisely as do the dipnoans. These are the "fringe-finned" ganoids or *Crossopterygii*. Two features of this group are of extreme interest. In the first place, the swim-bladder is divided into two lobes, in this respect resembling the lungs of the air-breathing land vertebrates. In the second, the paired fins are thick and fleshy at the base and have stout skeletons made of cartilage that foreshadow the bony skeleton in the

five-fingered hand of the land animals (Fig. 110, p. 184). Because of this and other features of the *crossopterygians,* it is believed that they are the ancestors of the land vertebrates.

Bony fishes constitute the dominant tribe of living fishes and are well known, since they include our common game and food fish. In these the skeleton is made of bone. The swim-bladder is entirely isolated from the throat and lies in the upper part of the body cavity as a gas-filled float.

Amphibia. The frogs and salamanders constitute a class of vertebrates that are only partially adapted to life on the land and have many features to remind us of a fishlike ancestry. Indeed, they are certainly the most primitive class of land vertebrates, and they clearly



FIG. 175. A typical reptile, the Florida alligator.

evolved from fishes. The salamander is a typical representative of the class (the frog being a modern and extremely specialized form). Because its members live partly in water and partly on land, the class has received the name Amphibia (Gr. *amphi,* on both sides, + *bios,* life). *The metamorphosis from an aquatic youth (tadpole) to a terrestrial adult life distinguishes amphibians from all other land animals* (Fig. 14, p. 28).

Reptiles. The reptiles constitute a very large class of vertebrates and one that for long geologic ages completely dominated the Earth. The group includes the alligators (Fig. 175), crocodiles, lizards, turtles, and snakes, and the extinct dinosaurs and pterodactyls. The alligator is a very typical reptile.

Reptiles are cold-blooded, egg-laying animals. In shape, many of them closely resemble an amphibian, but they all differ from the amphibians in the way the young develop. The reptile lays its eggs on the land, i.e., out of the water. These are provided with stored-up food in the form of yolk so that the young can develop fully enough to crawl about and care for themselves immediately upon hatching. In other words, the reptiles are completely adapted for terrestrial life.

Although united by such features as their cold blood, their egg-laying habit, and various details of skeletal structure, the many different stocks of reptiles specialized greatly; some returned secondarily to an aquatic life, and one group, the extinct *pterodactyls,* became batlike creatures of flight.

Birds. The birds constitute a very well-defined class of vertebrates characterized by the presence of feathers and warm blood, and by the egg-laying habit. In them the front limbs are specialized as wings. The birds diverged from one group of reptiles at about the same time the mammals were developing from another.

Mammals. The mammals are warm-blooded. They bring forth their young alive and nourish them with milk. All of them bear hair, though in some, as the whale and the elephant, the hair is almost lost through specialization. They constitute the dominant group of land animals of the Cenozoic and modern worlds, and some (seals, porpoises, and whales) have secondarily returned to the sea.

The mammals did not appear on the Earth until early Mesozoic time, and there is clear evidence that the ancestral types descended from one of the primitive groups of reptiles.

PLANTS

A Simple Classification of the Plant Kingdom

Phylum **Thallophyta** — bacteria, fungi, seaweeds, etc.
Phylum **Bryophyta** — moss plants.
Phylum **Pteridophyta** — ferns.
Phylum **Arthrophyta** — scouring rushes, *calamites, sphenophylls.*
Phylum **Lepidophyta** — club mosses, "ground pine," *lepidodendrons, sigillarias.*
Phylum **Pteridospermophyta** — *seed ferns.*
Phylum **Cycadophyta** — cycads, *williamsoniellas, cycadeoids.*
Phylum **Coniferophyta** (gymnosperms) — *cordaites,* pines, sequoias, ginkgoes.
Phylum **Angiospermophyta** — flowering and fruiting plants, hardwood trees, etc.

Phylum Thallophyta

Plants of simple structure, such as bacteria, fungi, and seaweeds, are embraced for convenience in a single phylum, the Thallophyta (Gr. *thallos,* young shoot, + *phyton,* plant), so named because of their soft,

nonwoody nature. The *bacteria* are single-celled, microscopic, and soft-tissued. *Diatoms* are aquatic plants, likewise single-celled and microscopic, which live in vast numbers near the surface of the seas and lakes, and form one of the chief sources of food for all the marine animals. They secrete delicate siliceous shells which accumulate over large areas of the modern ocean floor as *diatom ooze.*



FIG. 176. Calcareous algæ. A " water biscuit " from the bed of Little Conestoga Creek, near Philadelphia, Pennsylvania. Left, external view of the colony; right, a median section showing the concentric laminæ of algal deposit about an angular pebble. Slightly less than natural size.

