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AERIAL PHOTOGRAPHIC INTERPRETATION

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AERIAL PHOTOGRAPHIC INTERPRETATION

Principles and Applications

DONALD R. LUEDER

President, Geotechnics and Resources, Incorporated

McGRAW-HILL BOOK COMPANY, INC.

New York Toronto London 1959

AERIAL PHOTOGRAPHIC INTERPRETATION

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To the memory of my father

RAYMOND EUGENE LUEDER

Civil Engineer

Teacher

Helper of Youth

PREFACE

This book is intended to be of use to a wide variety of readers who are, have been, or are going to be interested in the possibilities and applications of the *new natural science of aerial-photographic interpretation*. Until now, there has been no such general work to which such people could refer.

In the interest of usefulness, the book also devotes brief supplementary consideration to *photo analysis, photo reading,* and *photogrammetry,* particularly in terms of their relation to practical studies in the earth sciences.

In the first chapter of Part I, the reader will learn that interpretation is not the same subject that has gone by that name in military and scientific circles within the past few years, but that it is a new intellectual discipline, using induction and deduction, based upon wide knowledge, and that it treats the earth's surface as an integrated physical and ecological whole.

The remaining chapters of Part I, devoted to the elements of the photographic pattern together with their significance and interpretation, point out that the imperfect state of our present knowledge necessitates the completion of some honest and valid interpretations that are heavily qualified and even merely educated guesses. One will realize that interpretation as interpretation may be wrong and that its validity must remain a function of the knowledge and experience of the interpreter. In completing his perusal of Part I, the reader will be exposed to many of the uncertainties of interpretation and will become further convinced that reading alone will not "make" an interpreter.

Part II describes the formation of landforms composed of unconsolidated materials and their appearance as depicted in the aerial-photographic perspective. This will also provide an opportunity to practice the use and applicability of the principles presented in earlier chapters. Variations in pattern that are exhibited by rock types, as well as the reasons for their occurrence, may be studied.

In Part III, the reader may learn about the various ways in which the aerial-photographic techniques can contribute to the main terrain branches of *civil engineering,* to the many subdivisions of *geology and mineral exploration,* to *geophysical evaluation,* to *agricultural* and *land-use studies,* to *forestry* and *botanical studies,* to *urban planning* and other *regional investigations,* and to the general field of *military studies*. Last, and quite important, he will be able to read of various practical aspects associated with interpretive operations, as well as with the aforementioned basic aspects of photogrammetry.

For the *student,* young or old, at college or work, who wishes to learn and use interpretation, the recommendation is made that he begin at the beginning and proceed to the end, skipping only those chapters of Part III that are completely foreign to his field.

For the *teacher,* the arrangement of the book as a whole is believed suitable for classroom presentation. There are no classroom problems as such, this being left to the imagination and ingenuity of the instructor, who should have no trouble with such a broad spectrum of possibilities.

For the person who wants to use the book as a manual, it is possible to do so provided that basic sections are chosen for expansion along the lines of interest. Part I may be used as a manual of principles and elements, Part II as a manual of landforms and geomorphology as seen through the air photo, and Part III as a manual of practice.

For the *practical person,* who wishes to know what aerial-photographic interpretation can do, without caring how, the recommendation is made that he confine his reading to Chapter 1 and Part III.

When this effort was first envisaged, the author felt a certain amount of doubt concerning his ability to fill a whole book. He now, probably like most other writers, realizes the absurdity of such a doubt. Because of the variety of topics and factors that should be covered, the problem has not been one of filling a book but rather one of keeping the book to a reasonable length without excessive dispersiveness and/or cursory treatment.

Consideration has been given to the balance of fact, speculation, and opinion. It was originally thought that the book should be composed only of facts. This approach soon raised questions. What *is* a fact? And what opinion? What is experience? And what speculation? How are value and readibility consistent with *facts* alone? The original approach was soon discarded. Facts appear, but so does speculation because speculation points to the future; and opinion because, in a "first" book of sorts, the author feels that opinion has merit (if only that it is a starting point for dispute).

As a last prefatory remark, let it be understood that the author hopes that this book will be read because of an unprejudiced interest in the subject. Agreement is not necessary, only interest. It has been the author's objective to include the essence of his (and others') experience, knowledge, and *current* understanding of a broad and complex subject, for the reader's consideration.

Donald R. Lueder

ACKNOWLEDGMENTS

How does one acknowledge all the aid that is received in the preparation of a book? It is virtually impossible, since one would have to search back through his development to select those people who most guided and aided his training and progress as well as those who directly facilitated the production of the final synthesis, the book, per se. Only a few may be selected, therefore, and these, unfortunately, must be almost entirely restricted to persons in the latter category. With this in mind, the author begins.

First, he acknowledges the efforts of M. Dan Morris, who first encouraged him to produce a book and approached the publishers in his behalf. May everyone have such a friend.

Next, he must thank his major contributors: H. S. Scott, who prepared Chapter 20 on geophysics; R. N. Parkinson, for the sections on structural geology; Walter Creswick and W. H. Rockwell, for the chapter on agricultural surveys; and J. F. Cunningham and V. Merritt, for their discussions of forestry.

Other contributors have been Ta Liang, on landslides; F. M. Hanna, on the Airborne Profile Recorder; D. K. Erb, with a brief section on ground water; R. A. Dunbar, with a section on interpretation in tropical areas; and J. G. Wilkinson, with a section on photogrammetry. J. G. Wilkinson also reviewed the original manuscript in so far as it touched specifically upon photogrammetry, and many of his suggestions are incorporated herein.

To make one exception in this cataloguing of direct contributors, the author wishes to pay tribute to his original mentor and the true originator of the subject, D. J. Belcher. His early observations and presentations were largely responsible for the author's embarkation in the field.

Thanks for the use of their extensive aerial-photographic libraries are given to The Photographic Survey Corporation and Hunting Technical and Exploration Services Limited.

Permission to publish various individual photographs throughout the books has been acknowledged in the corresponding legends. Of particular note is the permission given by the U.S. Office of Naval Research for publication of photos included in their Cornell volumes.

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AERIAL PHOTOGRAPHIC INTERPRETATION

*

I

Principles and Theories of Photo Interpretation

INTRODUCTORY STATEMENT

It is the primary purpose of Part I to define, indicate the significance of, and discuss the ramifications of the major and minor elements of the aerial-photographic pattern. These include *landform and rock type*, the *surface-drainage pattern, erosion features, gray tones,* and *miscellaneous details.*

A chapter is devoted to each of these subjects, and it must be emphasized that every attempt has been made to give them a fairly complete treatment, consistent, of course, with limitations on space and knowledge. In providing this treatment, fundamentals are discussed, but considerable space is also devoted to the exposition of affecting factors, supporting evidence, discouraging indications, and unknown quantities. This treatment is intended to show that, while each element has an a priori simplicity, its true significance is quite complex and may be contingent upon such things as academic knowledge, regional experience, selective field check, and photo experience.

Let the reader of this book, who is interested in learning the process of interpretation, make no mistake. A complete and thorough understanding of the subject matter of Chaps. 1 to 6 in all its complexity is absolutely essential to effective aerial-photographic interpretation.

This essence of the subject must be thoroughly absorbed before the material of Part II can be properly appreciated. To the extent that it is not absorbed, the reader will not truly obtain a full appreciation or become a really good interpreter.

There is one other point. The subject matter of Part I contains a certain small amount of material that may be found in other books, or may already be possessed by the reader. This is necessary to "set the stage," provide adequacy of treatment, or develop an approach. Most of it is set in small type and may be omitted by anyone who feels already proficient.

1 AN EXPLANATION OF AERIAL-PHOTOGRAPHIC INTERPRETATION

1-1. Interpretation and the Aerial-photographic Field. Though quite young, the general field of aerial photography already has developed a number of broad divisions, each having a remarkable diversity and all having a complex structure of overlap. As a consequence, it is often difficult to separate specific divisions and subdivisions for purposes of discussion. This difficulty exists in connection with aerial-photographic interpretation and its related techniques. The effectiveness of the technique is responsive to developments, products, and limitations in most of the other divisions of photographic endeavor. In some cases, the effectiveness is inextricably bound to branches of the photo field that appear far removed, and it is misleading to discuss the interpretative, or related, aspect without considerable attention to the "foreign" branch. In other cases, various details and fields of operation are dependent upon various types of products, equipment, etc., and a description of interpretation could well be laden with qualifications and provisions. Such a situation does not promote clarity and understanding. Though it would be simple to include voluminous technical details on films, filters, processing, papers, negatives, lenses, etc., in this book, an attempt has been made to divorce the discussion of interpretation from all but the most essential aspects of overlapping fields. This approach is believed acceptable because the *basic principles* of interpretation are unchanged, regardless of the types or characteristics of materials, processing, and equipment. Only the details of interpretative effectiveness are changed.

Such an approach requires that the reader have an adequate perspective of the aerial-photographic field in general, together with the small but important position within it that is occupied by interpretation and its subordinate methods. With such a perspective in mind, the field has been divided into seven broad divisions:

1. Manufacture of aerial-photographic materials and supplies (films, papers, chemicals, etc.)
2. Manufacture of aerial-photographic equipment (cameras, photogrammetric devices, processing machinery, etc.)
3. Fabrication and developmental research on materials, supplies, and equipment
4. Execution of aerial-photographic missions (operational planning, photo exposure, equipment maintenance, ground control, etc.)
5. Processing of photographic materials (development, printing, tone control, enlargement, etc.)
6. Utilization of processed materials to obtain practical information (mosaic preparation, photogrammetric analysis, *photo interpretation*, etc.)
7. Operational and developmental research on processing and utilization

1-2. Utilization of Processed Materials. This division of the photographic field is the practical branch to which all the other divisions owe their reason for existence. It is the objective of the division to use the final products of the other fields—aerial prints, negatives, diapositives, and ancillary equipment—in such a way that reliable practical information concerning the earth's surface, its inhabitants, and some of its physical phenomena can be rapidly, economically, and reliably obtained.

The division may be separated into three categories: (1) mosaic preparation (qualitative and quantitative), (2) photogrammetric analysis (quantitative), and (3) photographic-detail evaluation (qualitative and quantitative). Each of these categories will be discussed briefly.



Fig. 1-1. A single mosaic sheet in preparation. A single contact print has been trimmed and is being visually matched for detail. Since no control network of any kind is visible, it is probable that this mosaic is a photograph lay-down, although it could be a scale-ratio mosaic (Chap. 24). (*Photographic Survey Corporation.*)

1-3. Aerial-photographic Mosaics. A definition of a "mosaic" has been given by the American Society of Photogrammetry (3).* This manual defines a mosaic as "an assembly of individual aerial photographs fitted together systematically to form a composite view of an entire area covered by the photographs. The mosaic gives the appearance of a single photograph, producing a complete record of the area photographed."

The basic tool of the photogrammetrist or interpreter is the individual contact aerial-photographic print. Such a print is rarely larger than 10 by 10 inches. It is prepared by bringing a 10- by 10-inch aerial negative in contact with a sheet of sensitized paper and passing light through the negative to act upon the paper emulsion. The paper is then processed. A 9- by 9-inch contact print, taken with a 6-inch focal length, even at the small scale of 1:60,000, covers a total area of only about 72 square miles. It is apparent that it is desirable to have a photographic view of areas much larger than this. Such a view can be obtained by overlapping individual points so that a composite picture with continuous detail is obtained. The general setup is illustrated by Fig. 1-1.

Though there is little room (Sec. 24-7) in this book for a discussion of mosaic preparation, it is important to mention the various classes of mosaics. These are as follows:

1. *The controlled mosaic.* Assuming that the terrain and photography is suitable for rectification, an assembly of photographic prints rectified to allow continuous matching of detail as well as adherence to an established control grid. On such a mosaic, the photographic images of all ground control points are located at their true horizontal position, and horizontal measurements may be made with reasonable accuracy after allowing for distortions due to terrain relief and possible dimensional changes in the reproduction materials.

2. *The scale-ratio mosaic.* Assuming that terrain and photography are suitable, an assembly of photographic prints brought to a common scale by projection printing to scale factors obtained from map distances to allow the best possible fit of contiguous photo detail. On such a mosaic, horizontal measurements are highly approximate.

3. *The photo lay-down.* An assembly of contact prints assembled to form a pictorial representation of the ground, with the best matching of contiguous photo detail that is possible without any manipulations of the prints. On such a mosaic, horizontal measurements are highly approximate and should be used only for very rough comparisons.

It is obvious that the preparation of mosaics is

* Such numbers in parentheses indicate references, which are listed in the Bibliography at the back of the book.

an important aspect of the utilization of processed aerial-photographic materials. The mosaic provides a detailed two-dimensional view of a large land area to any reasonable degree of accuracy desired. In this respect, it is an infinitely detailed base map and can be satisfactorily used for this purpose (Secs. 24-7 and 24-9).

To the interpreter, the mosaic has one additional value. It provides him with a picture of the broad regional trends that might be missed in his inspection of individual prints. This function of the mosaic is extremely important, and it should be a basic rule of the interpreter to preface and accompany his evaluation by reference to any mosaics that might be available.

Unfortunately, the mosaic has a serious disadvantage in so far as interpretation is concerned. It cannot be examined steroscopically; i.e., two mosaics cannot be examined under a stereoscope to provide a three-dimensional view of the terrain covered. This disadvantage effectively relegates the place of the mosaic in interpretation to that of a highly detailed planimetric base map with geological and geographical overtones, which can be used for general reference and planning only.

1-4. Photogrammetric Analysis. "Photogrammetry" is officially defined by the Committee on Nomenclature of the American Society of Photogrammetry as "the science or art of obtaining reliable measurements by means of photographs." There are two broad divisions of photogrammetry, "terrestrial" photogrammetry and "aerial" photogrammetry. The terrestrial photogrammetrist uses ground photographs, the aerial photogrammetrist uses aerial photographs. It is the latter division that is encompassed by the general field of aerial photography under item 6 of Sec. 1-1.

There is no justification in a book on interpretation for a detailed discussion of photogrammetry. The reader who desires technical information is referred as before to (3). Some general information—distortion, radial plot, stereo models, etc.—appears in Chap. 24 of this text, largely in the interest of convenience.

It is sufficient to say that photogrammetry is a complex science, with many subdivisions, that utilizes principles of geometry, mathematics, optics, and physics to obtain reliable details concerning the conformation of the earth's surface. It is concerned with the quantitative characteristics of the terrain: elevations, distances, and contours. These quantities are derived from rectified aerial photographs by viewing them through complex stereoplotting instruments and keying photo features to previously located ground control. Although dependent upon strict adherence to severe operational specifications, and therefore requiring considerable expensive equipment, photogrammetry has provided rapid, relatively economical methods for the preparation of dependable topographic maps covering large areas. It has recently attained, after a period of some thirty years, the acceptance that it deserves from other scientific fields.

Photogrammetry has little relation to photo interpretation. For some time, the interpreter has been forced to struggle against an indiscriminate use of the word "photogrammetry" to describe his operation. This usage of the word has little justification, and it is hoped that it will gradually disappear with an awakening comprehension of the true meaning of the terms involved.

1-5. Photographic-detail Evaluation. The category given this name is concerned with the visual examination of aerial prints, negatives, and mosaics to obtain a wide assortment of nontopographic information about the land. Unlike photogrammetry, it is not primarily interested in the quantitative conformation of the terrain. Rather its objective is to examine the various components of the landscape—hills, ridges, valleys, plains, soils, rocks, streams, forests, fields, factories, roads, etc.—and evaluate them so as to provide reliable practical information for various sciences such as geology, engineering, agriculture, and forestry.

There are several examination techniques for providing this information. They may be described, from simplest to most complex, as "photo reading" "photo analysis," and "photo interpretation."

All these methods are commonly called "photo interpretation." Actually, they are separate techniques which supply practical information in proportion to their increasing difficulty.

Lack of understanding concerning their respective refinements and capabilities has created considerable confusion in assessing their applicability and use. More important, it has retarded their healthy development as a method of solving practical problems dealing with the land (like the previously described indiscriminate use of the word "photogrammetry").

It is of value, then, to distinguish between the techniques which have been called photo reading, photo analysis, and photo interpretation. Each has a fairly well defined level of operations which affects its practical value. This level should be understood not only by the would-be specialist,

but also by the person who may be considering use of these techniques for a practical purpose. Costs, for example, may be quite different for a given area that is evaluated by means of photo analysis rather than by photo interpretation. So also may the types of information derived differ.

1-6 Photo Reading. The technique of photo reading is concerned mainly with the *recognition* and *respective positions* of man-made features and equipment, animal life, and common terrain features. It is interested in the photographic appearance (in plan) of such things as buildings, bridges, artillery pieces, cultivated fields, hills, streams, rock strata, beaches, woodlands, roads, airports, and animal herds. As the map reader is acquainted with the conventional symbols appearing upon a map, so the photo reader can distinguish between various objects registered upon an aerial photograph.

Basically, the photo reader considers and uses the aerial photograph as an exceptionally detailed base map or map supplement. In doing this, he differs from the interpreter quite markedly. To the reader, a mosaic is often as suitable as, or more suitable than, a contact print. In addition, the reader may often dispense with a stereoscope. The photo interpreter could not function completely with only a mosaic, or without a stereoscope.

Photo reading is the simplest of the evaluative techniques. It is the method used by the majority of "interpreters" in the lower echelons of the military services, and indeed is the "interpretation" practiced by many professional geologists, engineers, and photogrammetrists.

1-7. Photo Analysis. "Analysis" is defined as "the process of separating anything into its constituent parts or elements, or the examination of anything to distinguish its component parts separately or in their relation to the whole." Photo analysis is concerned with such an operation, applying it to the various features of the photograph. It includes all the aspects of photo reading, but adds to them an evaluation of the numerics and interrelationship of photo features. The areas of fields may be determined and classified as to size, position, and use. Bridges and roads may be classified as to type and capacity. The relationship between terrain and land use may be ascertained. Streams may be divided into perennial, intermittent, and swale types. Watersheds may be outlined and measured. Gullies may be delineated and classified as to economical erodible capacity. Visible rock outcrops may be outlined.

The photo analyst not only uses the photograph —occasionally the mosaic—as a base map, but also reaches practical scientific conclusions of a qualitative or semiquantitative nature by analyzing the arrangement, size, and visible physical characteristics of features appearing on the photo.

The procedure of photo analysis is exceptionally valuable in providing many types of basic data, particularly those susceptible to classification. Indeed, photo analysis may be termed the classificatory branch of photo utilization.

The photo analyst usually uses a stereoscope, and often uses the planimeter, stereocomparagraph, contour finder, or other simple photogrammetric, geometric, and electronic instruments.

1-8. Photo Interpretation. Finally, there is photo interpretation. As art, science, or trade, this technique is the most advanced and difficult of the evaluative methods. It includes all the characteristics assigned to photo reading and photo analysis, but also imposes three additional criteria: (1) the invariable use of a stereoscope, (2) a careful examination of all the elements of the air-photo pattern, and (3) a *deductive* and *inductive* evaluation of these elements in terms of common sense and field experience, supported by the interpreter's academic and practical background.

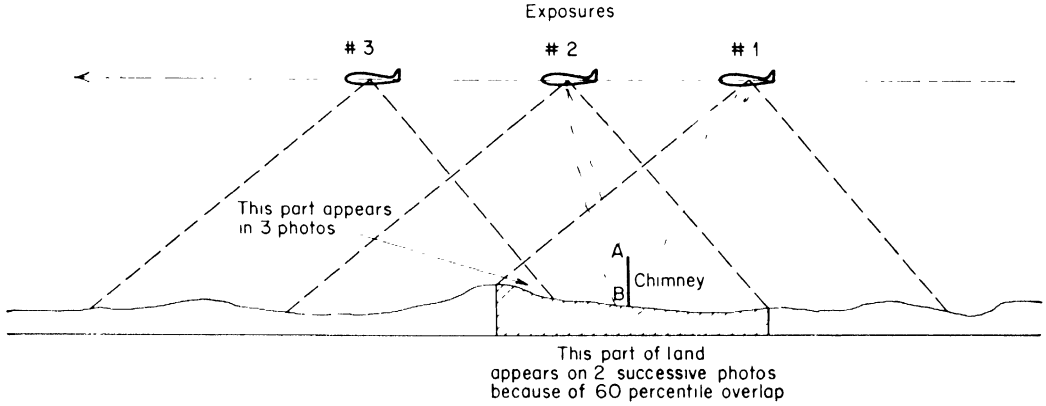
Adherence to these criteria makes it possible for a qualified interpreter to obtain *reliable qualitative information concerning the location, type, and characteristics of the soils, rocks, water conditions, and problems associated with the area examined.*

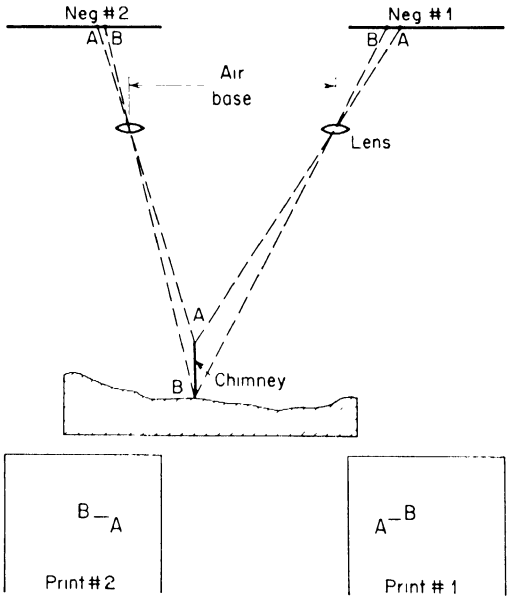
A complete understanding of the implications inherent in these statements is necessary for a proper appreciation of photo interpretation.

1-9. Stereoscopic Requirement. A stereoscopic, or three-dimensional, view is essential to photo interpretation. *No really effective interpretative use of aerial photography can be made without it.*

In order to obtain the stereoscopic effect, it is necessary to regulate the frequency at which aerial exposures are made so that each picture overlaps the previous one by 60 per cent. Thus each object on the ground will appear on at least two consecutive photographs and will be seen in three dimensions when the two pictures are viewed stereoscopically (Fig. 1-2).