Plants probably evolved in the water and developed there for long ages before they could adjust themselves to the conditions upon the land. This is inferred, at least, from the fact that nearly all the *thallophytes* are still aquatic plants. Some of the seaweeds attain a length of 100 feet. Regardless of size, however, these plants have no woody tissue and no circulatory system, for they lack the vascular tissue that serves to conduct the sap in higher plants and at the same time forms woody growth. It is for this reason that they can not successfully leave the water. Those forms that do live on land, such as fungi and lichens, are all small, and grow only where there is considerable moisture. All the thallophytes have a simple system of reproduction by means of spores.

Most of the thallophytes are poorly adapted for preservation as fossils. A number of types of the algæ, however, cause the precipitation of calcium carbonate, which settles over them to form a limy deposit. Fig. 176 shows such a deposit (a " water biscuit ") formed by a mold-

like colony of microscopic blue-green algæ that covered a pebble in a stream bed. The deposit has a finely laminated texture due to the addition of concentric films of the calcium carbonate. Similar limy deposits occur in rocks of all ages as far back as the Archeozoic, and include the very earliest direct evidence of life on the Earth.

One group of these lowly plants, known as the *coralline algæ* or *nullipores,* plays a very important role in the formation of modern "coral reefs," commonly depositing as much as 25 per cent of the reef.

Phylum Bryophyta

This small phylum, including the mosses and liverworts, represents the simplest stage of adaptation to land life. Like the thallophytes, they lack vascular tissue, hence remain very small and thrive only in moist places. Almost nothing is known of them as fossils.

Phylum Pteridophyta

The great tribe of the ferns constitutes the phylum Pteridophyta (Gr. *pteris,* fern). They are the simplest of plants to be well adapted to land life. They have well-developed vascular tissue and are differentiated into roots, stem, and leaves. Whereas many of the ferns are small and herbaceous, the tree ferns of the tropics have woody trunks and commonly reach a height of 20 to 50 feet, bearing a crown of large fronds. Ferns are distinguished above all else by the fact that *they reproduce by means of spores borne on the under sides of the leaves or on slightly modified leaves,* never in strobili (or cones).

Ferns are among the oldest fossil land plants known, being recorded first in the Lower Devonian rocks. They have been a prolific tribe in all subsequent ages.

Phylum Arthrophyta

The scouring rushes and their kind constitute a well-defined tribe characterized by regularly jointed stems, whence the name (Gr. *arthron,* joint). The existing horsetail or scouring rush (*Equisetum*) grows abundantly in moist places in many parts of the country. In all the arthrophytes the stem has only a thin cylinder of woody tissue around a large center of pith. Reproduction is by means of spores which are borne in strobili at the tips of the stems.

Modern arthrophytes are mostly small and the race is decadent, having passed its climax in the late Paleozoic, when giant scouring rushes (calamites) grew to the height of trees and had stems as much as 12 inches in diameter (Fig. 105, p. 179).

Phylum Lepidophyta

The *scale trees* or lepidophytes (Gr. *lepis*, scale) constitute another well-defined tribe of plants that occupy a humble place in the modern world but were very important in the Paleozoic forests (Fig. 106, p. 180). The ground pines or club mosses are modern examples. Like the arthrophytes, these plants bear spores in strobili at or near the tips of the stems.

Many of the Paleozoic species attained the size of forest trees. In these the leaves, when shed, left prominent scars regularly spaced over the bark of the trunk and limbs (Fig. 107, p. 181). The name lepidophyte refers to these characteristic markings.

Phylum Pteridospermophyta

The oldest and most primitive seed-bearing plants were fernlike in everything but their fructification, whence the name (Gr. *pteris*, fern, + *sperma*, seed). They are commonly known as *seed ferns*.

The distinction between the spore-bearing and seed-bearing plants is comparable to that between the egg-laying and the viviparous animal, both in its nature and in its significance. The egg is a simple cell, deposited to hatch into an embryo that must look out for itself at a very immature stage of its development; the spore, likewise, is a single cell cast free to generate and grow as best it can. On the other hand, the viviparous animal retains the egg in the mother's body until it has developed into an embryo of considerable complexity before birth liberates it to shift for itself. Similarly, the seed is an embryo plant formed after the fertilization of the ovum, which is retained and nourished by the mother plant until considerable size has been attained and food is stored up to give the new plant a good start in life. The development of seed is a very considerable specialization. That it was an obvious advantage is suggested by the dominance of seed-bearing plants on the modern lands.

The seed ferns were common from the late Devonian to the end of the Paleozoic, when they died out, having given rise meanwhile to other phyla of seed-bearing plants.