It is false economy to buy alternate prints of an area to save costs. The entire overlapping coverage, though it doubles the cost and requires the





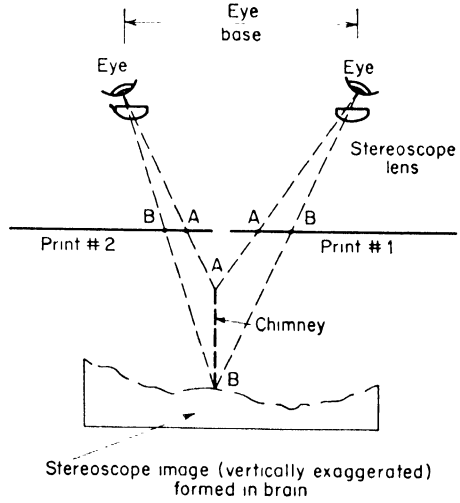


Fig. 1-2. Three schematic illustrations of the process of stereo photography and stereo viewing. The first shows the process of overlapping photography in flight. The second shows the registration of a vertical object on both negative and print (note that *A* and *B* are reversed on the print). The third indicates that a stereo image is formed in the brain by viewing the prints in their original relative positions. However, this image is vertically exaggerated (Sec. 24-10). It might be noted that the stereoscope lenses are required only to focus the eye more easily. It is possible to see stereoscopically without lenses. (*Hunting Aerosurveys Limited.*)

use of a stereoscope, is well worth the extra investment, because of the exceptionally better terrain picture that it provides. This point is illustrated by Fig. 1-3. Stereopairs such as that of Fig. 1-3 are viewed as shown in Fig. 1-4.

1-10. Elements of Air-photo Pattern. The complete air-photo pattern comprises the total arrangement of all the natural and man-made features appearing upon the photograph of the area being analyzed. The elements of the pattern are individual landscape features and collections of such features that compose the complete picture. Included as elements are:

1. Landform
2. Area surface-drainage network
3. Erosion details
4. Photographic gray tones
5. Vegetative details
6. Boundary characteristics
7. Cultural details
8. Fourth-order forms
9. Microdetails of the terrain

Each one of these elements, if present, must be evaluated to perform a complete photo interpretation of any area appearing upon an aerial photograph. The evaluation may be made in terms of the element's area pattern, its individul significance, or both. For example, the area pattern of a drainage network may afford a clue concerning some of the physical characteristics of the soil and rock in which it has developed, while a single gully, representing a component of the network, may provide information of a supplemental or corroborative nature. The terms of evaluation for any specific element, of course, depend upon the nature of the element's expression and the interpreter's ability to analyze it.

The significance of each element will be discussed in Chaps. 2 to 6, but it is important to emphasize here that the proper evaluation of each element provides additive information which, when assembled and analyzed in accordance with the principles of convergent evidence, enables reliable information to be obtained. Like the assembly of various elements of legal circumstantial evidence, evaluations of air-photo elements can be assembled to arrive at a conviction.

1-11. Deductive and Inductive Evaluation. Webster's New Collegiate Dictionary defines deduction



Fig. 1-3. The first stereopair shows the difference between the value of a three-dimensional stereo view and the two-dimensional view obtained from a single print. The three-dimensional effect may be obtained by viewing the pair through a lens-type stereoscope as shown in Fig. 1-4. The two-dimensional area view is obtained by simply viewing *either side* of the pair with the naked eye.

as "reasoning from the general to the particular, or specifically from given premises to their necessary conclusion." Similarly, induction is defined as "reasoning from particulars to generals." These definitions are exactly descriptive of the mental processes of interpretation. The interpreter may examine large-scale features such as the area drainage network. By deducing the causative factors which would logically and physically produce such a pattern, he infers specific characteristics of the material within the area covered by the network. Following such an evaluation, he may examine the specific characteristics (cross section, length, etc.) of an individual gully within the pattern, and by inductive exercise of logic and experience infer additional or corroborative characteristics which can be expanded over the entire area typified by similar gullies.

The process of interpretation sounds rather simple, but it is actually laden with all the difficulties of logical reasoning, i.e., the possible erection of unconscious sophisms.[1]

1-12. Background Necessary. Statements have been made to the effect that interpretation is essentially a technician's job, one that requires some training and experience but which can be quickly absorbed and successfully practiced by anyone of average intelligence. This statement may be considered applicable to photo reading, and in some measure to photo analysis, but certainly not to the technique of interpretation as it is described in this book.

Truly effective interpretation—practical interpretation—requires considerable experience and a broad background of knowledge. This experience and background, by their very extensiveness and diversity, are not quickly attained or easily utilized.

First, the successful interpreter[2] should have an academic background in various basic earth sciences such as physical geology, geomorphology, and pedology. Secondly, he should have received some formal training in the theory and practice of interpretation, as well as in fundamentals of photographic theory. Thirdly, he should have acquired photo experience—experience in the evaluation of air-photo patterns of similar landforms and materials as they develop in different climatic regions and in response to variations in local factors. Fourthly, he should have knowledge, training, and experience in the field for which he is interpreting. Fifthly, he should have acquired a reasonable amount of experience in selective field sampling—the correlation of repetitive photo details with actual field conditions. Sixthly, and

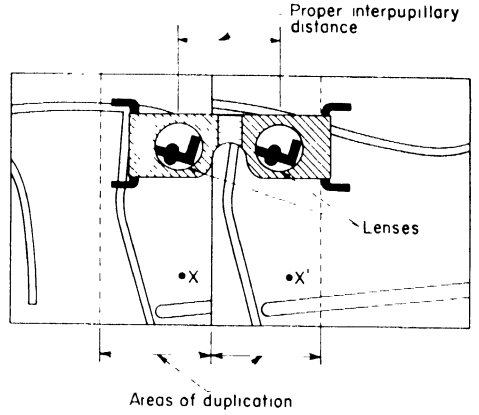


Fig. 1-4. In this book, there are numerous stereopairs such as those shown in Fig. 1-3, as well as several stereotriplets. These are viewed through a pocket lens-type stereoscope in the manner indicated above. The stereoscope is opened to the proper interpupillary distance (one lens beneath each eye). It is then positioned so that its interlens axis parallels the top of the prints and one lens is approximately centered over the items of detail that are repeated upon each photograph. To the viewer peering through the stereoscope but initially gazing at a plane beyond that of the printed page, the images will fuse, and a three-dimensional view will result. A lens-type stereoscope ranges in price from $5 to $15. If one is not available, a stereo image may be secured by holding a piece of cardboard vertically between the two photographs and again gazing beyond the plane of the page ("going into a trance") and looking at one picture with each eye. In this latter case the distance between eye and page will vary for different people. Details in the area indicated by X-X' may be viewed by sliding the stereoscope down while maintaining its parallelism to the top of the print and its position with respect to the print edge.

[1] Believing that we know the truth, we erect logical theories, and come to logical conclusions, upon its base. Actually, we may be wrong because we do not know the truth, but merely think we do. As Lecomte Du Nouy has said (53):

"There is no scientific truth in the absolute sense. The phrase *ad veritatem per scientiam* is an absurdity. There are only certain groups of sensations [and their resultants beliefs] which, in our experience, have always succeeded each other in the same order, and which we assume will succeed each other in an identical fashion within a limited future. This is the essence of our scientific truth. As long as we do not know the relationships between a physico-chemical phenomenon and the phenomena pertaining to life and psychology which may accompany it, we shall not be able to say that we know its whole significance."

[2] More accurately, as will be explained later (Sec. 7-23), the professional scientist who uses aerial-photographic interpretation as a major technique.

hardest to explain, understand, or evaluate, he should have a certain intuitive sense for the significant details of the photo pattern.

Most of these conditions of qualification are treated more thoroughly in later sections and chapters.

1-13. The Nature of Qualitative Information. Section 1-8 included a statement to the effect that photo interpretation provided a means of obtaining reliable qualitative information concerning the land. The nature of qualitative terrain information should be clearly understood.

Topography—contours, distances, and elevations—is quantitative information. Planimetric areas, slopes, cut-and-fill volumes, tree densities, etc., are all quantitative in nature.

Descriptive information concerning the nature and characteristics of the land is qualitative. Included in this category are items such as the following:

1. Location, origin, and texture of various unconsolidated deposits and soils
2. Origin, type, and structural characteristics of bedrock
3. Location of sand, gravel, clay, boulder fields, and organic deposits
4. Delineation of well-drained, imperfectly drained, and waterlogged areas
5. Location of areas of shallow or variable overburden
6. Location of sidehill seepage, potential landslide areas, springs, faults, and high salinity
7. Nature of the vegetative complex
8. Nature of surficial drainage and erosion net
9. Nature of the land-use complex
10. Nature of the environmental relationship between any or all terrain factors

Air-photo interpretation is concerned with the determination of reliable information on items such as the above.

1-14. The Practical Value of Interpretation. Section 1-13 leads naturally into a discussion of the practical value of interpretation. The practical value may be summarized by saying that *there is no aspect of human endeavor involving relatively large areas of land surface that cannot benefit materially from reliable advance knowledge concerning the qualitative characteristics of the area being studied.*

It might be said that aerial-photographic interpretation provides the broad framework of qualitative data within which a framework of quantitative data can be erected. The method of erection is unimportant. It may be based upon photogrammetry, photo analysis, field boring, ground or airborne geophysics, statistical analysis, field sampling and testing, or combinations of all. The important thing is that it be planned and executed in accordance with advance knowledge of a qualitative nature.

1-15. Philosophy of Interpretation. To be successful in photo interpretation, certain basic premises should be accepted by the interpreter. These premises may be said to comprise the philosophy of interpretation.

The interpreter must first realize that within the limitations imposed by materials, equipment, and processing, the aerial photograph *provides a true qualitative picture of the landscape in its infinity of detail.* Further, he should accept the fact that, although detail increases with scale, at any reasonable scale (1:2,500 to 1:30,000), the aerial photograph shows most of the *significant area details* that could be discerned from the ground, as well as many details and trends that would be normally indiscernible from the ground. He must be convinced that these details can be successfully evaluated to provide an intelligent, reliable estimate of ground conditions by using the processes of deduction and induction in conformance with logic and physical laws. Lastly, he should have a conviction that a failure to obtain reliable information is due to interpretative failure or improper selective field work (or both) rather than to a deficiency of the photograph (again within limitations imposed by materials, equipment, etc.).

This latter statement may be rephrased by saying that if reliable information is not being obtained from aerial photographs, the fault lies not so much with aerial photography as with our inability to use it properly. We have simply not progressed to a sufficient extent, or completed enough research and/or selective field checking, to extract the maximum amount of data from the photo perspective.[3]

1-16. Sequence of Interpretation. The recommended sequence of interpretation begins with an examination of any ground data that may be available in the form of maps (topographic, geologic, agricultural-soil), references, borings, field reports, etc. Following this, mosaics of the area (if avail-

[3] Of course, the photos must not be misused by attempting to extract from them information that should not reasonably be extractable, e.g., the shape of aggregation in the *B* horizon of a soil profile.

able) are studied for evidence of large-scale trends. Next, the photographs are given a rapid preliminary examination under the stereoscope. Finally, detailed interpretation, involving the successive evaluation of the air-photo elements, is begun. Usually, the interpreter starts with an evaluation of probable origin, landform, and type. This is followed by analysis of the surface-drainage network and any erosion features. In succession come evaluations of gray shades, boundary characteristics, vegetation, microdetails, etc. Finally, the indicative weight of each element is compared with all the others, and a conclusion is formed upon the basis of convergent evidence.

At any point(s) within this sequence, the interpreter may find it desirable or necessary to insert a photo-planned field reconnaissance or sampling trip for purposes of securing more reliable information or expanding the results of interpretation more broadly. In fact, it may be said that a selective field check is an important integral part of the photo-interpretative method.

2 ORIGIN, LANDFORM, ROCK TYPE

2-1. Introduction and Order of Discussion. The most important and useful element of the aerial-photographic pattern is that described by the composite noun "origin–rock type–landform."

It can usually be expected that, once the origin–rock type–landform of a given area has been established, a large proportion of the interpretation is complete and the remainder will follow with comparative ease. This is due to the fact that the various origins, rock types, and landforms are directly reflective of the characteristics of the materials with which they are associated.

Being a composite noun, origin–rock type–landform can be separated into its components. Actually, for clarity of treatment, it must be separated not only into its components, but also into a proper order for discussion of them.

The order of discussion that will be followed in this chapter will be as follows:

1. A definition and discussion of origin
2. The natural processes affecting origin
3. The various origins
4. A definition and discussion of rock types
5. A consideration of relief features
6. A definition and discussion of landform
7. The various landforms
8. The importance and insufficiency of origin, rock type, and landform to interpretation

Some of the following discussion is academic, or beyond the usually conceived scope of a book on aerial-photographic techniques. Actually, however, as is emphasized repeatedly throughout the book, *a fairly academic background in earth science is required for successful interpretation. This background is particularly necessary in the analysis of landform.* Thus, the justification for the inclusion of much of the information that appears in this chapter and in Part II. Such background material is set in smaller type introduced by headings preceded by a star, and may be omitted in reading by the person who feels proficient in these academic subjects.

2-2. Definition of Origin. The earth's surface is composed of consolidated, semiconsolidated, and unconsolidated materials, existing in an infinite variety of mixtures, habits, depths, areas, compositions, interminglings, heights, expressions, etc.

All these materials, in each of their infinitely variable occurrences, came into being through the operation of various natural processes in various combinations; i.e., they have *natural origins*, i.e., *geological origins*, or more simply, *origins*.

Webster's New International Dictionary defines origin as "the fact or process of coming into being from a source; derivation." Geological origin is covered by this definition, but something more specific would do no harm. The heterogeneity of materials and occurrences, mentioned in the first paragraph above, apparent to the most casual observer, results from the operation of natural processes *in such a way that characteristic and fundamental differences are created on a repetitive basis.*

With this in mind, geological origin may be defined as *a natural process, or combination of processes, responsible for the formation of earth materials having typically different and repetitive characteristics related to such items as topography, mode of occurrence, physicochemical compositions, lithology, etc.*

★ 2-3. Natural Processes Affecting Origin. The various natural processes that are responsible for the formation of fundamentally different earth materials are:

1. Mass stress and strain (S)
2. Changes in pressure-temperature-volume relationships (PVT)
3. Weathering (W)
   a. Physical (W_p)
   b. Chemical (W_c)

4. Erosion and transportation (T) and deposition (D)
   a. Water (T_w, D_w)
   b. Glacier (T_g, D_g)
   c. Wind (T_a, D_a)
   d. Gravity (T_r, D_r)
5. Special chemical processes (C)
6. Biotic processes (B)

The letters in parentheses after each item may be considered a general symbol for the general process to which they pertain.

It is desirable to discuss each of these processes in slightly more detail. The discussion will not go into scientific refinements, but will be concentrated upon the major facets that characterize each process.

★ 2-4. Mass Stress and Strain. Mass stress and strain occur over the surface of, or within, the earth as a whole; over or within relatively large portions of the earth; and over the surface of, or within, individual rock bodies and collections of such bodies.

The stress is created by forces that are ultimately related to large, omnipresent, elemental forces, e.g., gravitational attraction and repellence, shrinkage and expansion caused by mass cooling and heating, eccentricity of the Antarctic ice cap, etc.

Stresses affecting the earth as a whole are caused by the direct action of these forces. Stresses affecting parts of the earth are caused by differential chain reactions to such forces as they proceed through conditions of anisotropy. Stresses within relatively localized rock bodies are the end products of such chain reactions.

The strains that result from the application of mass stresses are the large faults, plastic flow features, and mass warping that cause variations in the topography of the earth's surface and are reflected by the presence of mountains, basins, escarpments, etc.[1]

It may be said that the original natural process, i.e., the ultimate geological factor affecting all earth materials, is mass stress and strain.

★ 2-5. Changes in Pressure-Volume-Temperature Relationships. As a result of mass stresses and strains, any relatively stable condition of temperature, pressure, and volume that may exist within any given subsurface solid, plastic, or liquid portion of the earth may change. For example, the creation of a deep-seated fault will tend locally to relieve the pressure on one portion of the earth and increase it on another. The temperature and/or volume of both parts will then have to change; i.e., expansion, contraction and a possibly complex series of chemical reactions will occur until another new state of relative stability is acquired. In this new state of physicochemical equilibrium, it is reasonable to expect that the solid, plastic, or liquid body will have acquired new physical and chemical characteristics.

Obviously, such changes are chainlike, creating new forces, stresses, and strains that are part of an incessantly and complexly changing system.

Not all PVT changes occur at comparatively large depths beneath the surface. Some occur quite close to the surface. One example is stress imposition by constantly increasing depth of sediment and the pressure-volume changes that occur thereafter. Another example is stress release and consequent rebound following the retreat of glaciers.

★ 2-6. Weathering—Physical and Chemical. Weathering is a general name for the physical and chemical processes through whose operation masses or particles of solid, sound, fresh (i.e., "unaltered") mineral aggregations are disintegrated, decomposed, and recombined. "Disintegration" refers to *physical* processes causing changes in the bulk, shape, surficial texture, continuity, and textural gradation of mineral aggregations. "Decomposition" and "recombination" refer to *chemical* processes causing changes in the chemical composition of mineral aggregates.

The *agents of disintegration* are *temperature changes, moisture content, running water, wind, gravity, glacial action,* and *biotic action.*

Temperature changes have an obvious effect upon mineral aggregations. All substances have characteristic coefficients of expansion and contraction. When a combination of such substances, e.g., a mineral aggregation, undergoes, as a whole, a given change of temperature, it is easy to visualize the complex physical stresses and strains that are established at each mineral interface. Inevitably, these stresses and strains cause spalling of particles and changes in surficial texture. One common type of spalling is "exfoliation," caused by poor heat conductance from the surface of rocks inward.

Temperature changes, combined with moisture content, may result in freezing and thawing, causing ice shattering, cracking, and spalling.

Running water, wind, gravity, and glacial action physically carry fragments and particles of mineral aggregates from one place to another, changing their physical characteristics in the process. Although these agents truly cause disintegration, the author prefers to consider them as somewhat separate and special processes. They are discussed in the following section.

Biotic action refers to the penetration of mineral aggregations by plant roots and the resultant disintegrative forces that accompany root growth.

The processes of decomposition are the processes of *solution, carbonation, oxidation,* and *hydration,* as well as special *biotic processes.*

[1] Bijlaard (19 to 21) has published a series of interesting papers on the relations between certain topographic features and the mathematics of plasticity. Other references (138, 139) contain similar data. Hapgood (72*a*) has recently published a most interesting book on the shifting crust of the earth, together with considerations of stress, strain, and fracture.

Solution is a familiar process. The point to remember about it is that everything is soluble, even in pure water, though the degree of solubility varies and, for some "insoluble" substances, is minute. The solubility of materials increases tremendously if the solvent contains the radicals of salts, acids, or bases.

Carbonation refers to the action of CO_2 on mineral aggregates. Generally, the most effective action results from the solution of CO_2 in water, yielding carbonic acid. Carbonic acid may itself combine with carbonates to form soluble and removable bicarbonates. It may also precipitate carbonates under proper conditions.

Oxidation is a familiar process. It refers to the combination of an element or compound with oxygen (or, broadly speaking, to any increase in positive valence of an element or compound). The oxidation of iron compounds in rocks is a very common and widespread chemical change.

Hydration refers to the combination of a compound with water and the changes in composition that result.

Biotic action reflects not only the chemical processes related to biotic secretions, but also to those microorganisms that decompose mineral aggregates directly (Sec. 2-8).

More discussion of certain biotic processes, chemical transportation, and special chemical processes, some of which can be considered weathering in the strict sense, appears in Secs. 2-7 to 2-9.

★ 2-7. Erosion, Transportation, and Deposition—Physical and Chemical. The combined processes of erosion, transportation, and deposition are most important as modifiers of landscape, creators of lithology, and originators of sedimentary rock. As mentioned above, erosion and transportation are agents of both physical and chemical weathering because they do change the properties of mineral aggregates. Actually, they account for a good deal of that aggregate process called "weathering." However, because of their equal importance as landscape modifiers, they have been separated from the general discussion of weathering.

The agents of physical erosion, transportation, and deposition are running water (fluvial action of various regimens, Chaps. 4, 9, and 10); wind (aeolian deflation and deposition, Chaps. 4 and 14); glaciers (glacial plucking, abrading, plastering, ablation, Chap. 12); and gravity (land slippages, mass wastage, solifluction, colluvial fall, simple subaqueous settling, Chaps. 4, 10, 11, and 15). Descriptions of their action appear in the cited chapters.

The chief process of chemical erosion, transportation, and deposition is that of solution, although carbonation may also be classified as a partial process. Solution should, strictly, be classified only as an erosive process, the transportation being fluvial. Certain special processes of chemical deposition are discussed in Sec. 2-9.

★ 2-8. Biotic Processes. Those biotic processes that are responsible for the formation of earth materials may be divided into two major classes plus several types and subtypes:

A. Processes associated with the growth and life of plants, microorganisms, and higher animate life
  1. Those that physically weather or remove nonorganic material (Sec. 2-6)
     a. Root penetration
     b. Action of worms, rodents, ants, termites, etc.
  2. Those that chemically weather nonorganic material (Sec. 2-6)
     a. Action of plant (particularly root) secretions
     b. Direct decomposition by microorganisms
  3. Those that involve the deposition of new materials
     a. Precipitation of calcium carbonate due to the removal of CO_2 from carbonate-bearing waters by plants
     b. Deposition of calcium carbonates because of the action of denitrifying bacteria
     c. Deposition of silica by diatoms, sponges, etc.
     d. Deposition of iron and manganese by bacteria, algae, protozoa, and fungi
     e. Deposition of guano by birds

B. Processes associated with the death and decay of organisms
  1. Those that involve the chemical weathering of nonorganic materials
     a. Action of reagents released by the decomposition of recent plant residues
  2. Those that involve the deposition of new materials
     a. Accumulation of calcareous shells, skeletons, etc., as various limestones, oozes, phosphates, and marls
     b. Accumulation of plants and plant residues with or without intermixed inorganic matter (Chap. 15)

For the purposes of this book, the only significant biotic processes are *B1a* and *B2a* and *b*.

The aerobic chemical weathering of nonorganic materials occurs because the accumulated residues (*B2b*) of recently dead plant and animal remains are attacked primarily by soil microbes, and secondarily by the processes of physical and chemical weathering. This attack causes the decomposition of the discrete organic residues into an amorphous, black-brown substance called "humus" and is consequently termed, in aggregate, the process of "humification." Simultaneously with humification there occurs a process known as "mineralization" which does not lead to

humus formation but rather to the formation of basic constitutents such as minerals, water, and CO_2. This process is also initiated by soil microbes (85). During the processes of humification and mineralization, the discrete organic residues are broken into simpler compounds, and various gases and reagents are released. Prominent among these are *ammonia* (ammonification), which is converted microbially to *nitrites, nitrates, nitrous acid,* and *nitric acid; carbon dioxide,* which is partially returned to the atmosphere and partially converted to *carbonic acid;* and *organic acids,* which are derived from the decomposition of proteins. The reagents leach downward through any existing nonorganic materials and, by a complicated series of reactions, and interreactions, mostly of the oxidation-reduction type, attack their constituent minerals, altering them and removing many in solution (*B*1*a*).

The anaerobic chemical weathering of nonorganic materials is somewhat analogous to aerobic weathering, particularly since most anaerobic conditions are occasionally aerobic. Under anaerobic conditions, the nitrites and nitrates produced from ammonia are microbially converted into gaseous nitrogen compounds that enter the air. This is essentially a reduction reaction, as are most of the anaerobic humification processes. Because reduction rather than oxidation is the rule, anaerobic conditions release the typical reduction gases, methane, hydrogen sulfide, and carbon monoxide.

These aerobic and anaerobic processes may be jointly termed "biotic pedological attack," and they are responsible for varying actions at varying depths within a soil mass; i.e., they are partially responsible for the creation of a "pedological soil profile" (Sec. 7-9), some of which respond typically to climate and are called "climatogenic" (Sec. 7-9) and others of which are affected by other factors and are called "climatogenically subdued" (Sec. 15-1).

The accumulation of calcareous shells, skeletons, etc. (*B*2*a*), occurs because certain marine and freshwater organisms (algae, foraminifera, mollusks, corals) secrete calcium from original or precipitated (*A*3*a*) deposits. When these organisms die, their shells and skeletons are worked over by waves and transported by waves and currents to form accumulations and oozes. These accumulations become cemented and consolidated to various degrees, becoming organic limestones, "coral" rock, and marls of various types.

★ 2-9. Special Chemical Processes. There are a few special chemical processes that are responsible for the formation of earth material. These processes are as follows:

1. Processes of chemical deposition (yielding nonorganic limestones: oolitic, pisolitic, concretionary, travertine, stalactitic, stalagmitic, caliche, onyx)
2. Processes of chemical precipitation
   a. From water (salt, anhydrite, gypsum)
   b. From siliceous gels (chert, flint, jasper, geyserite, taconite)
   c. From ferruginous solutions

For the purposes of this book, and for the world in general, these processes are unimportant in terms of the volume of material produced (with the exception of the marine siliceous gels).

★ 2-10. Formational Origin and Lithological Origin. Different types and deposits of earth materials may be considered to have two types of origins, "lithological" and "formational."

The individual particles, minerals, matrix, etc., that comprise a given deposit or material have an origin that may be termed lithological. This origin is usually related to an extremely complex series of natural processes, extending ultimately to the magmatic state, whose aggregate effect is the existence of a given particle, with a given composition, at a given place.

For example, using the letters given in Sec. 2-3, a particle of quartz in a sand dune to the lee of a fluvial floodplain might have a lithological chain of origin as follows:

$$\text{Magma} \rightarrow S \rightarrow PVT \rightarrow \text{igneous rocks} \rightarrow W \rightarrow T_w \rightarrow D_w \rightarrow T_a \rightarrow D_a$$

$$\text{Magma} \rightarrow S \rightarrow PVT \rightarrow \text{sedimentary rocks} \rightarrow W \rightarrow T_w \rightarrow D_w \rightarrow T_a \rightarrow D_a$$

As can be seen, true lithological origin is complicated, uncertain, and obscure. Often it is unfathomable. Of course it can be, and often is, separated arbitrarily at some point in the complete chain, such as the igneous or sedimentary rock state. Whether it is or not is academic in so far as photographic interpretation is concerned.

The deposit of material as a whole has come into being, usually in a fairly direct manner, by means of one or more natural processes, whose combined action may be termed "the formational origin." Thus, the sand dune, of which the quartz particle formed a part, was created as follows:

$$\text{Fluvial floodplain} \rightarrow T_a \rightarrow D_a (\text{in dune})$$

It is the formational origin that is of importance to the interpreter.

2-11. The Various Primary Formational Origins. For the purposes of this book, and for geological discussion in general, it is quite practical to consider all deposits of earth material as having one of the following primary formational origins:

1. Rock bodies and residual soils [2]
   a. Igneous origin
   b. Sedimentary origin
   c. Metamorphic origin

[2] See footnote on page 16.

2. Unconsolidated deposits and nonresidual soils [2]
   a. Fluvial origin
   b. Marine and lacustrine origin
   c. Glacial origin
   d. Fluvioglacial origin
   e. Fluviomarine, fluviolacustrine, and other fluviocomposite origins
   f. Colluvial origin
   g. Aeolian origin
   h. Organic-complex origin

These origins must be discussed briefly, to appreciate their differences.

★2-12. Igneous Origin. The igneous origin is applicable to rock fragments and rock masses, or the soils and soil particles derived therefrom, resulting from the crystallization of fluid, semifluid, and gaseous matter that exists or existed beneath the surface of the earth.

Such matter, or "magma," as it is commonly called, exists, or originally existed, under a certain pressure-volume-temperature condition. In its original state it consists, or consisted, of a general complex of chemical compounds related both to its basic source of elements and to this *PVT* state. As a result of mass stress and strain, the original *PVT* state changes (changed), the magma migrates (migrated), and a new *PVT* results (resulted). If in this new state solidification occurs (occurred), an igneous rock-mass is (was) formed.

Schematically, the formational origin may be written as

$$\text{Magma} \rightarrow S \rightarrow PVT \rightarrow \text{igneous rock}$$

In this case, the formational and lithological origins are identical.

It may be of interest that igneous rocks resulting from the complete subsurface operation of these processes are called "plutonics" and "intrusives." Rocks whose final solidification occurred under subaerial conditions are called "volcanics" and are subdivided into "effusives" and "efflata."

Igneous rocks are discussed in Chap. 16.

★ 2-13. The Sedimentary Origin. The sedimentary origin may be applied to rock fragments and rock masses, or the soils and soil particles derived therefrom, that result from the consolidation and/or cementation of accumulated transported, precipitated, or deposited discrete materials.

The discrete materials may be derived from any source, including other sedimentary rocks. Usually, the site of accumulation is under shallow marine or fresh waters, and the sediments are deposited in layers or strata. With the passage of time, the sequence of layers thickens, and the sediments are subjected to consolidation (mass stress and strain) and/or special chemical processes (cementation), thereby becoming true rocks.

The lithological chain of origin, obviously, is likely to be complex. The formational chain is relatively simple:

$$\left.\begin{array}{l}\text{Consolidated source} \rightarrow W \rightarrow T \\ \text{Unconsolidated source} \longrightarrow T\end{array}\right\} \rightarrow$$

$$(S/PVT/C/B) \rightarrow \text{sedimentary rocks}$$

Certain sedimentary rocks have special chains of formational origin. These include the organically derived sediments, e.g., coal:

$$\text{Plants} \rightarrow B \rightarrow D_v \rightarrow (B/C/W_r) \rightarrow (S/PVT) \rightarrow \text{coal}$$

and foraminiferal limestones:

$$\text{Living organisms} \rightarrow B \rightarrow (T_w/D_v/D_w) \rightarrow$$

$$(C/S/PVT) \rightarrow \text{foraminiferal limestones}$$

Other special sedimentary rocks may have similar chains.

Sedimentary rocks are discussed and illustrated in Chap. 16.

★ 2-14. The Metamorphic Origin. The metamorphic origin is applicable to rock fragments and rock masses, or soils and soil particles derived therefrom, that result from the transformation of other rock masses because of changes in *PVT*, *S*, and *C* that act upon those masses, changing their crystalline, chemical, and physical properties.

Metamorphics have the following formational chain of origin:

$$\text{Igneous, sedimentary, metamorphic rocks} \rightarrow$$

$$(S \rightarrow PVT)/C \rightarrow \text{metamorphic rocks}$$

These rocks are discussed and illustrated in Chap. 16.

★ 2-15. The Fluvial Origin. The fluvial origin is applicable to unconsolidated deposits of material that have been transported by running water and deposited in layers as the result of a reduction in the velocity of water flow. The sources of material for fluvial action include all materials of the earth, regardless of origin.

The formational chain of origin is as follows:

$$\text{Source} \xrightarrow{\nearrow W \searrow} T_w \rightarrow D_w \text{(fluvial materials)}$$

[2] Residual soils are soils that have formed in place from underlying "consolidated deposits," i.e., *rock*. Nonresidual soils are those that have formed in place from "unconsolidated deposits," i.e., *transported materials*. The division between consolidated and unconsolidated is, of course, arbitrary. To the best of the author's knowledge, the arbitrariness is also a matter of opinion; i.e., no division has been accepted in terms of unconfined compressive strength, penetration, etc. This would seem to be an obvious step that would avoid much confusion in, for example, the classification of sedimentary "rocks" (Chap. 16).

The various fluvial unit landforms are discussed and illustrated in Chaps. 9 and 10.

★ **2-16. The Colluvial Origin.** The colluvial origin may be applied to unconsolidated deposits that have been transported completely, or almost completely, by the action of gravity and have come to rest because of a topographic obstacle or a reduction of slope and velocity.

Their chain of origin is simple:

$$\text{Source} \rightarrow W \rightarrow T_g \rightarrow D_g(\text{colluvial deposit})$$

Colluvial deposits are discussed and illustrated in Chap. 10.

★ **2-16a. The Marine and Lacustrine Origins.** The marine and lacustrine origins are applicable to unconsolidated deposits of material that have been deposited beneath the surface of saline or fresh-water bodies, largely according to the laws of velocity transport, or cast up from, and along the boundaries of, such water bodies by the waves and currents therefrom.

The formational chain of origin is

$$\text{Source (any)} \rightarrow \begin{matrix} T \\ (B/C) \\ C \end{matrix} \rightarrow \begin{matrix} D_e(\text{subaqueous}) \rightarrow \text{marine and lacustrine} \\ T_w \rightarrow D_w \end{matrix}$$

In common with most transitionally deposited materials, these have a complex chain of formation.

The various marine and lacustrine landforms are discussed and illustrated in Chap. 11.

★ **2-17. The Glacial Origin.** The glacial origin is applicable to deposits of unconsolidated materials that have been physically removed by mountain glaciers and continental ice sheets, carried within the ice mass during its plastic forward flow and deposited at its base during advance, or at its base and front during gradual, irregular retreat due to melting. The original source—the lithological origin—may be that associated with any type of rock or other unconsolidated deposit. The formational origin is

$$\text{Source} \rightarrow T_g \rightarrow D_g(\text{glacial deposit})$$

The various glacial landforms are discused and illustrated in Chap. 12.

★ **2-18. The Glaciofluvial Origin.** The glaciofluvial origin—as important as its name seems pedantic—may be applied to both mineral particles and deposits that were originally eroded and carried by a glacier but which have a present position, mass depositional state (lithology), and landform that are the primary creation of constructive glacial meltwaters and that usually, except for eskers, have a position that was beyond the glacial terminus at the time of deposition.

The lithological origin may be associated with any of the materials of the earth. The formational origin may be indicated as

$$\text{Source} \rightarrow I_g \begin{matrix} \nearrow D_g \\ \rightarrow \end{matrix} T_w \rightarrow D_w(\text{glaciofluvial deposits})$$

The various glaciofluvial deposits are discussed and illustrated in Chap. 13.

★ **2-19. Other Fluviocomposite Origins.** Other fluviocomposite origins, such as fluviomarine, fluviolacustrine, fluviocolluvial, etc., may be applied to those deposits of unconsoliated materials having mass characteristics that reflect the combined action of water transportation and action typical of other environments and/or forces.

Various fluviocomposite landforms and deposits are illustrated and discussed in Chaps. 10 and 11.

★ **2-20. The Aeolian Origin.** The aeolian origin is applicable to unconsolidated deposits of material that have been transported by *wind action* and deposited as the result of a reduction in wind velocity. The sources of material for aeolian action include only unconsolidated materials, although such materials can be derived from practically any source.

The formational origin may be depicted schematically as

$$\text{Source} \rightarrow T_a \rightarrow D_a(\text{aeolian deposits})$$

The lithological origin may be expected to have the usual complexity.

The major aeolian unit landforms are discussed and illustrated in Chap. 14.

★ **2-21. The Organic-complex Origin.** The organic-complex origin may be applied to deposits of unconsolidated material that contain extremely variable but usually major amounts of organic plant material in various stages of decomposition; that are intermixed with variable but generally minor amounts of nonorganic sediments deposited by fluvial, aeolian, marine, lacustrine, fluviomarine, fluviolacustrine, or glaciofluvial action or any combination of such actions; and that exist(ed) under a transitional environment between land and water. Such deposits can be said to have the following formational origin:

$$\begin{matrix} \text{Original} \\ \text{plants} \\ \uparrow (T_w/T_a) \\ \text{Nonorganic} \\ \text{source} \end{matrix} \rightarrow B \rightarrow (T_w/T_a/T_g/D_g) \rightarrow (W/B/C) \rightarrow D_w/D_g \rightarrow \text{organic-mineral complex}$$

$$\downarrow$$

$$\rightarrow (T_w/T_a/T_g) \rightarrow (D_a/D_w/D_g) \rightarrow$$

The above chain is rather inclusive. In actuality, for specific deposits, the formational chain may be fairly simple:

$$\left.\begin{array}{l}\text{Mineral source} \rightarrow T_a \rightarrow D_a \\ \text{Original plants} \rightarrow B \rightarrow D_g \rightarrow B\end{array}\right\} \rightarrow$$

organic-mineral complex

2-22. Definition and Discussion of Rock Types. Under each of the primary origins applicable to rocks (igneous, sedimentary, metamorphic) there are numerous different materials. These materials differ in many respects: texture, mineralogical composition, chemical composition, mode of occurrence, nature of original source, secondary origin, etc.

These materials may be classified according to each and every one of their differences and similarities to yield a rather complex [3] system of kindreds, series, suites, tribes, families, clans, subdivisions, divisions, etc. In this book, all these materials in all their variations are collectively called "rock types."

A rock type may be defined specifically as *any definitely consolidated material having an individually characteristic secondary origin, type of source, or physicochemical environment during solidification, alteration, or deposition, and/or typical physicochemical-mineralogical nature after solidification, alteration, or deposition.*

It appears obvious that a knowledge of the rock types within an area, if the knowledge and typing go far enough, provide any terrain specialist with much valuable information about the area in connection with soils, construction problems, geological history, economic value, etc. For this reason, a knowledge of the air-photo patterns related to various rock types is of great value to any terrain specialist. Such patterns are considered in Chap. 16. The sciences of petrology, petrography, etc., that are concerned with rock typing are mentioned in Chap. 7.

2-23. Relief and Orders of Relief. All terrain has relief, i.e., differences of height above any arbitrarily chosen datum. This relief can be classified into "orders." Orders were discussed by von Engeln (212):

> The relief forms of the earth may be divided into three classes, or orders, primarily on the basis of size. The forms of the solid earth as a whole, of the continents, and of the ocean basins are relief features of the first order. Plains, plateaus, and mountain ranges comprise the second order of relief; valleys, ridges, cliffs, basins, etc., make up the third order. The sorting which this classification requires is readily done, and the classification has significance because, as a group, the items of each order have an origin and a measure of permanence different from those of the other two orders. . . . Relief features of the first order seem to have a considerable degree of permanence. They constitute, as it were, the theaters in which geologic dramas are enacted. Stages, which in theaters are frequently altered and rebuilt to fit the succession of productions, may be figuratively compared with the plains, plateaus, and mountains of the second order of relief, and stage scenery, which may be many times shifted during the progress of a single play, matches the items of the third order of relief

Von Engeln's discussion should make it apparent that a first-order form (e.g., North America) may contain a variety of second-order forms (e.g., the Mississippi floodplain, the Atlantic coastal plain), which in turn may be comprised of numerous third- and fourth-order features (Sec. 6-7).

2-24. Comparative Significance of Various Orders of Relief. Relief features of the first order are of no practical significance to the interpreter. Interpretation is done within their boundaries, in full knowledge of their existence and general nature.

Relief features of the second order are occasionally of significance to interpretation because not all second-order features have been completely located and categorized. In such cases, identification indicates the geological processes that formed them, as well as their general characteristics, and provides a starting point for further inductions, deductions, and conclusions. As an example, consider one relief feature of the second order, that of the coastal plain, in von Engeln's classification (Sec. 2-25). It is apparent that it would be of value to establish this fact, if it were not known, because one would then be able to describe the area characteristics generally. In von Engeln's words, a coastal plain would be covered generally by the following description:

> Regional emergence of marine or lacustrine sediments of geologically recent date. The parent water body comprises one margin; the other abuts an old-land. The original surface is approximately flat, and departs from a horizontal plane in that it characteristically slopes gently toward the shore line. This surface slope is repeated as to direction, but with slightly greater degree of inclination, by the dip of the beds

[3] The uniform and adequate classification of every rock, according to even its dominant characteristics, would probably require a diagram of, say, six or eight linear dimensions, e.g., a three- or four-sided pyramid, plus other qualifiers on ocurrence, texture, etc.

of which the plain is composed. The stratification of the layers is well defined.

Relief features of the third order have a frequent significance to interpretation, for they are the true landforms that comprise the terrain appearing upon aerial photographs. The fluvial fans, small floodplains, rock ridges, glacial eskers, etc., are all third-order forms. Their identification or recognition, as well as a knowledge of their formation and general characteristics, forms the real basis of interpretation (Secs. 2-26 and 2-27).

Relief features of the fourth order are also frequently significant (Sec. 6-7).

2-25. Von Engeln's Classification of Second-order Relief Features. Von Engeln (212) provides a point of departure for geomorphological studies by presenting a classification of geomorphic units. He considers a geomorphic unit as a relief feature of the second order, resulting from either internal or external natural processes and having a uniform structure upon which subaerial processes act to produce third-order forms with a predictable pattern.

Von Engeln's classification of geomorphic units follows:

Group A: simple structures and generally unconsolidated sediments (coastal, tundra, glacial, fluvial, lacustrine, deltaic, loessial, and piedmont plains; desert *erg* areas)

Group B: simple structures and consolidated rocks (interior plains; open basins with centripetal dips; volcanic cones)

Group C: simple structures composed of consolidated rocks having a limestone composition (karst units; coral islands)

Group D: folded and faulted structures, composed of consolidated rocks of sedimentary origin (dome uplifts; fold mountains; fault-block mountains)

Group E: disordered structures and ancient rigid masses composed of igneous and metamorphic rocks existing as plains, plateaus, and mountains and having long erosional histories (ancient igneous masses; peneplains; continental glaciers)

2-26. Value and Insufficiency of the von Engeln Classification to Interpretation. The von Engeln classification of second-order features is of great value to interpretation. First, it provides an organization. Secondly, if the geomorphic unit is known, or can be established, it indicates, as mentioned previously, that within its boundaries there is a single *general* geomorphic history, a definite *general* structure, certain *general* physical characteristics, and a predictable *general* pattern of third-order landforms. Thirdly, it provides a basis for extrapolating experience and patterns between areas having different geographic locations.

These values—to emphasize the point of Sec. 2-24—are sufficient to provide the interpreter with *general initial clues* for the deduction and induction of practical characteristics regarding the rock, soil, drainage, etc., conditions within the area of interest.

Unfortunately, general initial clues are insufficient in themselves for practical interpretation, and the von Engeln system does not—nor was it intended to—provide anything more. It does not provide an orderly classification of third-order landforms, nor does it give *specific* information about the variations in terrain conditions, within the boundaries of a given geomorphic unit.

As an example, consider the various origins, third-order forms, and material types that may exist within the coastal-plain geomorphic unit:

1. Origins (marine, lacustrine, fluvial, fluvioglacial, fluviomarine and lacustrine, aeolian, organic-complex)
2. Third-order forms (doabs, dunes, beaches, beach ridges, fans, cones, floodplains, tidal marshes and swamps, fresh-water marshes and swamps, terraces, outwash mantles, cuestas, outliers)
3. Unconsolidated materials (gravel, boulders, sand, silt, clay, colloids, organic deposits, in an infinity of micaceous, glauconitic, limey, etc., phases)

Similar varieties may exist within the boundaries of other geomorphic units, such as tundra plains, glacial plains, ancient igneous masses, and even karst units.

Obviously, then, a knowledge of general geomorphological processes and their results, in terms of von Engeln's geomorphic units, is insufficient to locate and identify terrain conditions that have high practical significance.

The interpreter is forced to look beyond general geomorphology for aid. In doing so, he must use what might be called "specific geomorphology," i.e., the study of third-order landforms and, more particularly, unit landforms.

2-27. Landform and Unit Landform. Landform, in its broadest sense, implies the shape of the land, i.e., its topography. In this broad sense, it has little value to interpretation. The fact that a hill is a hill

may be of interest to the person climbing it or farming it or irrigating it, but it is only occasionally of importance to the interpreter or any other person trying to map the qualitative nature of the land. However, if the hill has special features, or a suggestive shape, which indicates or reveals specific information about its composition, texture, stratification, uniformity, then it is of great importance to the interpreter.

To cover this latter aspect of landform, the term "unit landform" is suggested. A unit landform may be defined as a *terrain feature or terrain habit, usually of the third order, created by natural processes in such a way that it may be described and recognized in terms of typical features wherever it may occur, and which, when identified, provides dependable information concerning its own structure and either composition and texture or uniformity.*

Some may object that this definition is "rigged." They are correct. But it is rigged for a specific and good purpose, one of practicability, and this may be considered as its justification.

In the above definition, the phrase "may be described and recognized in terms of typical features wherever it may occur" implies that a unit landform's visible characteristics persist through all but the most severe effects of differences and changes in geological age, geomorphic process, erosive stage, and climatic regimen.