Phylum Cycadophyta

The living sago palms or cycads represent an extensive tribe, mostly extinct, which has particular interest as the probable connecting link between the seed ferns and all higher plants, especially the true flowering plants (angiosperms). It is a great phylum, divisible into two well-

marked orders, the one (*Cycadeoidea*) entirely extinct, and the other (*Cycadales*) represented by the modern cycads. The cycads (Fig. 115, p. 191) possess short trunks and large pinnate leaves, and bear seeds in loose cones. The trunk is heavily armored with persistent leaf bases.

The cycadeoids (of late Paleozoic and Mesozoic age) bore conspicuous flowers.

Phylum Coniferophyta

The conifers constitute another great tribe of rather primitive seed plants characterized by the development of their seeds in cones, and, generally, by evergreen foliage. The leaves are as a rule needle-like or strap-like and have parallel veins. There are several orders. The pines are typical.

The oldest group of conifers is that of the *cordaites*, which were common in the forests from Devonian to Permian time. Unlike the later conifers, they had large, strap-like leaves, and their seeds were loosely arranged in racemes instead of being compacted into cones.

Other groups, including the pines, araucarians, and ginkgoes, are known throughout the Mesozoic and later periods.

Phylum Angiospermophyta

The most advanced of all plants are the hardwood trees and the true flowering plants, included in the phylum Angiospermophyta, of which at least 125,000 kinds have been described. They are all, of course, seed-bearing, but show a great advance over the other seed-bearing phyla in that their seeds are protected in a closed capsule or ovary. For this reason they are known as angiosperms (covered seed) in contradistinction to the gymnosperms (naked seed), which include the seed ferns, conifers, and cycads.

The angiosperms are commonly characterized as *the flowering plants*, but this is hardly justified, since even the conifers and cycadophytes have flowers of a sort, and many of the latter had large and complicated flowers, probably rivaling in size and brilliance the best of the angiosperms.

The angiosperms are first identified in the Lower Cretaceous rocks, where the characteristic net-veined leaves of deciduous trees make their appearance.

INDEX

(Asterisks refer to illustrations)

A

Acadian disturbance, 14*, 86–89
Acadian geosyncline, 78*, 79, 87
Acadian Mountains, 78*, 79, 80*, 81
Adirondack arch, 85
Africa, rift valleys in, 145
Aftonian interglacial age, 152, 160*, 161, 240
Age of Mammals, 213–236
of Reptiles, 190–209
Alaska, 121, 145
Algæ, 278–279
Algoman granite and mountains, 70
Algoman revolution, 14*
Alligators, 212, 276
Alps, 125, 144, 149
Amarillo Mountains, 91
Amber, insects in, 39, 42*
Amblypods, 217*, 218
Ammonites, 172, 205*, 208, 272
Amphibians, 28*, 184–186, 276
"Ancestral Rocky Mountains," 92
Andes Mountains, 125, 144, 145, 149
Andesites, Eocene, 142
Angara Shield, 60*, 73
Angiosperms, 192–193, 281
Animals, classification of, 258
Annelids, 170*
Anthozoa, 262
Antilles, 145
Apes, great, 230, 233
Appalachia, 76*, 77, 78*, 79, 80*, 81, 82, 91, 99
Appalachian geosyncline, 76*, 77, 78*, 79, 80*, 81, 87
Appalachian Mountains, 80*, 89–92, 103, 104*, 126–128
Appalachian revolution, 14*, 89–92
Arbuckle Mountains, 91
Archæopteryx, 202–203
Aridity, Mesozoic, 122, 123
Miocene, 146
Aridity, Pennsylvanian-Permian, 99–100
Silurian, 94–95
Armor, invention of, by animals, 169, 171
Art, Cro-Magnon, 252
Arthrodires, 182
Arthrophytes, 279
Arthropods, 273
Artifacts, 237–240
Atlantic Coastal Plain, 125, 128–129
Austin quarry, New York, 85*
Australia, Cretaceous glaciers in, 122
Permian ice age in, 101

B

Bacteria, 278
Baltic Shield, 60*, 73
Barton geosyncline, 129
Basalt, Cenozoic, 138–139, 142, 143, 145
Basin and Range province, 135*, 137, 141*, 143
Basins, deep-sea, 10
Batholiths, Cascade Mountains, 142
Mesozoic, 111, 113
Paleozoic, 90*
Sierra Nevada, 140
Bats, 231
Bears, 229
Belemnites, 207*, 208, 272
Belly River formation, 120
Beltian system, 65–67
Beresovka mammoth, 34–35
Bering land bridge, 220, 226, 232
Big Bone Lick, Kentucky, 46
Big Horn Basin, 130
Birds, 277
Cenozoic, 212–213
Mesozoic, 201–203
Blastoids, 175*, 176, 268
Blue Ridge fault, 90
Bogs and fossils, 44, 45, 46