The generality that unit landforms are "usually of the third order" avoids the normal designation of second-order landforms (geomorphic units) as unit landforms without prohibiting their designation as such should it be desirable. Although such geomorphic units, e.g., a coastal plain, do have a typical landform with typical characteristics that satisfy the above definition, they also include numerous other landforms (Sec. 2-26) with quite different characteristics. Whether or not they are called a unit landform depends upon their suitability for such classification, the objective of classification, and the classifier's viewpoint. Most of von Engeln's geomorphic units (coastal, fluvial, lacustrine, deltaic, lava, piedmont, and loessial plains, interior plateaus, nested saucer basins, volcanic cones, karst, coral islands, and continental glaciers) give information on two of the three items: structure, composition and texture, and uniformity. Therefore it is permissible to consider them as *second-order unit landforms,* containing within their boundaries various *third-order unit landforms,* some of which may be the same, on a smaller scale, as the larger forms within whose borders they occur (i.e., a small floodplain on a fluvial-plain geomorphic unit). Other geomorphic units (tundra and glacial plains, *erg,* dome uplifts, certain fold mountains, fault-block mountains, ancient shield masses, and peneplaned masses) may be classified as second-order unit landforms only with considerable doubt and hesitation. Probably they should not be so classified since the amount of information that they provide concerning their own structure *and* either composition and texture *or* uniformity is nebulous in the extreme.

2-28. Qualifying Terms for Unit Landforms. In the previous section, unit landforms were qualified by the terms "second order" and "third order." There are other qualifying terms that may be used. For example, "complex" and "simple." A simple unit landform, such as an esker, or a fan, has no other landforms included within its borders. A complex unit landform has. Most complex unit landforms are of second-order magnitude, e.g., a coastal plain, but they may conceivably be of third-order magnitude.

Two other terms are "constructional" and "tectonic." Constructional forms have come into being largely through processes of deposition and may *usually* be thought of as unconsolidated. Tectonic forms have come into being by processes of mass stress and strain, together with *PVT* variations, and are invariably consolidated.

To demonstrate complete possible nomenclature: a coastal plain might be properly termed a complex, constructional, second-order unit landform; an esker would be called a simple, constructional, third-order unit landform; a lava plain would be termed a simple, constructional, second-order unit landform; while a volcanic cone might be termed a simple, tectonic, second- (or third-) order unit landform.

2-29. A Classification of Unit Landforms. A first attempt at the classification of unit landforms appears as Fig. 2-1. This classification, and its accompanying symbol system, is initially divided according to origin. It had its inception in a paper by the author (105) which described a system for the map designation of engineering soils (Appendix B).

While this system may be incomplete or controversial, it has the advantage of providing a start for the orderly consideration and designation of terrain on the highly important basis of unit landform.

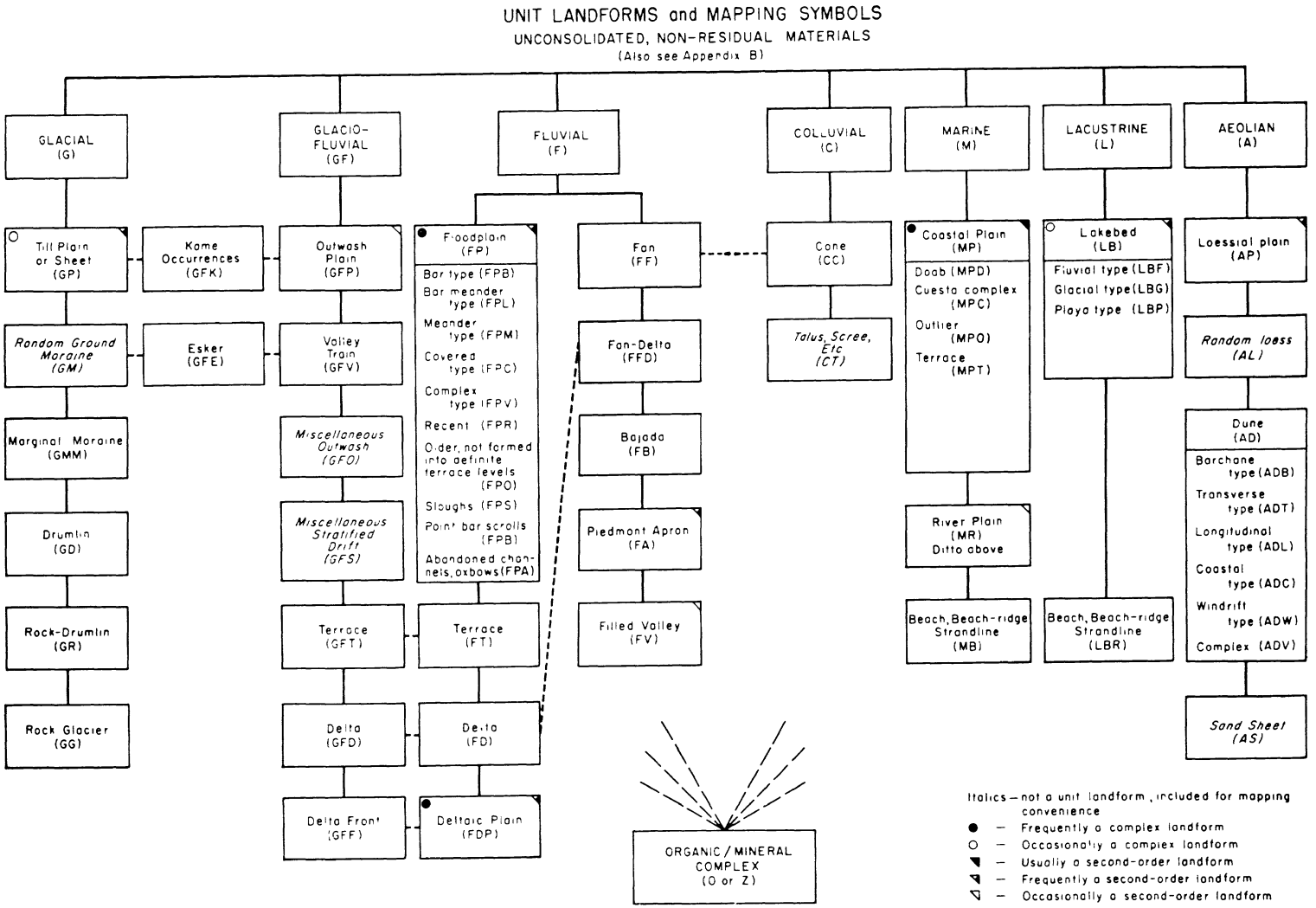


Fig. 2-1. A schematic representation of the relations between landforms of various origins, including suggested mapping abbreviations (Chap. 24).

Most of the unit landforms that appear in Fig. 2-1 *are discussed and illustrated in Part II.* In that part, and henceforth throughout this book, the term "landform" will be used as a substitute for "unit landform."

2-29a. Significance and Insufficiency of Origin–Rock Type–Landform to Interpretation. In terms of the previous discussion, it should be apparent that the establishment of the origin and rock type or landform pertaining to a given area is of great importance to interpretation. Similarly to the establishment of the geomorphic unit (which may *be* the unit landform), general characteristics of the terrain can be predicted. These are usually less general than those for the geomorphic unit alone. For example, if the esker landform is recognized, it is *almost completely described* in terms of its predominant textural composition, its general uniformity, and its general structure. Only a slight bit of additional information may be gained from further interpretation. In comparison, establishment of the fluvial-plain geomorphic unit only indicates the presence of unconsolidated, roughly horizontally stratified, horizontally and vertically intermingled materials having highly variable composition, texture, and location.

As mentioned in Sec. 2-1, the establishment of the origin–rock type–landform combination is *a most important part of the interpretative process.*

Unfortunately, except in cases similar to the esker above, the recognition of landform alone is not usually sufficient for the completion of *practical* interpretation. Engineers are not satisfied to know that a given area is a fluvial terrace. They wish to know whether it is predominantly composed of coarse gravels, medium sands, or silty clays. Geologists are not satisfied to know that they are in a nested saucer basin. They want to know the location of the various rock types and the structural features that exist in association with them. Agriculturalists and engineers are not satisfied that they are studying a fluvial-covered floodplain. They must know the location and extent of the gravels, sands, silts, clays, and organic materials in their various drainage conditions.

A recognition of landform alone will only occasionally answer such questions. Yet, proper interpretation can often answer these and similar practical inquiries. Why? Because it goes beyond landform. It recognizes and capitalizes upon the logical fact that *different materials have different responses to the forces of weathering and deposition, which are reflected by differences in surface drainage, tone, erosion features, slopes, etc.* It therefore proceeds to analyze such features and draws logical inductions and deductions from them. In this respect, it goes far beyond the other earth sciences with their common terrain-evaluative methods.

In the following chapters, these features are discussed and illustrated.

3 SURFACE-DRAINAGE PATTERNS

3-1. Definition of Surface-drainage Pattern. With the exception of landform, the surface-drainage pattern is probably the most consistently reliable indicator of ground conditions available to the photo interpreter.

This pattern may be defined *as the arrangement of surface drainageways and shallow subsurface drainageways covering an area, in the complete detail of their density, orientation, uniformity and plan, etc.*

The shallow subsurface drainageways refer to those swales which carry water during wet weather, either as shallow surface runoff or as shallow near-surface percolation caused by saturation. Anyone who has walked across country in the northeastern United States, during mid-spring, will remember getting his shoes wetter than expected in such swales.

It is important to note the word "area." No particular size of area need be specified. It may be an acre, a square mile, or a hundred square miles. The pattern may, indeed, have a certain significance as a whole, while a certain sector of it may have significance regarding a part of the whole. The important thing is that the surface-drainage pattern provides information regarding the physical characteristics of materials. Taken as a whole, the pattern indicates characteristics which have a tendency to cover a broad area, while individual elements of the pattern—gullies, individual swales, bends, separate streams, etc.—may provide information regarding a large area, a small area, or a specific location.

3-2. Infiltration and Runoff. When rain falls, a certain amount is evaporated in transit. Another portion is intercepted by, and evaporated from, the ground vegetation. The residue comes into contact with the mineral ground surface. Neglecting all complications due to surface-vegetation type and density, the water which reaches the mineral ground surface, i.e., the soil or rock, either soaks into the ground or runs over its surface.

That portion which soaks into the ground flows beneath its surface by various means and at various levels, emerging ultimately as subsurface runoff and ground-water flow or disappearing into the "permanent" ground water. It may be called "infiltration."

3-3. Primary Justification for Surface-drainage Analysis. The surface-drainage pattern developed in area materials is largely a function of the infiltration-runoff ratio(s) characterizing these materials. The infiltration-runoff ratio(s), in turn, is (are) primarily dependent upon the physical characteristics of the materials themselves (at least, for a given climatic regimen). This second statement is a well-established hydrologic fact. It is true that other variables have an important effect upon the infiltration-runoff ratio. These variables include the type and density of vegetative cover; the natural moisture content of the soil; the existence of frozen soil; the tilth, aggregation, and other profile characteristics of the soil; the mineral composition of the soils or rocks; special geochemical conditions created by the climate-mineral complex; and any special physicochemical effects, e.g., swelling, that are typical of the soil profile. However, these effects are *almost always* [1] *superimposed upon the primary factor of soil or rock texture and composition, and it is this factor which, over the relatively long periods of geological erosion and climatic change, has exerted the dominant effect upon the development of the runoff, or surface-drainage, pattern.*

In further explanation, relatively impervious materials (clay, shale), because of their fine texture, will resist infiltration and promote runoff.

[1] In certain instances, where bedrock controls, the fracture or bedding system has exerted a dominant influence. The italicized statement should be interpreted as excepting this condition.

The runoff will erode surface drainageways with ease, creating a relatively dense drainage network. In contrast, relatively pervious materials (gravel, sandstone), because of their coarse texture, will have a comparatively high infiltration capacity and will resist the formation of surface drainageways (Fig. 3-1) unless they are influenced by special factors such as violent water flow of considerable quantity and velocity, the development of planes of weakness, etc. This may be reworded to say that, in general, a well-developed drainage pattern implies relatively low infiltration and relatively impervious materials, while a lack of surface drainage is indicative of high infiltration and general perviousness. As always, there are exceptions and special cases, but as a general rule this one is hard to beat.

This, then, is the primary justification for surface-drainage analysis: *it gives a clue concerning the infiltration-runoff ratio, infiltration capacity, perviousness, and texture of the materials in an area.*

3-4. Other Values of Surface-drainage Interpretation. Although relative textures, perviousness, and infiltration-runoff properties are the primary characteristics of area materials that can be obtained inductively from an analysis of surface drainage, there are other valuable indications of terrain conditions that can also be derived. These include:

1. Extent and location of materials having significant differences
2. Degree of uniformity of materials
3. Location and extent of localized changes
4. Localized or general factors of control
5. Existence of, and depth to, bedrock or hardpan
6. Origin of underlying bedrock

It is axiomatic, after the discussion of Sec. 3-3, that significantly different drainage patterns indicate the locations and areal extent of materials having significantly different characteristics, in terms of texture, perviousness, etc. The only difficulties are those associated with a decision concerning the nature of significant differences. These can be resolved largely through the exercise of common sense and the application of experience.

It is almost equally obvious that a uniformly developed pattern, in all its detail, indicates a material having a certain measure of uniform physical characteristics over the area of uniformity. Conversely, nonuniformity of pattern indicates a nonuniform material, the degree depending upon the extent and nature of nonuniformity.

If the foregoing paragraph is acceptable, then it is equally acceptable to consider a localized change in drainage pattern as being indicative of a localized change in material characteristics. Figure 3-2 provides a schematic illustration of a

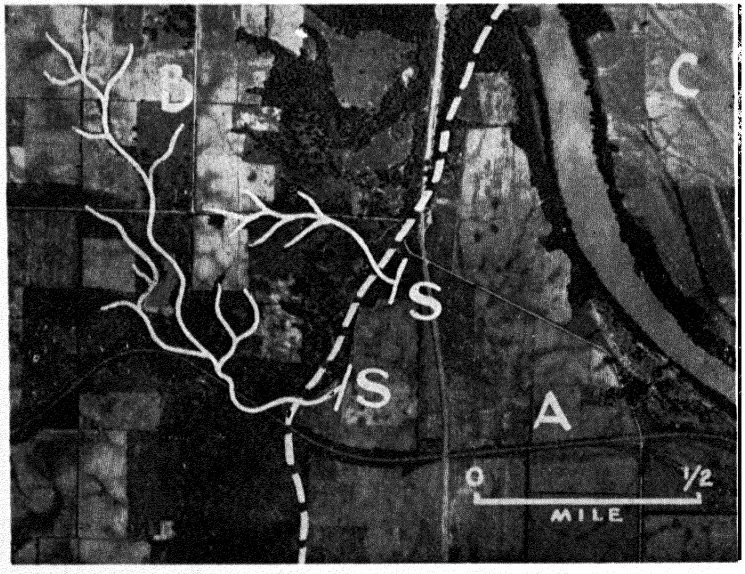


Fig. 3-1. The boundary between a relatively impervious upland (B) and a porous lowland (A) is shown by the dashed line. However, it is also revealed by the ends of the disappearing streams (S). When these streams contact the porous materials, they disappear beneath the surface. This photo was originally selected and annotated by the Cornell group (43). (*Indiana. USDA, Commodity Stabilization Service.*)

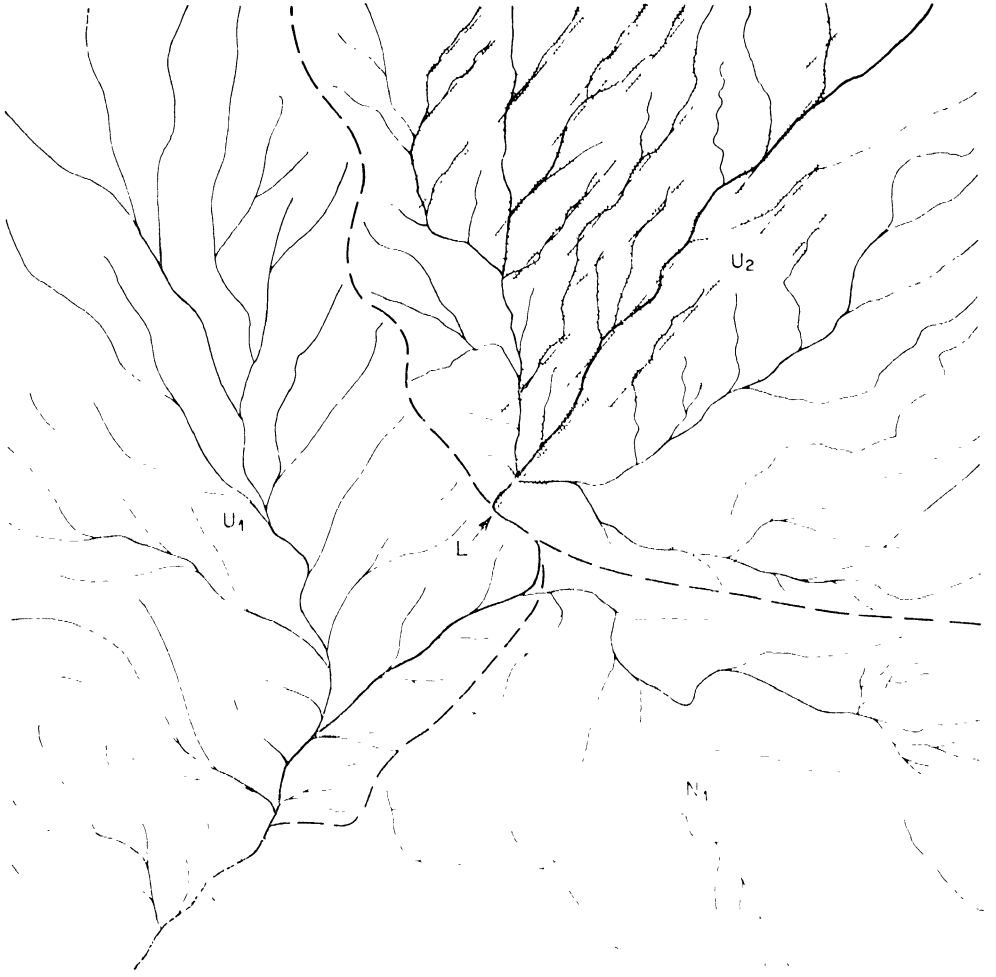


Fig. 3-2. A schematic presentation of uniformity (U_1, U_2) and nonuniformity (N_1), localized change (L), boundaries between different materials (mostly coincident, in this case, with catchment boundaries), and appearing and disappearing orientation (shaded areas).

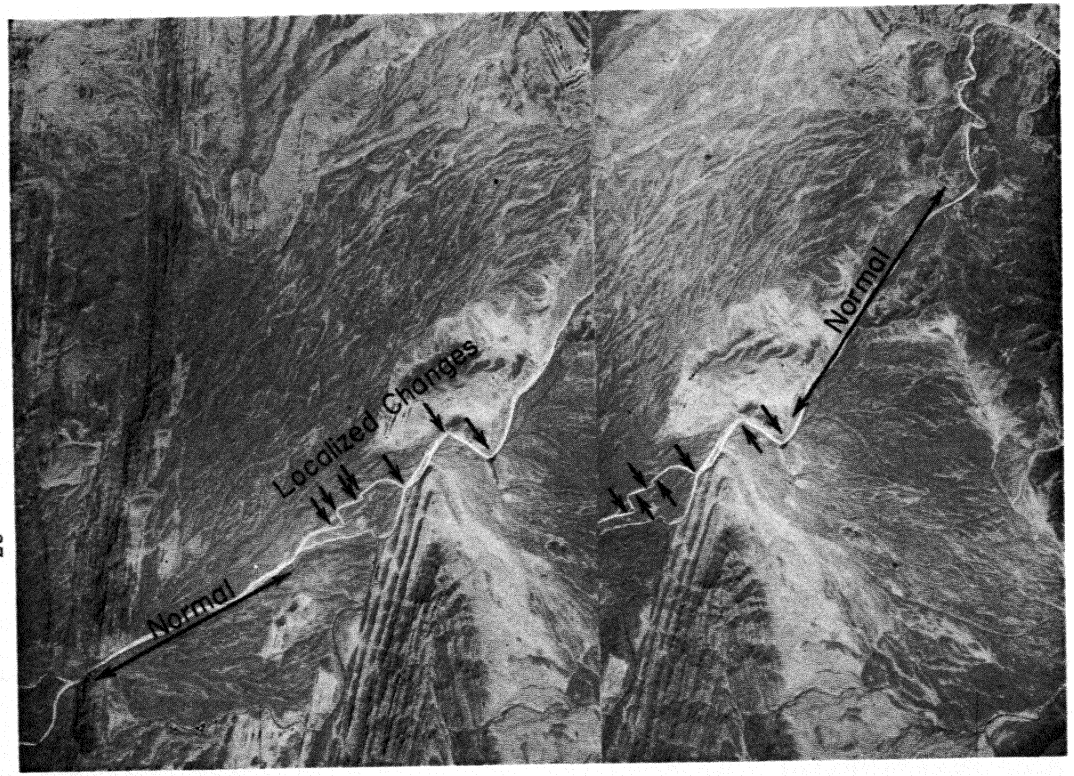
drainage pattern showing location, extent, uniformity, nonuniformity, and localized change.

Although somewhat less indicative, it is also true that the type and extent of erraticism in an otherwise uniform drainage pattern may provide a clue concerning the type and extent of material control that causes it.

Control indications, such as those illustrated by Fig. 3-2, may be indicative of the existence of and depth to bedrock. If a repetitive design appears, such as that at U_2 of the figure, it is almost a definite indication of bedrock at or near the depth of stream erosion. If the pattern appears and disappears, it may be due to a variation in the depth of overburden, to a variation in depth of stream erosion, or, rarely, to a coincidental reflection of deep structure. It is usually the first or second or a combination of the two.