Boulder Batholith, 113
Brachiopods, 168*, 174, 175*, 176, 263–265
Brains, mammalian, 214
Breaks, 11, 12
Brontosaurus, 195*
Bryophytes, 279
Bryozoa, 176, 265–266
Burgess shale, 169, 170*

C

Calamites, 179, 279
Californian geosyncline, 104*, 110, 140, 141*
Callville formation, 8, 9
Cambrian, 13, 14*, 76*, 79, 84
  life, 167–172, 174, 176, 177
  paleogeography, 76*
Camels, 222–223, 234
Canadian Shield, 60, 67–73, 76*, 78*, 80*, 82, 162
Carnivores, 227–229
Carpathian Mountains, 144
Cascade Mountains, 135*, 142, 143, 147
Cascadia, 76*, 77, 78*, 79*, 80*, 82*
Cascadian revolution, 14*, 131, 142
Casts, 39
Cats, 228–229
Catskill delta, 78*, 87–89, 178
  formation, 95
Caucasus Mountains, 149
Cave dwellers, 241–242
Caves and fossils, 43, 44*
Cenozoic, 125–166
  climates, 145–146
  length, 23, 125
  life, 210–236
  paleogeography, 124*, 213–236
Cephalopods, 172, 173*, 174*, 205*, 207*, 270–273
Cestracionts, 183
Chinle formation, 114*, 115, 116*
Cincinnatian series, 13
Civilization, beginning of, 253
Clams, *see* Pelecypods
Classes, 257
Climates, Cenozoic, 145–146
  Mesozoic, 121–123
Climates, Paleozoic, 92–103
Coal, Pennsylvanian, 82–83, 96–99
Coast Range Batholith, 111
Coast Ranges, 135*, 141*, 142
Coconino sandstone, 7, 9
Cœlenterates, 261–263
Colorado Mountains, 83
Colorado Plateau, 114, 134–136, 143
Colorado, Texas, implements at, 254
Columbia Plateau, 135*, 138–139, 143
Columbian geosyncline, 104*, 110
Comanche series, 119
Condylarths, 219
Conifers, 181, 281
Connecticut fault troughs, 108–110
"Continental drift," 102–103
Copper, Pre-Cambrian, 73
Coprolites, 41
Coral reefs, 93, 98, 99*
Corals, 122, 175*, 176, 208, 262–263
Cordaites, 178, 181, 281
Cordilleran geosyncline, 76*, 77, 78*, 79*, 80*, 81, 82*, 93
Correlation, 6–10
Coryphodon, 219
Craters of the Moon National Park, 140
Creodonts, 217*, 218
Cretaceous, 14*, 107, 111–113, 118–121, 134
  climate, 121–122, 123
  life, 191–193, 197–201, 202–203, 204, 205*, 206, 207*
  paleogeography, 5, 106*
Crinoids, 175*, 176, 177*, 267–268
Cro-Magnon man, 240, 251–253
Cromer flints, 244
Crossopterygians, 182–183, 184*, 275–276
Crustaceans, 273–274
Crustal movements, and evolution, 12
  as basis for chronology, 10–11
  Cenozoic, 126–128, 131, 134–142, 144–145
  Mesozoic, 105, 108–113, 120
  Paleozoic, 81, 84–92
Cultures, human, 239–240
Cycadeoids, 191, 280–281
Cystoids, 175*, 268

D

Dakota sandstone, 112*, 113*, 119
Dates, geologic, 23
Dead sea, Permian, 99–100

DeGeer, G., 158–160
Deltas, Devonian, 87–89
  Permian, 99
Deserts, Permian, 99–100
  Silurian, 94–95
Devilfish, 270, 273
Devonian, 14*, 81, 87, 92
  climate, 95–96
  life, 173*, 174, 175*, 176, 177–178, 182–185, 187
  paleogeography, 78*
Diatoms, 278
Dinaric Alps, 144
Dinosaurs, 41, 108, 109, 194–198
  eggs of, 198
Dipnoans, 182–183, 274–275
Dire wolf, 226*, 228
Disturbances, 10–11, 13
Dogs, 228
Drainage, Pleistocene, 162–163
Drift, Pleistocene, 153–156
Driftless area, 149–150
Dunkard series, 90
Dwyka tillite, 100, 101*

E

Earth, age of, 16–23
  origin of, 57–59
Echinoderms, 175*, 266–268
Echinoids, 176, 207*, 266
Elephants, 224–227
Embryology and evolution, 28–29
Eocene, 14*, 128, 129, 134, 142, 144, 145
  climate, 145, 146
  life, 231
  paleogeography, 124*
Eohippus, 218*, 219–220
Eoliths, 238*, 239
Epochs, 13
Eras, 12
Esmeralda flora, 146
Evolution, 24–33
  and geologic chronology, 11–12
  evidences of, 30–31
  method of, 31–33

F

Falls of St. Anthony, 156–158
Families, 257
Faulting, Basin and Range Province, 137
Faulting, Newark series, 108–110
  Sierra Nevada, 140
Faunal succession, law of, 6
Feet, mammalian, 215–216
Ferns, 178, 191, 279
Finger Lakes, 164
Fishes, 274–276; *see also* Sharks, etc.
  Devonian, 96
  fresh-water, 182, 185–186
  oldest, 182
Flint workers, England, 243–244
Floras, *see also* Plants
  cosmopolitan, 181
Florida, in Cenozoic, 128, 129
Folsom, New Mexico, implements at, 254
Footprints, 39, 41, 42*, 183, 195
Foraminifers, 175*, 177, 211, 259–260
Forests, fossil, Mesozoic, 190–191; *see also* Plants
  of Arizona, 115, 190
  of Yellowstone, 46, 142, 143
  oldest, 177, 178
"Fossil controversy," 49–51
Fossil Forest of Arizona, 115, 190
Fossils, 34–55
  and chronology, 11–12, 53
  as evidence of evolution, 30–32, 52–53
  climatic implication of, 52
  distortion of, 47, 48*
  geographic significance of, 51–52
  interpretation of, 47–53
  marine, 47
  nature of, 34–37
  preservation of, 37–47
  reconstruction of, 53–55
Foxhall flints, 244
Franciscan series, 118
Front Range, 112, 113*
Fusulines, 175*, 177, 260

G

Ganoids, 275–276
Gaspé delta, 88
Gastropods, 168*, 172, 173*, 207*, 270
Genera, 257
Geologic column, 5–10, 13–15
Geologic time chart, 13–15

Geologic time, scale of, 16–23
Geosynclines, 4; *see also* Appalachian, Cordilleran, etc.
  Mesozoic, 105–107
  Paleozoic, 77
Giants Causeway, 145
Gibbons, 230
Gilboa forest, 96, 178*
Ginkgoes, 191
Glacial ages, 151–152
Glacial Lake Agassiz, 157*, 158, 162, 164, 166
Glacial Lake Algonquin, 161
Glacial time, scale of, 160*
Glaciation, Permian, 100–103
  Pleistocene, 147–166
  Pre-Cambrian, 71, 74
Glacier National Park, 147
Globigerina ooze, 259*, 260
Gowganda conglomerate and tillite, 70*, 71
Grand Canyon, 7–9, 134–136
  Pre-Cambrian of, 61–64
Grand Canyon disturbance, 63*, 64
Grand Canyon system, 61*, 62–64
Granite, Pre-Cambrian, 67–69, 70, 73
Graptolites, 175*, 177, 262
Grass, fossil, 210–211
Grazing teeth, evolution of, 210–211, 232
Great Lakes, development of, 163–166
Green River Basin, 130
Greenland, 93, 121–122, 145
  ice center, 150*
Grenville limestone, 68*
Ground-sloths, 36*, 235
Gumbotil, 154
Gypsum, Mesozoic, 122, 123
  Permian, 100
  Silurian, 95

H

Harrisburg surface, 126*, 127
Hermit shale, 7
Hesperornis, 202, 203*
Hexacorals, 263
High Plains, 133
Himalayas, 125, 144, 145, 149
Holloman quarry, Oklahoma, implements at, 254
Homo diluvii testis, 49, 50*
Homologous structures, 26–27
Horses, fossil, 30–31, 218*, 219–221, 234
Huronian system, 14*, 70–72
Hutton, James, 16
Hydroids, 261–262

I

Ice age, Permian, 100–103
  Pre-Cambrian, 70, 71
Ice, Pleistocene, 147–166
  direction of flow of, 149
  distribution of, 147–151
  drainage changes from, 162–165
  duration of, 156–161
  effects of, 161–166
  thickness of, 150–151
Iceland, 145
Ichthyornis, 202
Ichthyosaurs, 40*, 200, 201*
Idaho Batholith, 111*, 113
Illinoian drift, 152, 154, 155, 160
Illinoian glacial age, 160, 240
Illinois River, 164
Imprints, 39
India, Permian ice age in, 101
Insectivores, 206, 216
Insects, 273
  in amber, 39, 42*
  Mesozoic, 206
  Paleozoic, 188
Interglacial ages, 151–152, 160, 240
Intertonguing of formations, 9
Invertebrates, Cenozoic, 211
  Mesozoic, 206–209
  Paleozoic, 167–177, 187–189
Ipswich flints, 244
Iron ore, Lake Superior, 71–72