The very shape of the drainage pattern may be indicative of the origin and type of rock that underlies a given area—under either transported overburden or residual soil. Fractures and control are often characteristic of certain rocks, and when these appear as elements of the drainage pattern —as for pattern U_2 of Fig. 3-2—these rocks are indicated. Additionally, certain rocks have typical

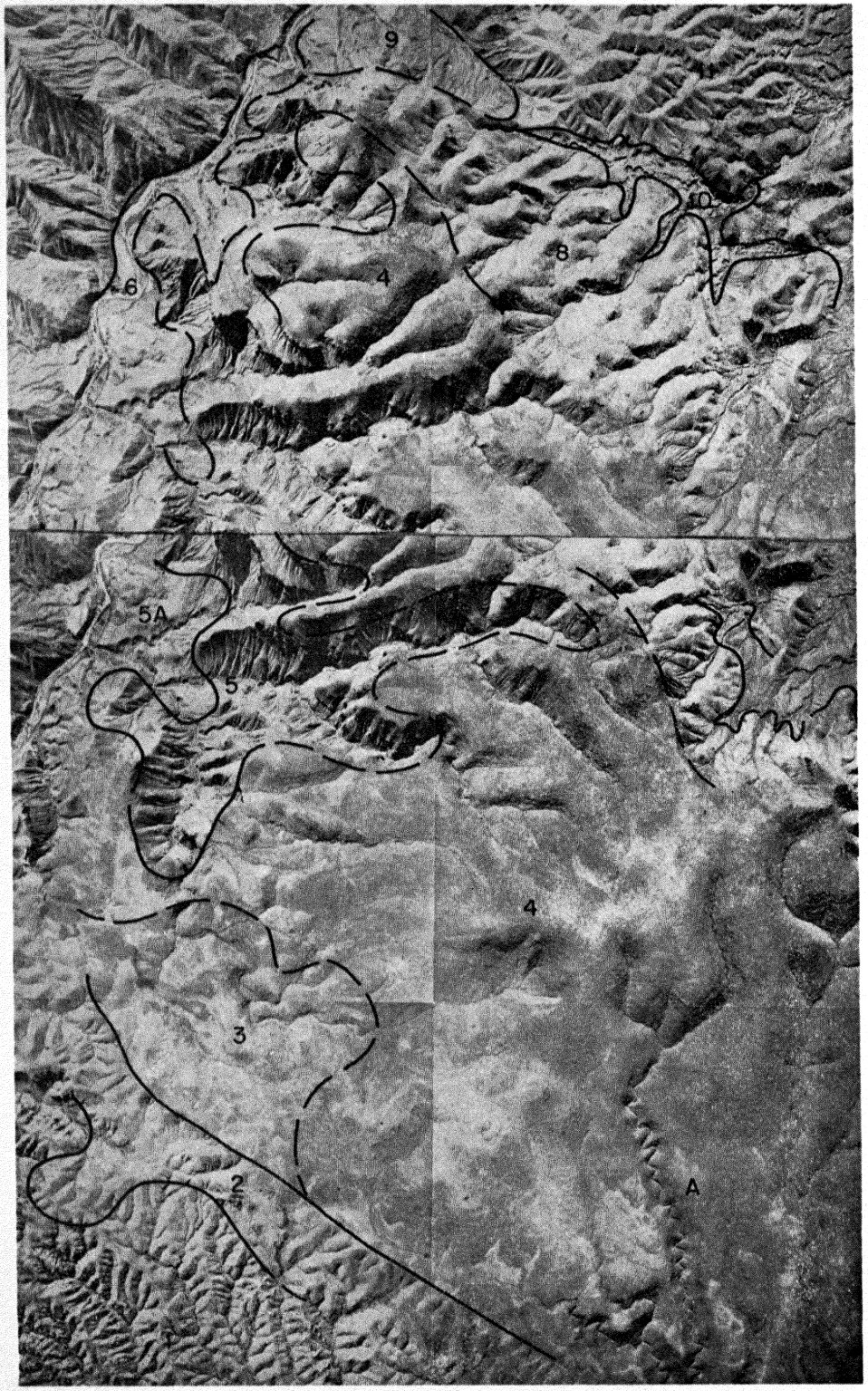
(a)



(b)

Fig 3-3. (a) This stereotriplet shows a good example of areal localized change that indicates a change in depth of overburden. Note that in the upper portion of the picture (as indicated by the fine, drawn lineations, emphasizing the geological structure), the over-all control is horizontal. Even the tributaries of gullies developed in the unconsolidated materials pick up this trend, indicating shallow overburden. At the areas marked *L*, the gullies do not display this trend, but are random or contrarily oriented. The depth of overburden should be deeper in these areas, and they probably are coincident with the channel of an old river course (*R*).

(b) Straight stretches of a normal stream course are interrupted by localized changes caused by impingement from shallow bedrock. (*Middle East. Hunting Aerosurveys Limited.*)


9
10
8
6
4
5A
5
4
3
2
A

patterns that develop because of the formational, erosional, and physical characteristics of the rocks themselves. Such patterns are true indicators of rock types and origins (Chap. 16).

3-5. Destructional and Constructional Drainage. To analyze surface-drainage patterns correctly, it is convenient to distinguish between surface-drainage patterns that have been created in virgin materials, solely by a process of destructional erosion along the shortest downward path, and those drainage patterns whose development has been modified in a pronounced way by the operation of constructional-depositional-geologic processes.

In this book, patterns of the first type are termed "destructional" and those of the second type "constructional."

All drainage is, in reality, destructional; i.e., in the process of following a downward path, it erodes the land and therefore destroys it. However, there is a distinction that can be made in regard to the path which it chooses for a course.

Normal drainage—here termed destructional drainage—proceeds initially along the shortest downward path, largely unaffected by any terrain factors save competence of the formations that it contacts and tectonic movements which may have created obstacles to its course by means of elevation or fracturing. In the first case, the drainage courses veer; in the second, they are channeled. Destructional drainage might be called normal drainage. It may easily be described by geomorphological terms such as "consequent," "subsequent," "insequent," and "resequent" (see any textbook on geomorphology). Its patterns are somewhat repetitive and have been characterized by names such as dendritic, random, lattice, etc. (Sec. 3-14). Further, the patterns can be described easily by characteristics such as those discussed in Secs. 3-6 to 3-11. These patterns, terms, and characteristics—and destructional drainage in general—are associated with large areas, usually composed of rock or semiconsolidated materials. Most of the figures in this chapter illustrate destructional patterns.

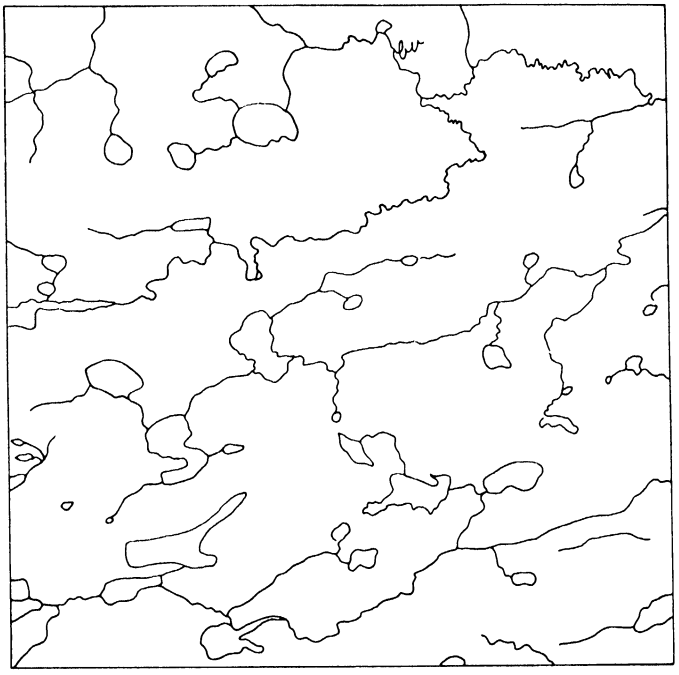
There is also a class of drainageways that owes its development and details to the initial operation of geologic depositional processes. This class, termed constructional drainage (for lack of a better term), is destructional in the true sense; i.e., it erodes, but its initial and dominant pattern of drainageways is channeled in a manner that is typical of the process that created it. It is invariably associated with unconsolidated materials and may often be confined to relatively small areas. It is not easily defined by classical geomorphological terms, but may be typified by descriptive terms such as "deranged," "erratic," and "braided," or by the names of the process associated with it, such as "point bar," "meander scroll," "outwash," "fan," etc.

To the interpreter constructional drainage patterns are as important as destructional patterns. However, such patterns are best studied in conjunction with their parent geomorphic process. *Accordingly, they are not considered further in this chapter* (see Chaps. 9 to 15 for illustrations).

3-6. Characteristics of the Drainage Pattern. Every drainage pattern may be described in terms of its major characteristics. These characteristics, as used by the interpreter, are (1) degree of integration, (2) density, (3) degree of uniformity, (4) orientation, (5) degree of control, (6) angles of juncture, (7) angularity, and (8) type and simile.

These terms can be applied to the description of constructional drainage patterns. However, they are usually of little significance when so used. Con-

Fig. 3-4. A fine example of the value of the surface-drainage pattern as an indicator of terrain conditions. By using the surface-drainage pattern alone (and without a stereoscope), it is possible to delineate areas of apparent terrain differences (areas 1 to 10). The drainage pattern clearly indicates their location and extent. It must be realized that the indicated terrain differences are not due solely to composition of material, but they also indicate other things, such as topography, which affect the development of the drainage pattern. For example, area 5 is a sidehill erosion phase of area 4. So is area 8, but the difference between 5 and 8 suggests that a sidehill position is not the only factor of difference. Areas 1, 4, 5, 7, 8, 9, and 11 are all areas of uniformity (Sec. 3-9), while areas 2, 3, 5A, 6, and 10 show varying degrees of nonuniformity. Area 4 has a very low density of drainage, although integration is fairly good (Secs. 3-8 and 3-7). Does this indicate porousness? Areas 1 and 11 have very high density and integration (indicating high erodibility), and the areas of deep local change indicate that area 4 is occupied by a deposit overlying that of area 1, which is just being cut into. Area 3 has other indications of local change. Actually, a great deal more can be extracted from an analysis of drainage alone, but of course the interpreter also uses landform, microtexture, boundary characteristics, tone, etc., in this case, and could construct a pretty good map of terrain conditions. For the benefit of the interested reader, area 4 is porous, being a light-colored (rhyolitic) lava (Chap. 16). (*Arizona. U.S. Forest Service.*)



(a)

(b)

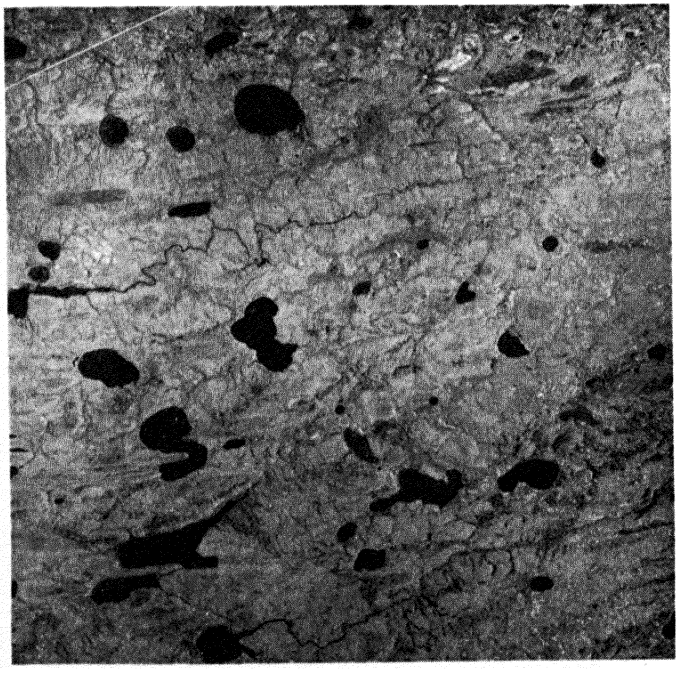
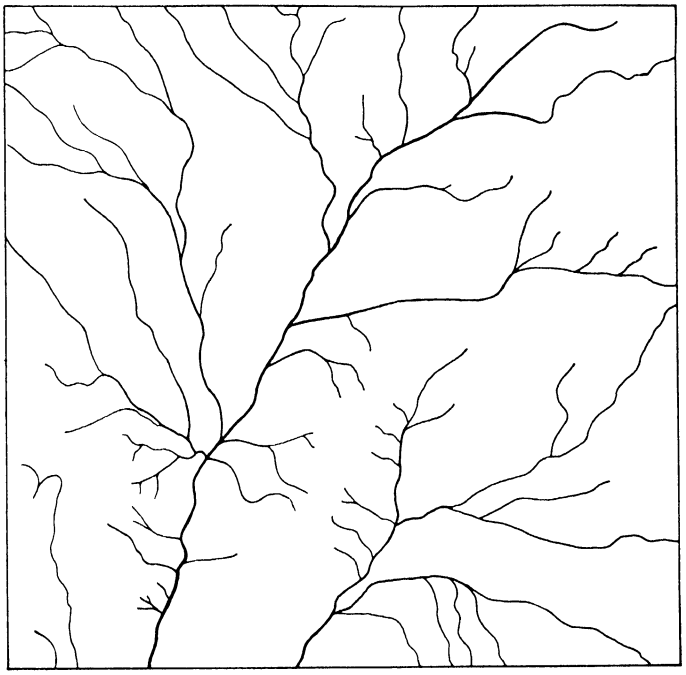
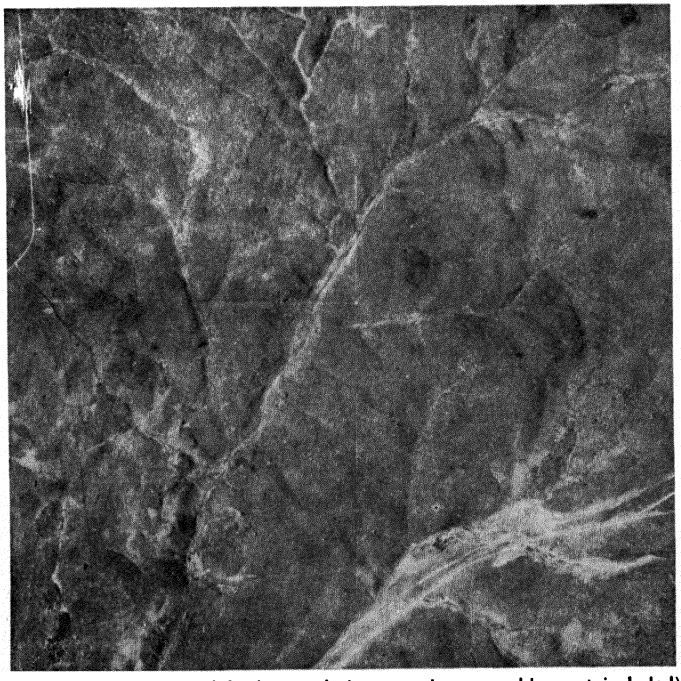


Fig. 3-5. Examples of low-density (Sec. 3-8) poorly and well-integrated drainage patterns. Note that the path down the tributaries from the well-integrated pattern to any other point on the system is quite direct. The contrary is true for the poorly integrated pattern. The well-integrated pattern, if described by simile (Sec. 3-14), would be called "tree-

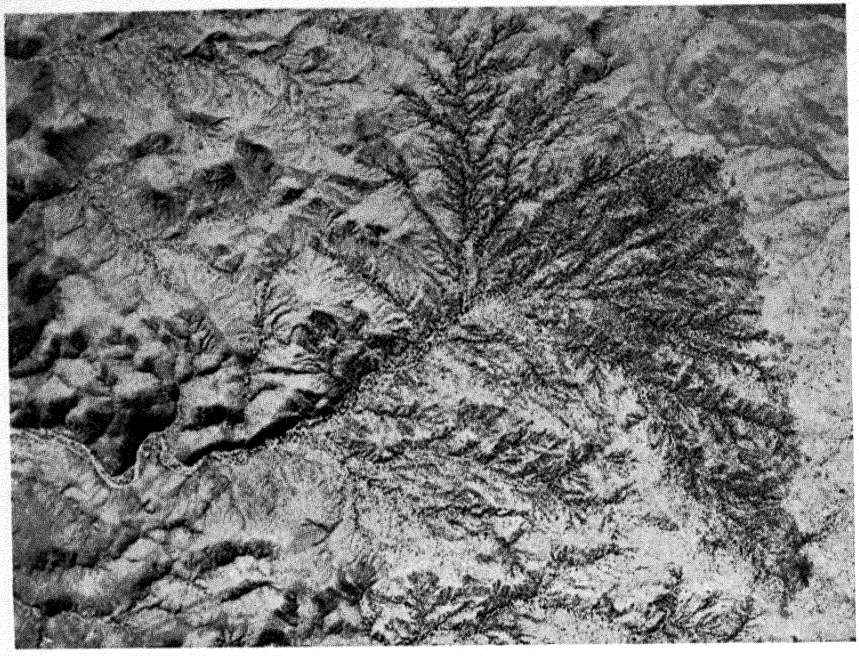
(c)





(d)

like," or "dendritic," while the poorly integrated one would be termed "deranged." The poorly integrated pattern is developed on a glacial plane (horsetail permafrost drainage not included). (*Canada, New Mexico. Photographic Survey Corporation, U.S. Forest Service.*)



(*a*)



(*b*)



(c)



(d)

Fig. 3-6. Four single aerial-photographic views of surface-drainage patterns having various degrees of integration. The two integrated patterns show (a) a very high density (Arizona) and integration, reflecting degree of erodibility and uniformity, and (b) a high density (New Mexico) and degree of integration, partially indicative of uniformity. The nonintegrated patterns show (c) the effect of low position and relative youth (coastal plain of New Jersey) and (d) high position but relative youth (marginal moraine in Ontario). Both patterns have high density even though nonintegrated. (*U.S. Forest Service, Aero Service Corporation, Photographic Survey Corporation.*)

structional drainage reflects primarily the type of geological deposition and frequently varies widely in short distances. While integration, density, orientation, etc., exist, they are reflective of geological activity, not subaerial erosion. Consequently, they lose some of their significance to interpretation because they do not reflect the uniform action of water on materials of varying types. It is recommended that constructional drainage patterns be described according to origin, landform, or simile, keeping the above terms in mind as a check list that will aid description. In other words, it is recommended *that the terms be considered applicable to destructional drainage only.*

For example, the constructional drainage pattern of a meander deposit might be described as a "typical, scroll-type, closely spaced, point-bar pattern." This would include both descriptive terms and mode of deposition and would enable the reader to visualize the pattern in most of its significant detail. Comparatively, a destructional drainage pattern created in slate by water erosion would require description in terms of density, uniformity, etc. Only by such description could it be adequately visualized by a reader, and only by such means could its significant details be subject to inclusion rather than omission.

The following sections discuss each of the drainage characteristics listed above.

3-7. Degree of Integration. This refers to the degree of unity exhibited by a drainage pattern.

A pattern having a high degree of integration within the confine of any given area has the characteristic that a line from any point on any drainageway to any other point on any other drainageway may be traced along the existing stream channels in a fairly direct manner. The concept of high integration is a difficult one to describe in words, though it is easy to visualize. The distinction between a highly unified, or highly integrated, pattern and a fragmental, or nonintegrated, pattern is best shown by illustration (Figs. 3-5 and 3-6).

These figures show that the degree of integration is relative and is dependent largely upon the size of the area considered, since most drainage patterns are integrated if you consider them over a large enough area. However, it is believed that the concept of integration is a real one and is sufficiently illustrated to allow its tentative acceptance by the reader, subject to confirmation by experience.

The degree of integration is indicative of: (1) uniformity and degree of erodibility (texture, perviousness, infiltration-runoff ratio), (2) length of erosion, and (3) existence and location of modifying factors such as materials characteristics, topographic expressions, etc.

The previous figures (3-5 and 3-6) illustrate effects of youth and position on integration.

3-8. Density. This refers to the number of drainageways per unit of land surface. A pattern of high density is covered with numerous closely spaced drainageways. One having low density has relatively few drainageways per unit of area. A pattern may be either integrated or nonintegrated and have either low or high density.

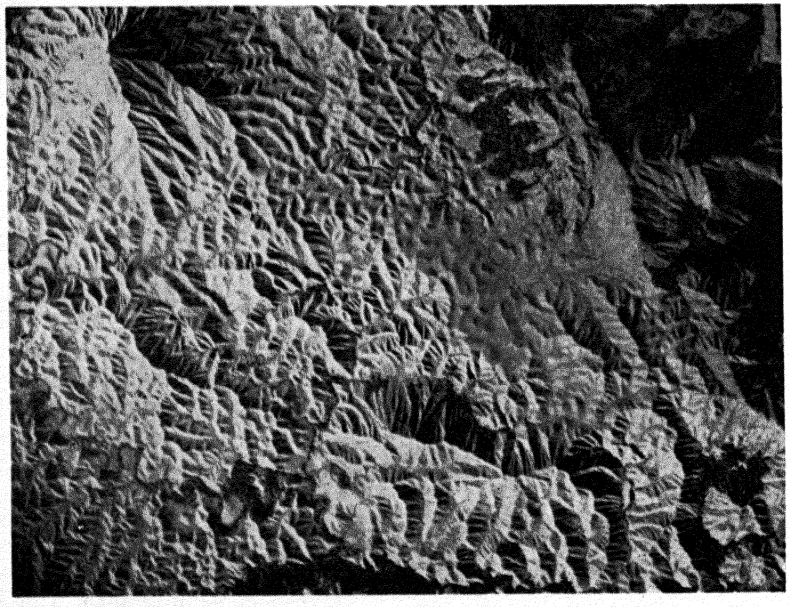
Density of pattern is indicative of: (1) degree of erodibility (texture, perviousness, infiltration-runoff ratio), (2) length of erosion, and (3) special climatic conditions.

Figures 3-7 to 3-10 illustrate some aspects of the situation. There are various methods of measuring and expressing density.

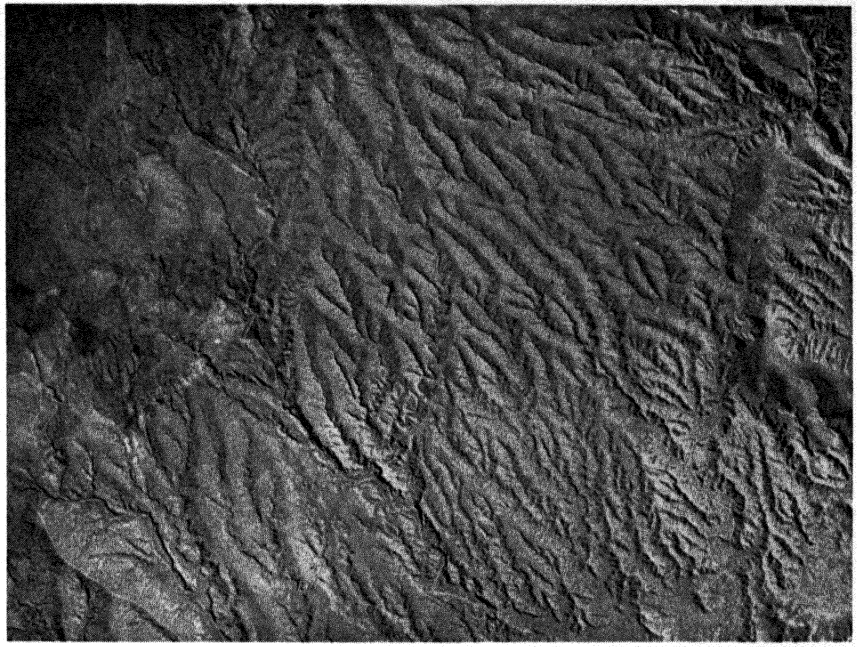
3-9. Degree of Uniformity. This refers to the relative homogeneity of the pattern. A uniform pattern is similar, regardless of whether it is examined in part or as a whole. A nonuniform pattern has areas whose individual subpatterns are different from those of other areas. A pattern may have any combination of integration and density and still be either uniform or nonuniform.

The degree of uniformity is indicative of: (1) uniformity of erodibility and materials (texture, perviousness, etc.), (2) uniformity of erosion history, and (3) boundaries between areas of different characteristics of history.

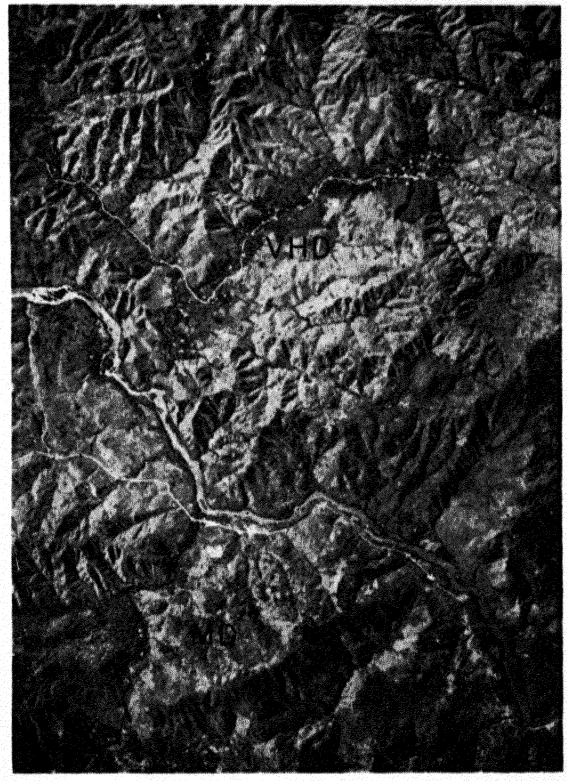
A pattern covering a large area may be non-



(a)



(*b*)



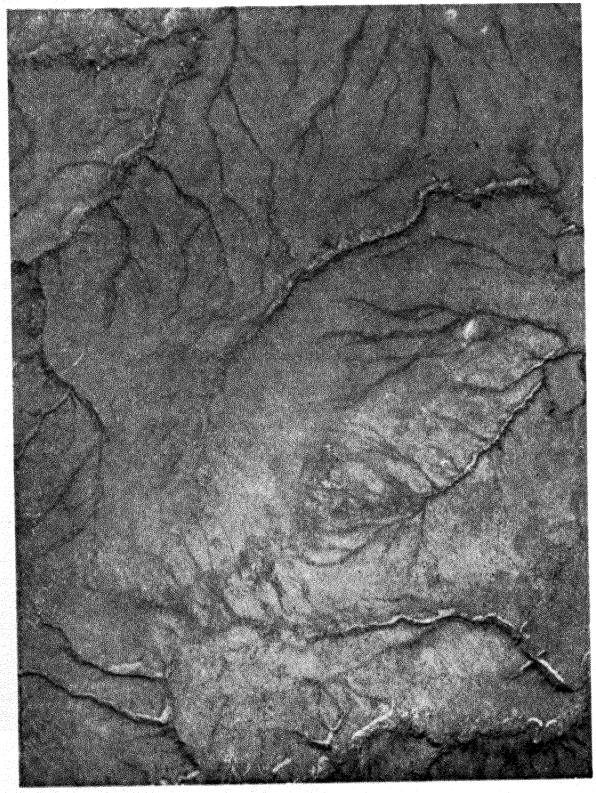
(*c*)

Fig. 3-7. Three single aerial views illustrating very high density of drainage pattern. Pattern (*a*), Philippines, is carved in uniform shales. Pattern (*b*), Arizona, is eroded in semiconsolidated valley fill (Chap. 10). Pattern (*c*), Brazil, has a very high density (*VHD*) on one side of the river, and a much lesser, approaching a medium density (*MD*), on the other. The river has probably carved its course along the contact between the two rock types. All the photos have been adjusted to a scale of 1:40,000. (*U.S. Army, U.S. Forest Service, Prospec.*)



Fig. 3-8. Two pictures of medium- and (on facing page) one of low-density drainage patterns. All three photographs are reduced to 1:40,000. (*Photographic Survey Corporation, RCAF, U.S. Forest Service.*)

(*a*) **This pattern from Ceylon has a rather odd shape, which lowers its degree of integration. However, it is uniform.**



This figure (Yukon) has medium density, is well integrated, and is uniform. It displays no orientation, control, etc. (*b*)



This pattern (Utah) appears nonuniform as a whole, although a larger view might show that the sickle shapes (black lines) are characteristic, repetitive, etc., making the pattern uniform. Integration is high-medium. (c)

uniform as a whole, but may be composed of numerous component areas, each uniform in itself. Therefore the large area may be separated into smaller areas having different erosive characteristics, and the boundaries of these areas drawn with a fair amount of certitude (Figs. 3-3, 3-11, and 3-12).

3-10. Orientation. This refers to those directional aspects of a drainage pattern that are superimposed upon those of downward flow. Orientation implies direction, and the description of an oriented pattern requires a specification of direction or directions. A nonoriented pattern is random in nature. A pattern may have any combination of integration, density, and uniformity and be oriented or nonoriented.

Orientation indicates the effect of geological factors in addition to those of subaerial destructional erosion, e.g., relatively shallow bedrock, structural features (192), tectonic movement, constructional drainage, etc. Some types of constructional deposition are characterized by typical oriented patterns.

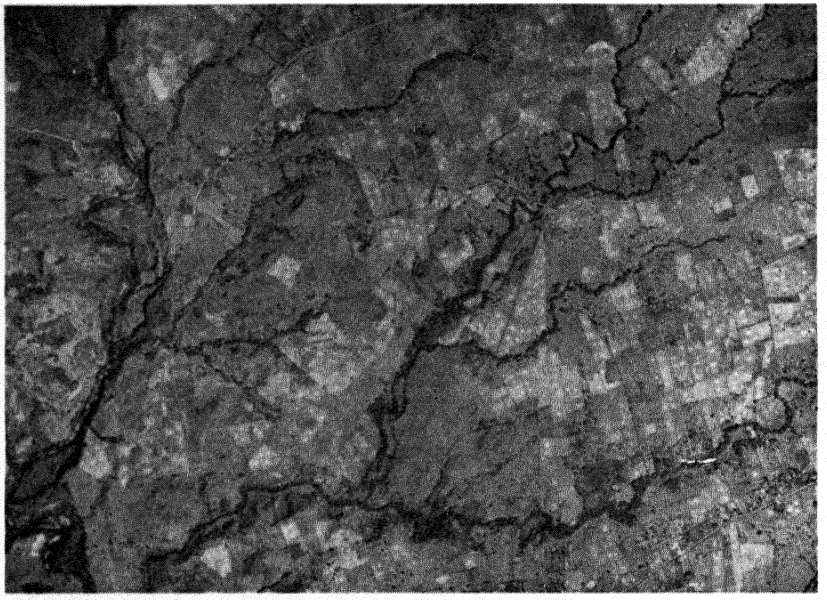
Figures 3-8 and 3-9 illustrate some aspects of orientation.

3-11. Degree of Control. This refers to the relative dominance of orientation. An oriented pattern having a high degree of control is characterized by drainageways that follow oriented directions almost exclusively, even in detail. An oriented pattern with a low degree of control has a general, often vague, orientation.

The degree of control provides clues concerning the geological factor causing orientation and also provides information on specific area characteristics such as relative depth to bedrock.

Figures 3-13 to 3-15 show areas of high and low degrees of control. Figure 3-8 (Ceylon) shows moderate control. Also see Fig. 3-3.

3-12. Angularity. This refers to the abruptness of directional change exhibited by the component streams of the pattern. High angularity implies sharp, and often abnormal, changes in stream direction. Low angularity implies relatively gradual changes in stream direction. Angularity can be confined to a single location along a stream, as



(a)



(b)

Fig. 3-9. These two single photographs display the nature of a low-density pattern. (a) The pattern is uniform and well integrated and has some angularity. (b) The pattern appears nonuniform, but is fairly well integrated. Both photographs are adjusted to a scale of 1:40,000. (*Central America, New Jersey. U.S. Department of Agriculture.*)



Fig. 3-10. This single photograph, like Fig. 3-3, illustrates a variety of uniform drainage patterns, having different densities, uniformities, control, etc. If lines were drawn around the various patterns, a first approximation to a proper terrain map would result. (*Arizona. U.S. Forest Service.*)



(a)

Fig. 3-11. These two photographs show uniform patterns (*U*) of distinctly different types. Note the color change (*C*) (Chap. 5). The pattern in (*b*) is developed in lava flows. [(*a*) *Utah.*]



(b)

(a)

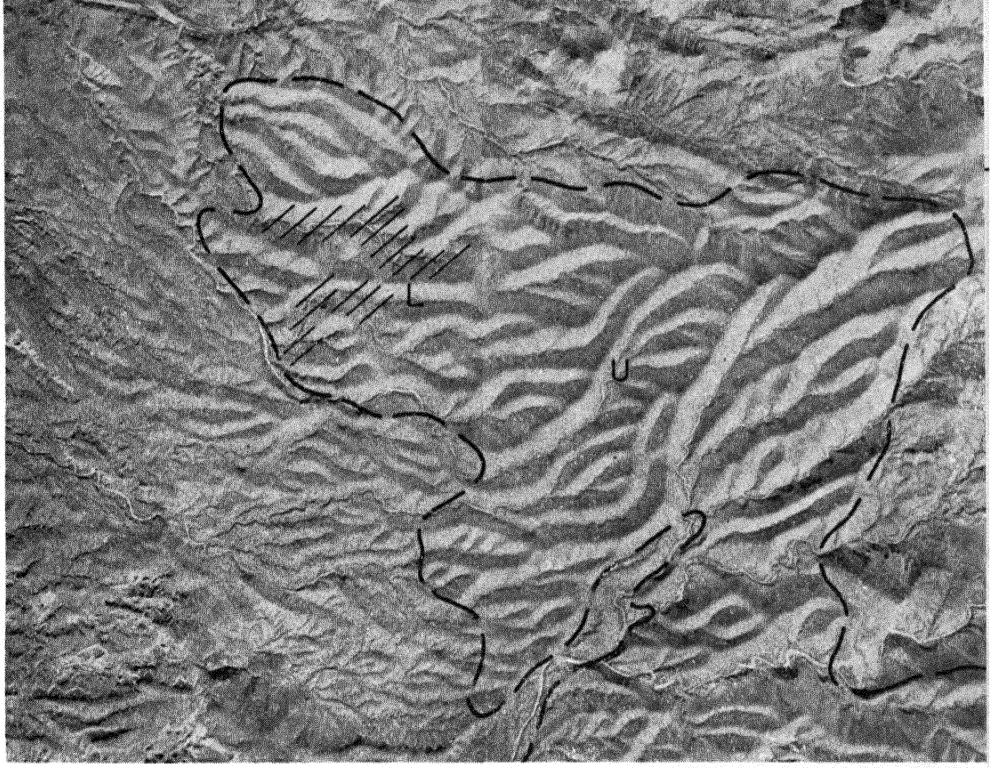
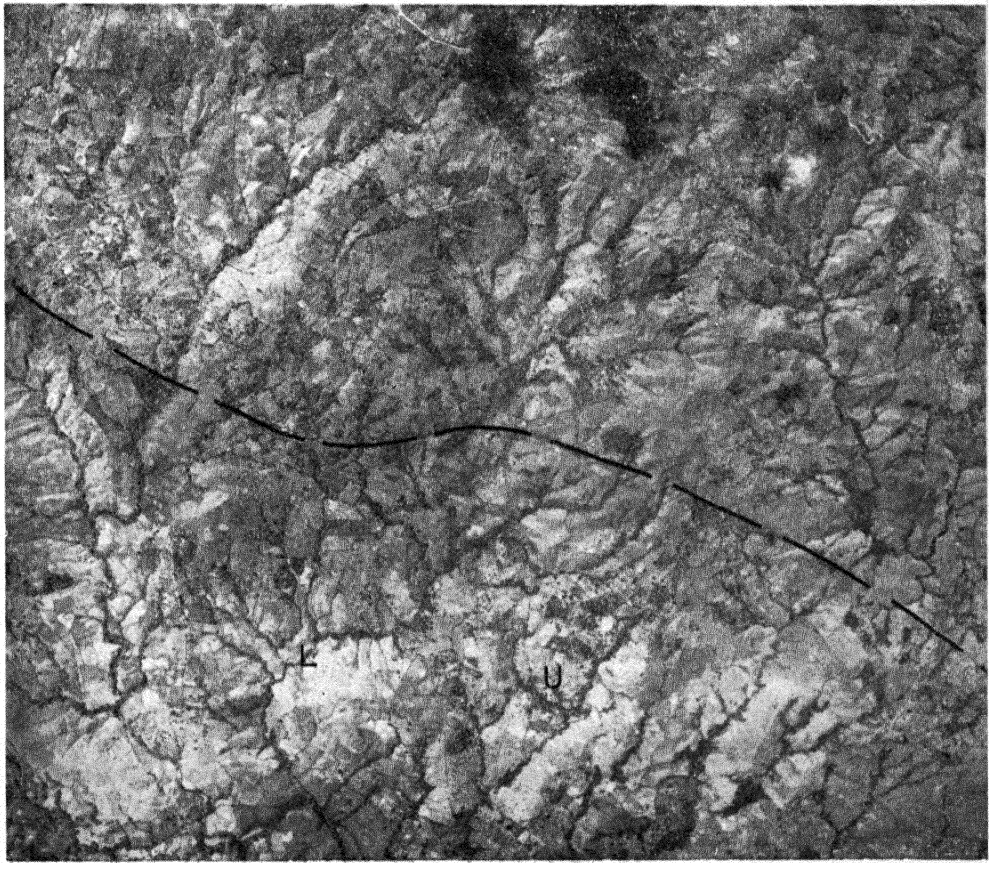


Fig. 3-12. Two more examples of uniformity (*U*). Possible localized changes are indicated by *L*. [(*a*) *Arizona.*]

(b)



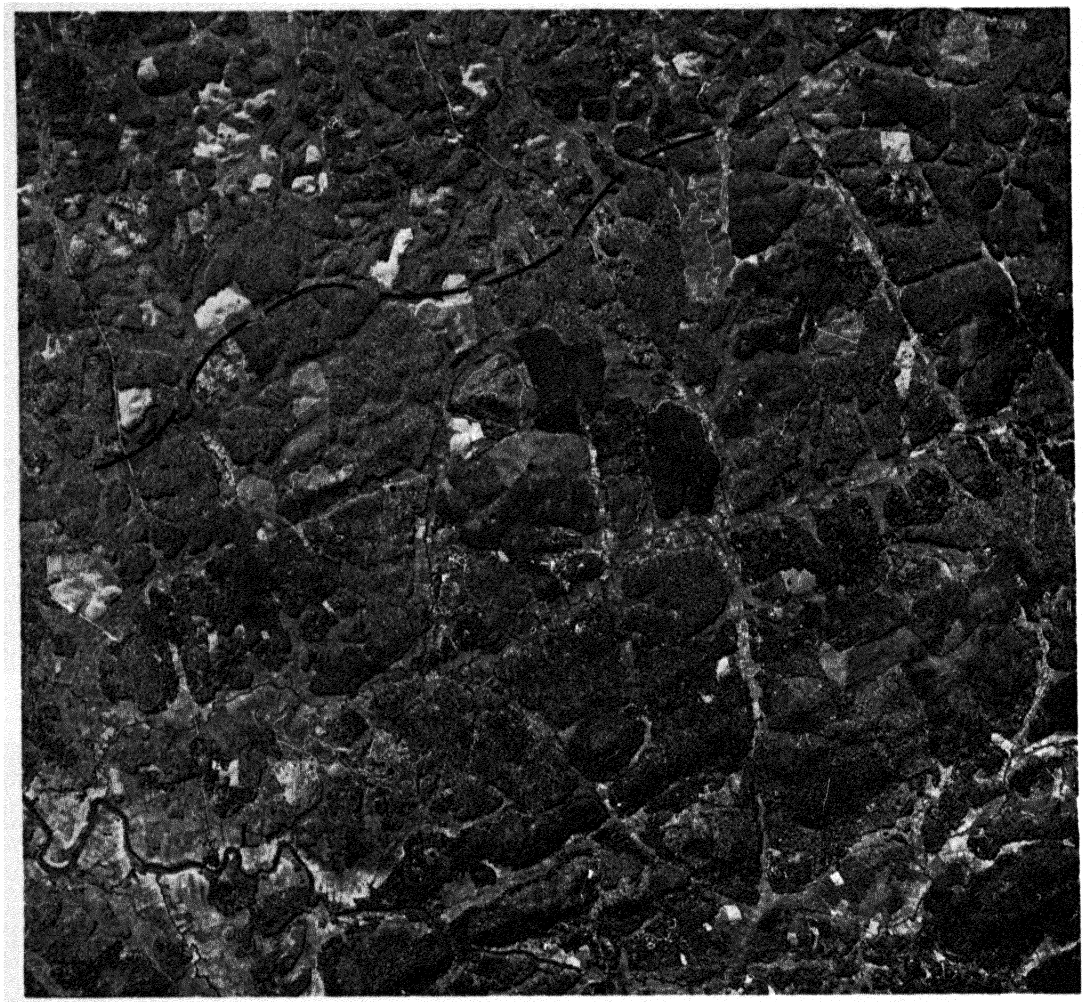


Fig. 3-13. This example (Ceylon) shows a pronounced intersecting (joint) orientation. The actual drainage lines are subdued by the paddying practices, which tend to flatten and fill the valleys on this island. A possible boundary, indicated by the joint pattern, is shown by the line. Note the tone-indicated natural levees (*L*) near the stream. Numerous other examples of orientation, degree of control, and angularity appear in this book, particularly in Chaps. 16 and 19. (*Photographic Survey Corporation.*)

shown in Fig. 3-1, or to a single river, or to an area. Generally, in the latter case, it is related to orientation, although the orientation and angularity may be different.

The existence, degree, repetition, and other details of angularity provide clues concerning the existence and location of erratic conditions and materials, hidden faults, fractures, shear zones, underground structures, etc.

Some examples of angularity are shown in Figs. 3-13 to 3-15.

3-13. Angles of Juncture. This refers to a special aspect of orientation and angularity, the angle of juncture between a stream and its tributary. Normally, uncontrolled and nonoriented patterns are characterized by an acute upstream angle between streams and their tributaries, However, some types of rocks and structures are characterized by distinct, typical, repetitive angles of juncture which diverge from the acute-angle normality and which serve as definite indications of the rocks or structures involved.

Chapters 15 and 16 include some examples of indicative regularity.

3-14. Common Patterns of Special Significance. There have been attempts to differentiate surface-

drainage patterns with names that are descriptive of the patterns as a whole: dendritic, deranged, lattice, trellis, radial, braided, annular, etc. To a certain extent, these descriptive terms are valuable as a shorthand description of major characteristics of the pattern and, by association, certain geological factors which they reflect. However, they supply only a portion of the description that is pertinent to an evaluation of surface drainage and do not eliminate the necessity for consideration of the terms discussed in Secs. 3-6 to 3-13. For example, a dendritic pattern may have innumerable combinations and degrees of integration, density, and uniformity, each of which is indicative of different area characteristics. A trellis or lattice pattern, may, in addition, exhibit further innumerable combinations and degrees of orientation, control, and angularity. To fully describe the significant aspects of a surface-drainage pattern, it is necessary to separately evaluate all its major characteristics. It is certainly permissible and helpful to include a descriptive name in the analysis, but it is not permissible to use the descriptive name alone. This latter practice should be discontinued since it often serves as only slightly more than a misleading evidence of erudition.

3-15. Component Classes of the Drainage Pattern. A normal drainage pattern can be divided into three, and sometimes four, classes: (1) primary drainageways, (2) secondary drainageways, (3) tertiary drainageways, and (4) rill-gully drainageways.

The primary drainageways are the largest ones appearing on the photograph and may be *arbitrarily* defined as those streams which display definable expanse of water surface at a scale of 1:62,360 (1 mile to the inch), i.e., exceed 100 feet in ground width.[2] These streams are important in that they are perennial, often have survived geological changes, and have been able to superimpose their flow across all but the most competent rock types. The characteristics of such streams should be examined for indications of geological history and important regional trends.