J

John Day Basin, 143
Judith River formation, 120
Jurassic, 14*, 105, 107, 121, 134
  climate, 121, 122–123
  life, 195–201, 201–203, 204, 205*, 206, 207*, 208, 209
  paleogeography, 104*

K

Kaibab limestone, 7
Kansan drift, 154*, 155, 156*, 160

Kansan glacial age, 160, 240
Keewatin ice center, 149, 150*, 155, 162
Keewatin lavas, 14*, 69
Keweenawan system, 14*, 72–73
Keyhole brachiopod, 28–29
Killarney mountains, 14*, 73
Knoxville formation, 118

L

Labrador ice center, 149, 150*, 154, 155, 162
Lake Michigan, 163, 165*
Lake Superior, 163, 164, 165*
  iron ore 71–72
Land animals, first, 183
Land bridges, 220, 226, 232, 235
Land plants, first, 177–178
Lands, erosion of, 2
Laramide Mountains, 106*, 107
Laramide revolution, 14*, 111–113, 137
Laramie River, course of, 133
Laramie series, 107, 120
Latah formation, 139
Laurentian gneiss, 68*, 69
Laurentian revolution, 14*
Lavas, Cenozoic, 138–139, 142
  Pre-Cambrian, 69, 72–73
Leda clay, 162
Lemuroids, 230
Lepidodendron, 179–180
Lepidophytes, 280
Lewis thrust, 112
Lewis tongue, 120
Life, Cenozoic, 210–236
  Mesozoic, 190–209
  Paleozoic, 103, 167–189
  Pre-Cambrian, 66, 75, 169
Lizards, 212
Llanoria, 76*, 77, 80* 81, 82, 91, 99
Loess, 155, 156*
Lungfish, 182–183, 185–186, 274–275

M

Malaysia, 2*, 81
Mammals, 213–236, 277
  archaic, 214*, 230–231
  Cenozoic, 213–236
  evolutionary trends in, 213–216
  Mesozoic, 203–206
  modernized, 219–230
Mammoth, imperial, 227
  woolly, 37, 45, 161, 227, 233, 236, 243
Man, fossil, 237–255
  chronology of, 240, 242
Man, Cro-Magnon, 240, 251–253
  family tree of, 229–230
  in North America, 253–255
  Java, 240, 244–245, 250
  Neandertal, 240, 247–250
  Paleolithic, 240–253
  Peking, 240, 245–247
  Piltdown, 240, 250–251
Marcellus shale, 87
Mariposa slate, 118
Marsupials, 204, 206, 216
Martic thrust, 90
Mastodons, 224–226, 232
  American, 226, 233, 234*
Mesa de Maya, 143, 144*
Mesa Verde sandstone, 119–120
Mesocordilleran geanticline, 106*, 107, 113
Mesozoic, 105–123
  climate, 121–122
  length, 23, 125
  life, 190–209
  paleogeography, 5*, 104*, 106*
Metals, first use of, 240
Mexico, volcanoes, 143, 145
Millipeds, 187
Minnesota, human remains in, 255
Minnesota River, 157, 158
Miocene, 14*, 129, 133, 137, 139, 140, 142, 143
  climate, 146
  life, 232–233
Miring and fossils, 44, 45*
Mississippi delta, 129
Mississippi River, 157, 158
Mississippian, 14*, 81, 91, 92
  life, 176, 183
  paleogeography, 80*
Missouri River, 163
Moas, 213
Moenkopi formation, 114, 116*
Mœritheres, 224*, 225
Mohawk Valley, 164
Molasse, 144
Molds, 39, 41*
Mollusca, *see* Shellfish

Monkeys, 230
Morosaurus, 195*
Morrison formation, 107, 114*, 116*, 117, 123, 144*
Mosasaurs, 200, 201*
"Mother Lode," 111
Mountains, *see also* Appalachian, Rocky, etc.
  Cenozoic, 141–145
  erosion of, 2–3
  late Paleozoic, 81, 82
  Mesozoic, 111–113
  Pre-Cambrian, 73
Musk-ox, 235

N

Natural selection, 32–33
Nautiloids, 172, 272
Navajo sandstone, 114*, 116*, 117
Nebraskan drift, 154*, 155, 160
Nebraskan glacial age, 160*, 240
Neolithic man, 240, 253
Neoliths, 238*, 240
Nevadian disturbance, 14*, 110–111
New Zealand, 149
Newark fault troughs, 104*, 108–110
Newark series, 108–110
Niagara Falls and Gorge, 158, 164
Nickel, Sudbury, 73
Niobrara chalk, 119
North and South parks, Colorado, 112, 130
Nullipores, 279
Nummulites, 211, 260
Nut-jay, 32

O

Ohio River, 162–163
Old Red sandstone, 95–96
Old Stone Age, men of, 243–253
Oligocene, 14*, 129, 134, 140, 143, 144
  climate, 145
  life, 232
  paleogeography, 124*
Onondaga limestone, 87
Orders, 257
Ordovician, 14*, 81, 84–86, 92
  life, 171, 172, 173*, 174, 175*, 176*, 182
  paleogeography, 76*
Oreodonts, 223–224
Orogeny, *see also* Crustal movements
  Cenozoic, 140–143
  Mesozoic, 110–113
  Paleozoic, 81, 84–92
Ostracoderms, 182
Ostracods, 171–172
Ottawa Valley, 164
Ouachita geosyncline, 76*, 77, 81
Ouachita Mountains, 80*, 91, 104*

P

Pacific Coast, development of, 140, 141*
  geosyncline, 104*, 118
Painted Desert, 114
Paleocene, 14*
  life, 216–219, 230–231
Paleogeography, 1–5
  Cenozoic, 124*
  Mesozoic, 5*, 104*, 106*
  Paleozoic, 76*, 80*, 82*
Paleoliths, 238*, 239
Paleozoic, 77–103
  climate, 92–103
  length, 23, 125
  life, 167–189
  paleogeography, 76*, 78*, 80*, 82*
Palisade disturbance, 14*, 105, 110
Pamir Range, 149
Panama land bridge, 235
Paradox formation, 97
Payette formation, 139
Peking man, 240, 245–247
Pelecypods, 174, 269–270
  Mesozoic, 207*, 208
  Paleozoic, 173*, 174, 187
Pennsylvanian, 14*, 82–83, 91, 92
  climate, 96–99
  life, 172, 173*, 175*, 177, 178–181, 185, 186, 187, 188
  paleogeography, 80*
Periods, 13, 14*
Permian, 14*, 82, 89, 90, 91, 92, 99–103
  climate, 99–103
  life, 173*, 177, 181, 186, 187*, 188
  paleogeography, 80*
Petrifaction, 38
Phyla, 257
Phytosaurs, 115
Piltdown man, 240, 250–251

Pithecanthropus, 240, 244–245, 250*
Planets, 57*, 58
Plants, 277–281
  Cretaceous, 191–193
  first land, 177
Plants, flowering, 192–193, 281
  Pennsylvanian, 178–181
  Triassic, 190–191
Pleistocene, 14*, 131, 137, 140, 142, 143, 147–166
  calendar, 152
Plesiosaurs, 200, 201*
Pliocene, 14*, 129, 131, 133, 137, 140, 142, 143, 144
  climate, 146
  life, 233
  paleogeography, 124*
Pocono delta, 80*
Porifera, 260–261
Prairies, spread of, 210–211
Pre-Cambrian, 14*, 56–75
  climate, 71, 74
  life, 66, 75, 169
Primates, 218, 229–230
Protozoa, 258–260
Pteridophytes, 279
Pteridospermophytes, 280
Pterodactyls, 40*, 198–200
Puget Sound, 142
Pygope, 28–29

Q

Queenston delta, 76*

R

Radioactivity, as measure of time, 20–23
Radiolaria, 259*, 260
Rain, first, 59
Rainbow Bridge, 114
Rameses II, statue of, 17*
Rancho La Brea, 44–45
Raton Mesas, 143, 144*
Recapitulation, law of, 28–29
Red beds, Devonian, 96
  Mesozoic, 114–118
  Permian, 100
Redwall limestone, 7*, 8
Reefs, coral, 93, 98, 99*, 121
Reindeer, 235, 243
Reptiles, 276–277; *see also* Dinosaurs, etc.
  Age of, 190–209
  Cenozoic, 212
  marine, 200–201
  Mesozoic, 121, 193–201
  Paleozoic, 186, 187*
Rhinoceroses, 221, 232*
Ridgway tillite, 122, 146
Rocky Mountain geosyncline, 104*, 105–107, 111, 118–121
Rocky Mountain peneplane, 131–134
Rocky Mountains, 107, 125, 129–134, 135*, 147
  ancestral, 92
  birth of, 111–113
  northern, Pre-Cambrian of, 65–67
Rodents, 218