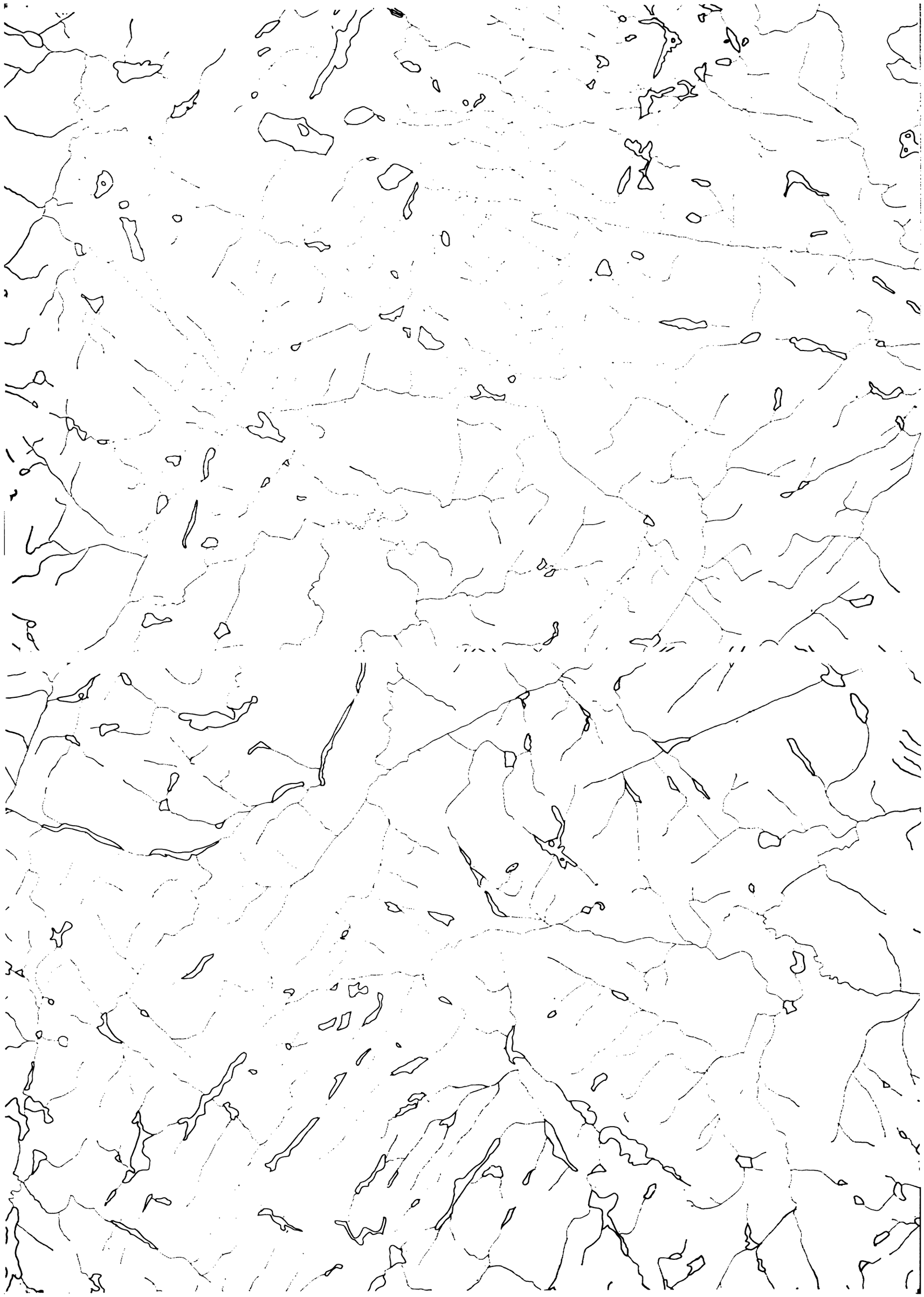
[2] Any other reasonable system should be acceptable The point is that various components of a stream network are susceptible to division into classes. This, of course, has been conceived before, and there are in common use today two systems for classifying streams according to "order." These are the United States and the Continental systems. While these systems, based upon the order of streams, are equally useful, they are also diametrically opposed, the highest order of one being the lowest order of the other. The new science of geomorphometry is slowly developing an orderly, quantitative classification for stream networks.

The secondary drainageways include all the tributaries to the primary streams except those of a tertiary classification. They may be perennial or intermittent. They do not show a definable expanse of water surface, but have *well-defined channels*, usually of considerable length. These streams provide the *major* clues, in so far as surface drainage is concerned, about the extent and broad physical characteristics of materials in the area. They also have considerable pure hydrological significance with respect to flood routing, runoff computation, etc. *The characteristics discussed in Secs. 3-6 to 3-13 refer primarily to the secondary drainageways.*

The tertiary drainageways include the small tributaries to the secondary drainageways. *They are always intermittent. They do not usually have definite channels of flow, but are instead loci of wet-weather swale drainage and shallow subsurface drainage that follow consequent or erosional swales.* This portion of the pattern almost never appears on even the most detailed topographic map. Yet it is ascertained easily on the aerial photographs, and its examination has considerable practical value. Its significance is briefly discussed in Sec. 3-16.

Usually there is an additional component of the drainage pattern—the rill-gully drainageways. These drainageways are the ultimate extension of, and often may be identical with, the tertiary drainage. Frequently they will be found as numerous, short, individual, intermittent, closely spaced gullies and runlets at the extreme ends of the watershed. In many cases, however, they are isolated or occur along the banks of any class of streams, particularly where stream cutting has proceeded to some depth. Often they are invisible at small photo scales. The rill-gully pattern, if discernible, usually has special significance to the photo interpreter and is analyzed separately (Chap. 4).

Fig. 3-14. The following reproduction of a drainage overlay (reduced from a mosaic at a scale of 1:60,000 to a scale of 1:180,000, covering approximately 800 square miles) shows a large area characterized by a poorly integrated, moderately dense, fairly uniform pattern displaying various orientations, a high degree of control, and a great angularity. The orientation possibly reflects large-scale fracture patterns possibly related to "elastic" fracture because of the triple principal stress conditions at the earth's surface [the surficial expression of plastic (?) crustal fracture, Sec. 2-5]. (*Canada. Hunting Technical and Exploration Services.*)





(a)



Fig. 3-15. Two examples of pronounced angularity in major streams, the one (a) having no apparent cause and the other (b) obviously related to structural control. [(b) Ceylon. *Photographic Survey Corporation.*]

Figure 18-3 shows the subdivision of an area drainage pattern into its component classes.

3-16. Special Significance of the Tertiary Drainage. The tertiary drainage has special significance to the interpreter. This significance is related to four items: (1) significance of characteristics displayed by secondary drainageways, (2) types of materials, (3) boundaries between different materials, and (4) practical problems.

The tertiary drainage, if it is simply a continuation in every important respect of the secondary drainage but has cut to shallower depth, implies that the secondary drainage reflects area characteristics which do not change at the surface and may be presumed, therefore, to have some depth and uniformity. If the tertiary shows a change from the secondary, the significance of certain characteristics displayed by the secondary may possibly be limited in a vertical direction.

The tertiary drainage, in some cases, may be a direct indicator of certain types of materials. This is particularly true for unconsolidated materials where tertiary drainage, of a constructional type, often is a dominant identification feature (Chaps. 9 to 15).

The tertiary drainage, typically developed on two different materials, will, where they approach, define fairly accurate boundaries between the two materials (Fig. 18-3).

The tertiary drainage has specific practical value. For example, a single tertiary drainageway may be undetected on the ground survey of an airport runway. However, it may be located on an aerial photograph and treated before runway construction and the probable subgrade failure that would follow its neglect. The tertiary drainage also makes it possible to define almost exactly the extent of a watershed, something which is impossible on practically all planimetric and topographic maps of medium-large to very small scale (1:5,000 to 1:63,360), where these drainageways do not usually appear.[3] Further, the tertiary channels are indicative of special conditions such as permafrost, sidehill seepage, springs, etc.

It is most probable that more research and field experience will develop considerable other significance that can be attached to the tertiary drainage, either generally or specifically.

3-17. Special Factors Causing Significant Differences in Drainage Patterns Developed upon Similar Materials. Materials having textures, compositions, vertical profiles, and parent materials that are essentially the same may have drainage patterns that are different in significant respects. The major factors that may impose their effect upon those of the above-mentioned dominant factors are those of: (1) climate, (2) age, and (3) erosional position.

Climate has, as might be expected, a tremendous effect upon the development and characteristics of a drainage pattern. This effect does not usually eliminate the essential characteristics of the drainage pattern. Rather, it tends to exaggerate, intensify, or subdue certain characteristics. There are many examples of such effects, among which are the humid-arid-tropic sequence of drainage patterns in shales and limestones (Chap. 16) and "functional drainage." This latter effect will be treated separately in Sec. 3-18.

Age has a similarly potent effect upon the development of a drainage pattern. Materials essentially similar in every other important respect—and existing in the same climatic regimen—may still have different drainage patterns because of significantly different ages. Because most rocks are old enough to have developed drainage patterns in which the relative effect of age has been subordinated to the factors of texture, composition, etc., the effects of age on drainage development is largely confined to unconsolidated materials such as those occurring on glacial plains and coastal plains.

Erosional position and history have an effect upon the drainage pattern developed in materials that are alike in all other respects, including those of climate and age. The effects are usually of less importance than those of other factors, but occasionally they are dominant or at least of noticeable

[3] Because of the exceptional difficulty of obtaining the necessary detail economically by ground survey and the lack of drainage interpretation in photogrammetric plotting. The author has seen relatively few topographic maps of even large scale and small interval that have proper representations of the complete tertiary drainage system. This is largely due to (1) a lack of appreciation of its existence and significance, (2) a similar lack of appreciation concerning its interpretation from the photographs, (3) economy and speed of photogrammetric plotting and drafting, and (4) excessive map detail.

The interpretation of this network should probably be added to the specifications of all planimetric and photogrammetric mapping based upon the use of aerial photography unless special considerations (such as condition 4 above) recommend its exclusion. The interpretations, moreover, should be completed by qualified people. Stereoplotter operators are not always well qualified, although they could be trained to be.

importance. Three common cases are due to effects of exceptionally low position, exceptionally high position, and uplifted position.

It is possible that the various special factors may operate so as to cancel each other's effects, creating a drainage pattern that does not show their individual effects. For example, a climate favoring intensive erosion, i.e., a dense drainage network, may be canceled by a very young age. There are innumerable variations and degrees of such combined effects.

3-18. Functional Drainage. The term "functional drainage" is based upon a concept first presented by Belcher (11). The words describing this important concept are here quoted:

> Functional texture is offered as a qualifying term for soil classification regardless of the method of survey. Aerial photographs show the effective drainage of the profile regardless of texture. The limestones have a well drained profile. *They are often red in color and lack evidence of complete surface drainage indicating a porous profile. However, this is a condition not related to the common conception of texture since the soils are high in active clay content. The process of weathering and profile development produces an open structure in which the clay particles are segregated into lumps with ample space between for percolating water.* (Italics are the author's.)

The porous limestone parent material absorbs the water and prevents waterlogging of the profile, a condition which would otherwise result in a consequent swelling and closing of the soil profile and closing of the soil structure. When compacted during construction this structure is destroyed and the immediate subgrade or fill reacts essentially as any other plastic clay. The qualifying term aptly applies to the plastic, well drained, clay-size soil materials of the high rainfall tropics. Although the colloid content of these inactive clays is high (as much as 90%) they will appear porous in photograph.

It is obvious that a good grounding in soil science, pedology, and climatology are necessary for an interpreter to analyze the various possibilities that may lead to a condition of functional drainage or texture.

3-19. Interpretation a Function of Inspection, Plotting, Evaluation, and Experience. As might be suspected from the foregoing sections, an accurate interpretation of the significance of a drainage pattern is not easily made. The most accurate interpretations are made by completing four steps: (1) inspection, (2) plotting, (3) theoretical evaluation, and (4) experience application.

Inspection, the first step, implies something more than a cursory glance. It implies a careful examination of the pattern at various points, a mental absorption of its classificatory characteristics, and a search for its most pronounced, repetitive, indicative, and less evident features.

Plotting, an important step in many cases, refers to an actual delineation of all drainageways. This step, often neglected, separates the drainageways from the mass of other detail in the photo and allows them to be evaluated more easily as a separate indicator.

The indicative significance of the drainage pattern results from a combination of *theoretical evaluation* and *experience application.* The theoretical evaluation is made in accordance with the content discussed in the preceding sections. However, as should be apparent, such a theoretical evaluation can be intelligently completed only if there is a basis from which to refer.

Such a basis is provided only by photo experience, the process of correlating photo details with actual field conditions. It is, in the final analysis, the most practically important part of drainage interpretation and the one that separates the professional interpreter from the student.

4 EROSION FEATURES

4-1. Definition of Erosion Features. Erosion features, primarily gullies, often reveal that *significant* bit of information which allows a correct interpretation to be made of soil texture, depth, stratification, and profile. In some cases, this information may be unobtainable from the examination of any other element. In others, it may corroborate—or may extend—information that has been already gained.

The interpreter must be acquainted with the various facets of erosion analysis, including the uncertainties. The first step in this acquaintance is an understanding of what is meant by the term "erosion features."

Actually, all landforms, except those recently deposited, reflect the ubiquitous process of erosion to a greater or lesser degree. In this book, however, erosion features are considered as a valuable indicator of qualitative conditions, and a specific definition is required.

Erosion features are terrain features of incised, shifted, or remnantal nature, usually of the fourth order (Sec. 6-7), *having topographic expressions that reflect incipient to early stages in the destruction of existing landscape through the removal or shifting of mineral matter at, or in the immediate vicinity of, their location.*

This definition, though far from perfect, implies a number of fairly important things about erosion features. The words "incised, shifted, or remnantal" imply that features carved into the land (e.g., gullies, blowouts); transient features remaining as the result of such carving in adjacent materials (e.g., pinnacles, horns); and features of mass wastage (e.g., catsteps, landslides) are all erosion features. The emphasis on fourth order implies a generally small size compared with normal landscape features but does not eliminate cirques, glacial troughs, and the rare third-order gully valley.

The stipulation regarding "incipient to early stages" implies that the features should be geologically fresh. It eliminates, admittedly at arbitrary points, such features as normal stream valleys, hills, etc., reflecting advanced stages in landscape formation, as well as ancient remnantal structures such as buttes, hogbacks, and karst phenomena. At the same time it definitely includes details such as the rill-gully pattern (Sec. 3-15), blowouts, catsteps, stream beds, channel scars, etc. "Removal or shifting of material at, or in the immediate vicinity" tends to eliminate features that are remnants of a long-active geomorphic process, and also extends the application of the term to features other than those carved into the landscape.

It may be wise to point out—for the benefit of the academically minded—that the word "shifted" should not be considered synonymous with accumulation. Terrain features such as colluvial cones, fluvial fans, etc., while they occur as a direct result of erosion, do not have topographic expressions resulting from removal of material in their immediate vicinity. Rather they are constructional unit landforms (Secs. 2-27 and 2-28).

4-2. Classification of Erosion Features. There are numerous types of erosion features. Most of these can not only be discerned on aerial photographs, but also have a greater or lesser significance to the accumulation of accurate qualitative terrain data.

Erosion features may be divided initially into those formed in unconsolidated and consolidated materials. Beyond this, they may be subdivided according to the process forming them:

1. Features formed in unconsolidated materials
   a. By water action (rills, gullies, pinnacles, channel scars, cut banks)
   b. By wind action (blowouts, yardangs)

c. By glacial action (grooves, nivation hollows)
d. By mass wastage (catsteps, solifluction features, landslides, soil and mud flows, etc.) [1]
e. By thermal action (polygons, hummocks, solifluction details, thaw forms)

2. Features formed in consolidated materials
a. By solution (sinkholes)
b. By glacial action (striae, cols, aretes, cirques, horns, troughs, grooves)
c. By combinations of water, wind, and temperature action (certain joints, buttresses, needles, pinnacles, *felsenmeere*)

Of all the above features, gullies may be considered the most indicatively varietal, the most widely distributed, and the most important to the interpreter.

GULLIES

4-3. Formation of Rills and Gullies. Fundamentally, the development of rills and gullies is easy to understand. Rain falls upon the ground. Depending largely upon the vegetative cover (interception, Sec. 18-4) and the duration and intensity of precipitation, more or less of the rain contacts the mineral soil. Depending upon numerous factors (infiltration, Sec. 18-6), a greater or lesser amount of such rain seeps into the soil. The remaining portion runs over the ground, becoming surface runoff. This runoff begins as individual droplets of water. The droplets, after contacting the soil, begin to move downward. As they do so, they coalesce with other drops, forming tiny streams called "rills." Each rill travels along the loci of low points within its tiny watershed, carrying mineral particles suspended within its flowing water body and rolling them along its bed. These comprise its "load." The maximum sizes and quantity of particles in the load are proportional to the velocity, quantity, duration, and depth of flow (Secs. 9-3 and 9-4). In the process of flow, the rill carves a definite channel both by abrading its floor (via the bed load) and by tearing away individual particles (by overcoming the frictional and cohesive forces that restrain them).[2]

By a continued process of the above action, a single rill may become a gully; or by coalescence of rills, larger flows may come into existence and immediately engage in gully erosion.

Rills are visible on aerial photographs only under certain conditions of scale and cover and are therefore relatively insignificant. Gullies, contrarily, are both visible and important.

4-4. Characteristics of Gullies a Function of Materials in Which They Are Formed. It is quite reasonable to expect that gullies, created by the removal of material, will have characteristics that reflect—to some measure, at least, and predominantly, at most—the type and variations of the material in which they occur.

A most casual inspection of gullies in different areas will reveal that their characteristics are different. It is conceivable that such differences are caused only by complexly variable differences in climate, water velocity, vegetation, and land-use practices and that they have *no* relation to materials. An inspection of the literature on the earth sciences would lead one to believe that this is their attitude, since these sciences tend to ignore gully characteristics completely. Such an attitude is surprising because it is contrary both to the general factual body of scientific knowledge and the intuitive proddings of logical thought.

In fact, gully characteristics *are* related to the materials in which they occur.

4-5. The Characteristics of Gullies. The characteristics of gullies that have significance to interpretation are those that, in aggregate, describe their topographic expression:

1. Characteristics of dimension (length, width, depth)
2. Characteristics of shape (cross section, plan, profile)
3. Characteristics of supplement (special features)

When an attempt is made to interpret terrain conditions by analysis of gullies, all these characteristics should be considered.

4-6. Characteristics of Gullies—Length. If water percolates into the soil, it carves no channels, but

[1] These terrain expressions are partially erosion features (where they have scalloped the landscape) and partially constructional landforms (where accumulation has taken place). It is preferable to consider them as erosion features.

[2] Mohr (131), in his fine book on the formation of tropical soils, discussed many of the factors that affected erosion. In the light of current knowledge, anyone could have written them, but at the time of Mohr's dissertation (the 1929 1934 period), the approach might have been described as refreshingly lucid with regard to the *fundamental factors that affect erosion, namely, the relations between* rainfall, runoff, particle sizes, cohesion, and porosity and how they affect erodibility, all else being equal. Some of his conclusions are illustrated schematically by Fig. 4-1.

if it runs over the soil, even with a low velocity, it eventually carves a channel.

The length of the channel is related primarily to the age of the gully, the hydrological details responsible for its formation, and the characteristics of the materials in which it is formed.

Length, obviously, bears a direct relationship to age. All other things being equal, including materials, the two are directly proportional.

While age may have an effect upon total length, so may materials and hydrology. It may be said, intuitively, that the length of a gully is directly proportional to both the erosional susceptibility of the material and the frequency, duration, volume, and velocity of runoff—all other things being equal, again.

One of the primary factors affecting erodibility is the textural gradation of the materials being eroded. It can be expected, therefore, that gullies in relatively impervious materials such as clays, silty clays, and semicemented materials, will tend to be longer than those developed in *most*[3] granular materials such as sands and gravels. Of course, as mentioned above, it is possible for an imbalance in the other factors to counteract this tendency (Fig. 4-1).

It is rather unfortunate that no quantitative observational data, prepared upon a comparative base, have yet been amassed regarding the relationships among length, texture, erodibility,[4] age, and hydrology. It is possible that such data would prove so complex as to defy other than general analysis. Even general analysis would be of value, however.

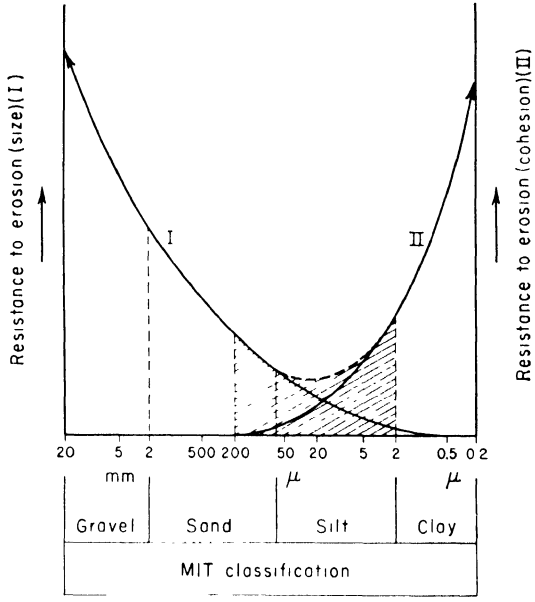


Fig. 4-1. A schematic presentation of the relative importance of particle size and cohesion on the resistance of natural soils to erosion by water. It will be noted that the silt and fine-sand sizes lie in a zone of variable combinations, all of which are relatively low, while very coarse materials and fine materials have substantial resistances to erosion, but for different reasons. It must be remembered that this diagram represents an estimate and is entirely qualitative. [*After E. C. J. Mohr* (131).]

4-7. Characteristics of Gullies—Width. The width of a gully refers to the horizontal distance between its upper erosion scarp faces, or zones. It is primarily related, like length, to the age of the gully, the hydrology of flow, and the type of materials in which the gully has been formed.

If all other factors are assumed constant, it should be apparent that gully width and gully age are directly proportional to each other.

Again, if all other factors are assumed equal, it may be predicted that different gully widths will reflect differences in the frequency, duration, volume, and velocity of runoff. Good examples of this are afforded by the dry "washes" of arid regions compared with gullies in similar materials within humid temperate areas.

Finally, in the absence of other variations, the differences in width of gullies are indicative of variations in the erodibility (porosity, cementation, texture, etc.) of the materials eroded. These variations reflect both the susceptibility to erosion along the scarp of the gully and the indirect back-weathering effects related to depths in excess of the critical height (Secs. 4-10 to 4-16). In certain cases, hardpans, claypans, etc., may cause rapid and anomalous widening. Mohr (131) mentioned and illustrated some of these cases. Proximity to base level also promotes widening.