S

Saber-toothed cats, 45*, 227*, 228*, 229, 234
St. Anthony Falls, 156–158
St. Croix River, 157
St. Lawrence Valley, 164
Salina formation, 94–95
Salt, oceanic, as measure of time, 18–20
  Permian, 100
  Silurian, 94–95
San Juan Mountains, Colorado, 122, 143
San Rafael group, 117
Sangamon interglacial age, 160, 240
Sauropods, 195–197
Scale trees, 178*, 179, 191, 280
Schooley peneplane, 126*, 127
Scientific names, 256–257
Scouring rushes, 178, 179, 191, 279
Sea urchins, 266
Sealevel, Pleistocene, 161
Sediments, as measure of time, 17–18
Seed ferns, 178, 179, 280
Sequoia, 192
Series, 13
Sharks, 182, 183, 274
Shellfish, 268–273; *see also* Gastropods, Pelecypods, etc.
  Mesozoic, 206–209
  Paleozoic, 172–176
Shields, 60–61
Shinarump conglomerate, 114*, 115, 116*

Sierra Batholith, 111
Sierra Nevada Mountains, 135*, 138*, 139*, 140, 141*, 147
Sigillaria, 180, 191
Silurian, 14*, 81, 92, 93
  climate, 93, 94–95
  life, 172, 177, 182–183, 187
Sinanthropus, *see* Peking Man
Smilodon, 45*, 227*, 228*, 229, 234
Smith, William, 6
Snails, *see* Gastropods
Snake River Valley, 139, 143
Snakes, first, 212
Solar system, 57–59
South Africa, Permian ice age in, 100–101
South America, Permian glaciation in, 101
Spanish Peaks, 143
Special Creation, 24
Species, 257
Spiders, 187
Spitzbergen, coral reefs, 98, 99*
Sponges, 177, 260–261
Squantum tillite, 101
Squids, 209, 270, 273
Starfish, 175*, 176, 267
Steele tongue, 120
Stegocephalians, 96, 115, 184–186
Stegosaurs, 197–198
Stone Age, 239
Struggle for existence, 32
Submergences, 1–2; *see also* Paleogeography
Sun and Earth, origin, 58
Sundance formation, 117
Sundance sea, 104*, 107
Supai formation, 8, 9
Superposition, law of, 5–6
Swiss Plateau, 144
Sylvania sandstone, 95
Systems, 13

T

Taconian disturbance and mountains, 14*, 76*, 84–86
Tarsioids, 230
Teeth, mammalian, 214–215, 225*
Temple Butte sandstone, 8, 9
Tetracorals, 263
Thallophytes, 277–278
Theriodonts, 26*, 187, 204
Thinopus, 183
Thorium, 20, 22
Thrusts, Alpine, 144
  Laramide, 111–113, 137, 140
Tillites, *see also* Glaciation
  Huronian, 71
  Permian, 100–103
Tillites, Ridgway, 122, 146
Timiskaming system, 14*, 69–70
Titanotheres, 221–222
Tonoloway group, 95
Toothed birds, 201–203
Toroweap formation, 7*, 8
Trachodon, 196*
Tracks, dinosaur, 42*, 108, 109
Trails, 39, 41
Tree ferns, 191
Tree of Life, 24*
Trees, deciduous, 191, 210, 281
Triassic, 14*, 108–110, 134
  climate, 121
  life, 190, 191, 194–195, 200, 203, 205*, 206, 208
  paleogeography, 104*
Triceratops, 196*
Trilobites, 167, 168*, 169*, 170*, 171, 273–274
Turtles, 200, 202*, 212
Tyrannosaurus, 196*, 197

U

Uinta Basin, 130
Uintatheres, 219
Unconformities, 4
  Pre-Cambrian, 61, 62, 64
Uniformitarianism, 16
Ural Mountains, 103
Uranium, 20–22

V

Variations, 31–32
Varve clays, 18, 158–160
Vero man, 254
Vertebrates, oldest, 182
Vestigial structures, 27
Vishnu schist, 61–64
Volcanic ash and fossils, 46, 143*

Volcanism, Cenozoic, 140–143
Mesozoic, 105, 110–111, 113, 142–143
Paleozoic, 84, 86, 92

W

Wabash River, 164
Washita sea, 106*
"Water biscuit," 278
Whitehorse sandstone, 100
Wichita Mountains, 91
Wind-blown sands and fossils, 46
Wingate sandstone, 114*, 116*, 117
Wisconsin drift, 152, 153–154, 155, 156*, 160
Wisconsin glacial age, 160*, 240
Woolly mammoth, 35*, 37, 45, 161, 227, 233, 236, 243
Woolly rhinoceros, 37, 235
Worm burrows, Pre-Cambrian, 66*

Y

Yarmouth interglacial age, 152, 155, 160, 240
Yellowstone National Park, 142
Yosemite Valley, 147

Z

Zion National Park, 114, 116*