4-8. Characteristics of Gullies—Depth. The depths of gullies, like length and width, are primarily related to age, hydrology, and materials. The statements made regarding these factors in Secs. 4-7 and 4-8 can be assumed to apply to depth. The analyses of Secs. 4-10 to 4-16 apply to

[3] An exception is completely granular fine to medium-fine sand which is highly erodible.

[4] Much investigation has been conducted upon the erodibility of soil in relation to its chemical and physical characteristics, slope, cover, and certain characteristics of flow. Baver (9) reviews this subject.

Table 4-1. Some Strength "Constants" for Various Soils (Partially after Terzaghi and Peck)

Material	Effective internal friction (ϕ_e), degrees	Effective cohesion (c_e), kg/sq cm	Unit weight (γ), pcf	Strength equations	Remarks
Clean dry gravel.					
Loose	30–45	0	110–120	$s = \bar{\sigma} \tan \phi_e$	$c_e > 0$ if cemented
Dense	35–45 (?)	0	115–125	$s = \bar{\sigma} \tan \phi_e$	$c_e > 0$ if cemented
Clean dry sand:					
Uniform					
Loose	28–30 (ϕ_s)	0	90–100	$s = \bar{\sigma} \tan \phi_e$	$c_e > 0$ if cemented
Dense	35 (ϕ_s)	0	105–110	$s = \bar{\sigma} \tan \phi_e$	$c_e > 0$ if cemented
Well graded					
Loose	35 (ϕ_s)	0	95–105	$s = \bar{\sigma} \tan \phi_e$	$c_e > 0$ if cemented
Dense	45 (ϕ_s)	0	110–120	$s = \bar{\sigma} \tan \phi_e$	$c_e > 0$ if cemented
Dry sand and gravel	Combinations of above	0	Combinations of above to 135	$s = \bar{\sigma} \tan \phi_e$	As above
Dry silts and silty sands:					
Loose	27–30 (ϕ_s)	Slight		$s = \bar{\sigma} \tan \phi_e$ or $s = c_e + \bar{\sigma} \tan \phi_e$	$c_e > 0$ if cemented, e.g., loessial
Dense	30–35 (ϕ_s)				
Dry clayey sands and clayey gravels	As for silts	Slight to moderate	100–110	As for silts	
Moist phases of above	As above	Slight to moderate	Variable	As above	As above
Stoney residual soils of variable texture	As for silts	Slight to moderate	Variable	$s = c_e + \bar{\sigma} \tan \phi_e$	c_e usually present in significant amounts
Glacial till, well-graded	20–40	Moderate to high	115–135	$s = c_e + \bar{\sigma} \tan \phi_e$	
Remolded clay	0 (sat.) to 30 (fairly dry) (ϕ_a)	Moderate to high		$s = c_e + \bar{\sigma} \tan \phi_a$	c_e a function of consistency
Natural clay:	(ϕ_a)				
Very soft	0	0.125	60–100	$s = c_e = \frac{q_u}{2}$	$q_u = 0.25$
Soft	0	0.125–0.25			$= 0.25 - 0.50$
Medium	0	0.25–0.50			= etc.
Stiff	0	0.50–1.00			
Very stiff	0	1.00–2.00			
Extremely stiff	0	2.00			

$\phi_e = \phi_s$ via slow shear test; $\phi_a = \phi_s$ via quick shear test; d = dry unit weight; other symbols defined in text.

that aspect of depth related to vertical sides. Of course, it is possible for gullies to have depths greatly in excess of their vertical sides.

4-9. Characteristics of Gullies—Cross Section—Soil-mechanics Theories. A consideration of soil-mechanics theories provides a reasonably sound basis for the hypothesis that different gully cross sections are developed in different types of material.

Wherever the ground surface is not level, there are forces that have a tendency to move soil and rock from a higher to a lower position. Certain of these forces, the downward components of gravitational attraction, are ever-existent. Other forces, including the downward components of surface water flow, those of subsurface seepage, and those associated with tectonic movements, may or may not be present.

That combination of forces which does exist subjects the interior of a given soil and rock mass to stresses that vary from point to point within the mass. It has been found that, because of such variations, the stresses on any plane passing through any point can be divided into normal and shearing components. Further, three theoretical, principal planes (major, intermediate, and minor), upon which the shearing stresses are zero, can be determined.

In accordance with Mohr's theory of rupture (132), if, at a given point within the mass, the combination of shearing and normal stresses on a plane inclined at $45^\circ + \phi_e/2$ from the major principal plane is equal to the imposed stresses on that plane, failure impends. If the stresses *tend* to become greater, failure occurs at that point and progresses through the mass, causing a failure by sliding (for soils assumed to have a definite yield point) or slumping.

To prevent sliding, the strength of a soil-rock mass on all planes passing through all points must exceed the stresses imposed upon those planes and points by the aforementioned gravitational and other forces.

The strength of a soil is a function of the *effective internal friction* (expressed as ϕ_e) due to the intergranular locking and physicomechanical bond between adjacent discrete particles; the effective *intrinsic pressure* (expressed as c_e) due primarily to the physicochemical bond between chemical constituents (*true cohesion*, c_t), but also including the transitory physicochemical bond due to moisture contents less than saturated (*apparent cohesion*, c_a); and extraneous environmental factors such as the root systems, frost ice lenses, etc. (*special cohesion*, c_s). Expressing strength by formula, a variation of Coulomb's empirical equation (40) can be written

$$s = (c_t + c_a + c_s) + \sigma \tan \phi_e \qquad (4\text{-}1)$$

$$s = c_e + \bar{\sigma} \tan \phi_e \qquad (4\text{-}2)$$

where c_t, c_a, c_s, c_e, and ϕ_e are as defined above; $\bar{\sigma}$ is the effective normal intergranular stress, on the potential plane of failure, tending to cause failure; and s is the shearing strength of the soil along the plane.

Any analysis which compares the imposed stresses, due to the aforementioned forces, with the presumed strength of a mass of soil that is not supported laterally by artificial means and which lies between high and low points may be called a slope-stability analysis.

The presumed strength, of course, is dependent upon the values of c_t, c_a, c_e, ϕ_e, and $\bar{\sigma}$ that are substituted in the preceding equation. Obviously, such values, in order to have validity for practical analysis, must be those that apply under the most adverse natural conditions that will be encountered, i.e., usually those of the wet seasons when soil masses tend to swell and strength is reduced.

The values of these quantities for various types of soil are quite variable and dependent upon many factors. Terzaghi and Peck (196) consider them in various portions of their book. Table 4-1, which summarizes their values, is based largely upon their discussions.

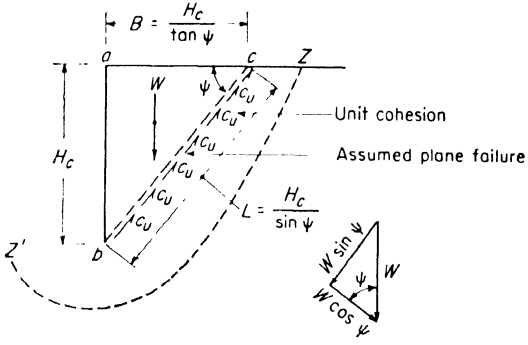
4-10. Characteristics of Gullies—Cross Sections—Critical Heights. By use of the general strength theory and physical constants discussed in Sec. 4-9, soil mechanics provides an approach to the analysis of gully cross sections.

Assuming laterally unsupported vertical slopes in deep deposits of homogeneous unconsolidated materials (Fig. 4-2) conventional statical analysis may be used (Fig. 4-2) to predict the maximum height to which such materials will stand without failing. This analysis shows that the maximum, or critical, height H_c is:

$$H_c = \frac{4c_e}{\gamma} \tan\left(45^\circ + \frac{\phi_e}{2}\right)$$

$$H_c = \frac{c_e}{\gamma} N_s \qquad (4\text{-}3)$$

where N_s is called the stability factor (195). This factor is a pure number depending only upon



Cohesive resistance:

$$\Sigma c_u = cL = \frac{cH_c}{\sin\psi}$$

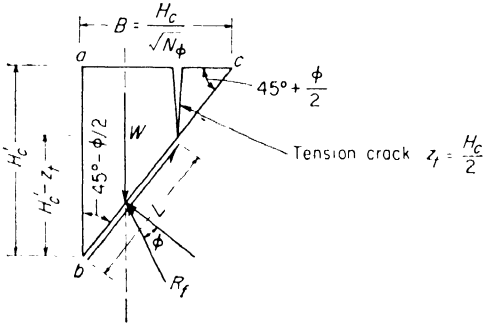
Frictional resistance:

$$\Sigma f_{bc} = f_{bc} L = W \cos\psi \sin\psi$$

Equilibrium:

$$W \sin\psi = \frac{cH_c}{\sin\psi} + W \cos\psi \sin\psi$$

Fig. 4-2



Cohesive resistance:

$$\Sigma c_u = cL = \frac{c(H_c' - z_t)}{\cos(45° - \frac{\phi}{2})}$$

Frictional resistance:

$R_f = cL$ (by equilateral triangle)

Equilibrium:

$$\frac{\gamma}{2\sqrt{N_\phi}}(H_c'^2 - z_t^2) = 2c(H_c' - z_t)$$

Fig. 4-3

Figs. 4-2 and 4-3. These schematic diagrams indicate the statical analyses that yield equations 4-1 and 4-3.

values of ϕ_i, slope angle β and a depth factor n_d reflecting the depth at which the unconsolidated material rests upon a firm base (bedrock, hardpan).

In deriving the above equation, a plane surface of failure was assumed. Actual surfaces of failure, as observed in the field, are curved to greater or lesser degree. Fellenius (56*b*) analyzed such surfaces, with respect to critical heights, and concluded that the proper form of theoretical equation 4-1 should be

$$H'_c = \frac{3.85c_c}{\gamma} \tan\left(45° + \frac{\phi_i}{2}\right) = \frac{c_i}{\gamma} N'_s \qquad (4\text{-}4)$$

where $N'_s < N_s$. This formula represents a reduction of approximately 4 per cent from the theoretical value derived on the assumption of planar failure.

Terzaghi (195) published the results of some model tests using gelatin as a substitute for unconsolidated soils. He came to the conclusion that a tension zone exists at the surface of a laterally unsupported mass and that, prior to failure, vertical tension cracks extend into the mass to a probable maximum of $0.5H_c$, provided that tension was caused by gravity alone and not by shrinkage. The existence of such cracks in soil masses, prior to failure, is common knowledge to any observer of land slippage. Based upon the probable maximum condition (tension cracks having depth $= 0.5H_c$), it can be mathematically determined (Fig. 4-3) that

$$H''_c = \frac{2.57c_i}{\gamma} \tan\left(45° + \frac{\phi_i}{2}\right) = \frac{c_i}{\gamma} N''_s \qquad (4\text{-}5)$$

where N''_s is less than N_s by approximately 36 per cent.

Terzaghi (195) goes beyond this to state that the conventional analyses involving tensional cracks assume saturated soil, but do not assume that the cracks are filled with water as they must inevitably be, under the worst condition. By some adroit reasoning based upon computations showing that the increase in driving moment is compensated by the decrease in driving moment afforded by neglecting the wedge above the crack, Terzaghi shows that

$$H'''_c = \frac{2c_c}{\gamma} \tan\left(45° + \frac{\phi_c}{2}\right) = \frac{c_c}{\gamma} N'''_s \qquad (4\text{-}6)$$

where N'''_s is less than N_s by 50 per cent.

Taylor (193) published data, modified by Terzaghi (195) and shown (simplified) in Fig.

4-4, giving the relationships between N_s, ϕ_e, β, and n_d. The N'_s case was used. These curves show that, in general, n_d has no significance upon the N_s, ϕ_e, β relationships for values of β greater than 60°. Since the fresh slopes carved by water flow in gullies (Fig. 4-5) are close to $\beta = 90°$ (say, 70 to 90°), values of n_d do not require consideration in analyzing fresh gully cross sections.

By use of Fig. 4-4 and Eqs. (4-4) to (4-6), it is possible to predict the theoretical critical heights for various ϕ_e, c_e combinations that might be considered analogous to the characteristics of real soils. These theoretical heights are shown in Table 4-2. It might be mentioned that Mohr's theory of rupture shows that for the third case ($c_e = 0$), no critical height is possible, the material being unable to stand at *any angle of slope* greater than its angle of friction in loose state, i.e., its *angle of repose*. Under certain circumstances, because of local and transient degrees of cohesion provided by natural but extraneous factors such as root systems, frost layers, and moisture films, slight cohesive effects may exist and a small H_c is possible. Although such a case is identical with case 2, because of its transience, it is considered as a special subdivision of case 3.

4-11. Characteristics of Gullies—Cross Sections—Extraneous Factors Tending to Reduce Critical Heights. The discussions of Secs. 4-9 and 4-10 assumed ideal soils and ideal conditions. Real soils occur in such a way and under such conditions that the critical heights that may be expected in them are less than those indicated by theoretical computations. A few of the major natural occurrences and factors that reduce critical heights are as follows:

1. Discontinuities
   - *a.* Fissures
   - *b.* Sand seams and other more permeable strata subject to occasional water flow
   - *c.* Intercalations and stratifications having significantly different physical characteristics and *lesser* strength
2. Climatic, hydrological, and environmental factors
   - *a.* Heavy rainfall, infiltration, and seepage
   - *b.* Desiccation
   - *c.* Freezing ice lensing and thawing
   - *d.* Increase in water content (clays)

The effects of these factors are variable and must be evaluated through a reasonable application of physical theories, particularly those of soil mechanics. Most of this has been done already, and as was mentioned above, the resultant of each of the above occurrences and factors is a decrease in critical height as computed theoretically.[5]

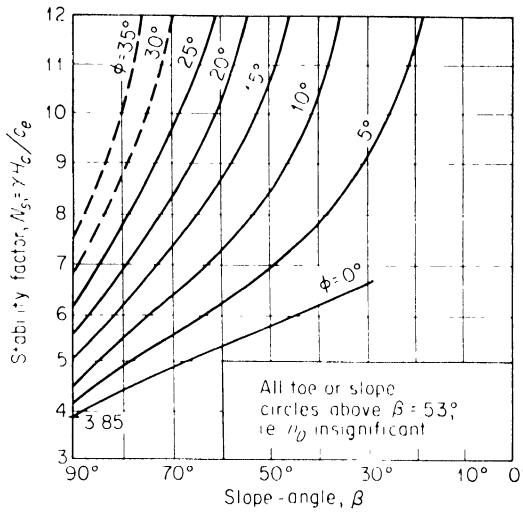


Fig. 4-4. This chart shows the relations between slope angles, stability factors, and angles of internal friction. [*After Terzaghi* (195) *and Taylor* (193).]

4-12. Characteristics of Gullies—Cross Sections—Critical Heights Not Exceeded. The discussions of Secs. 4-9 and 4-10 show that the cross sections of gullies developed in *all materials, except those having no cohesion,* should have vertical to near-vertical sides provided that the critical heights of the eroding materials are not exceeded.

The critical heights for certain theoretical materials fall within typical, though overlapping, ranges of magnitude. These theoretical materials have actual counterparts to which these ranges may be applied. In general, the ranges for these actual counterparts may be estimated as shown in Table 4-3. This table *is an estimate.* Consequently, it is subject to extensive revision in the light of actual field studies.

Tables 4-2 and 4-3 show that very young (that is, H_c not exceeded) gullies in clean granular ma-

[5] With the occasional exception of desiccation and certain types of freezing. Desiccation not only has a tendency to cause shrinkage cracking, and thus water accumulation and discontinuity, but also greatly increases cohesive strength (values of $q_u = 8$ tons per square foot are not uncommon). Surficial freezing provides increases in the tensional strength and thereby increases, usually temporarily, the critical height of various materials. Tschebotarioff (207) reports one case of this kind.

Table 4-2. Theoretical Critical Heights for Various Soil Types Computed According to Three Formulas

(For $\beta = 90°$ and $\gamma = 120°$)

	Theoretical Critical Heights, ft. (reduced from H_c case)		
	H'_c reduced 4% from H_c case	H''_c reduced 36% from H_c case	H'''_c reduced 50% from H_c case
Case I—Cohesive frictionless soils ($\phi_e = 0$)			
Formulas	$H'_c = \frac{c_e}{\gamma} N'_s = \frac{3.85c_e}{\gamma} = \frac{1.93q_u}{\gamma}$ (See note 1)	$H''_c = \frac{c_e}{\gamma} N''_s = \frac{2.57c_e}{\gamma} = \frac{1.29q_u}{\gamma}$	$H'''_c = \frac{c_e}{\gamma} N'''_s = \frac{2.00c_e}{\gamma} = \frac{1.00q_u}{\gamma}$
Very soft clays ($q_u = 0.25$)	8	5	4
Soft clays ($q_u = 0.25$–0.5)	8–16	5–11	4–8
Medium clays ($q_u = 0.5$–1.0)	16–32	11–21	8–17
Stiff clays ($q_u = 1.0$–2.0)	32–64	21–43	See Note 2
Very stiff clays ($q_u = 2.0$–4.0)	64–128	43–85	See Note 2
Extremely stiff clays (q_u 4.0 up)	128 up	85 up	See Note 2
Case II—Soils having cohesion and friction (ϕ_e and $c_e > 0$)			
Formulas	$H'_c = 4.2$ to $7.5 \frac{c_e}{\gamma}$ $= 2.1$ to $3.75 \frac{q_u}{\gamma}$	$H''_c = 2.8$ to $5.0 \frac{c_e}{\gamma}$ $= 1.4$ to $2.5 \frac{q_u}{\gamma}$	$H'''_c = 2.2$ to $4.0 \frac{c_e}{\gamma}$ $= 1.1$ to $2.0 \frac{q_u}{\gamma}$
For values of c_e equal to q_u of 0.25 to 1.0 only:			
$\phi_e = 5°$	9–36 ($N'_s = 4.2$)	5–21 ($N''_s = 2.8$)	4–16 ($N'''_s = 2.2$)
$\phi_e = 10°$	9–37 ($N'_s = 4.5$)	6–24 ($N''_s = 3.0$)	5–20 ($N'''_s = 2.35$)
$\phi_e = 15°$	10–41 ($N'_s = 5.0$)	6–25 ($N''_s = 3.2$)	5–21 ($N'''_s = 2.6$)
$\phi_e = 25°$	13–50 ($N'_s = 6.0$)	8–32 ($N''_s = 3.9$)	6–24 ($N'''_s = 3.1$)
$\phi_e = 35°$	16–64 ($N'_s = 7.5$)	10–41 ($N''_s = 5.0$)	8–32 ($N'''_s = 4.0$)
For values of c_e equal to q_u of 1.0 to 4.0 only:			
$\phi_e = 5°$	36–144 (N'_s as above)	21–84 (N''_s as above)	16–64 (N'''_s as above)
$\phi_e = 10°$	37–148	24–96	20–80
$\phi_e = 15°$	41–164	25–100	21–86
$\phi_e = 25°$	50–200	32–128	24–96
$\phi_e = 35°$	64–256	41–164	32–128
Case III*A*—Semi-cohesionless soils (c near zero)			
Formulas	$H'_c = 7.5 \frac{c_e}{\gamma} = 3.75 \frac{q_u}{\gamma}$	$H''_c = 5.0 \frac{c_e}{\gamma} = \frac{2.5q_u}{\gamma}$	$H'''_c = \frac{3.9c_e}{\gamma} = \frac{1.95q_u}{\gamma}$
For value of $\phi_e = 35°$ (dense sand) and $q_u = 0.1$ only	6	4	3 Say 2 to 3 feet because of seepage forces, surface cracks; temporarily greater

Table 4-2. Theoretical Critical Heights for Various Soil Types Computed According to Three Formulas (*Continued*)

Case IIIB—Cohesionless soils ($c = 0$)			
N.A.	0	0	0 Slightly or temporarily greater because of local surface effects, leaching, etc.

NOTE 1: Unconfined compressive strength, q_u is in tons per square foot.

NOTE 2: It is doubtful, at least in the author's experience, that frictionless soils will stand vertically and unsupported for appreciable lengths of time to the heights indicated by these formulas (Sec. 4-11). Therefore no heights are included.

terials may be expected to have vertical sides that seldom exceed 3 feet and practically never exceed 4 feet, even with well-developed *A* and *B* horizons (Sec. 7-9). Fat clay deposits, contrarily, may be expected to have vertical sides that seldom are less than 3 feet high, frequently are 4 to 10 feet high, but only rarely are more than 15 feet in height. The great mass of "in-between" soils may be expected to show a great range of variation, reflecting an infinite number of c_t, ϕ_t combinations. However, with the exception of deposits having low c_t and/or ϕ_t values (slightly dirty sands, dry silty sands, etc.) and maximum heights in the 4- to 10-foot range, most "in-between" soils will stand vertically to heights greater than 10 feet and not infrequently to heights exceeding 20 or 30 feet. Mohr (131) reports a gully in volcanic tuff with vertical sides in excess of 300 feet. All the above heights should be lessened if the gullies are developed in topographic situations where adverse backslope conditions exist.

4-13. Characteristics of Gullies—Cross Sections—Critical Heights Exceeded. Sections 4-10 to 4-12 discussed gullies whose depth was not greater than the critical heights of the materials being eroded. In nature, however, erosive action, once started, tends to occur both rapidly and persistently. If hydrologic and materials characteristics are such as to inhibit rapidity and persistence, the effect of age is usually sufficient to counteract the inhibition. The net result of natural erosive action is a depth of downcutting that soon exceeds the critical height of clean granular materials (because the critical height is negligible), clay deposits (because of relatively low critical heights and high erodibility), and certain frictional-cohesive soils having comparatively low critical heights. *The only gullies that may be expected to show vertical sides are those that are very young or those developed in materials with considerable strength because of cohesion plus friction* (but see Note of Table 4-3).

When the critical height of any laterally unsupported material is exceeded, the material must fail by sliding or slumping (Fig. 4-5).[6] The entire process of erosion begins again on both the slumped and freshly exposed material (Fig. 4-5), at the base *B'* and scarp *A'*. In addition, the slumped surface undergoes modification by sheet flow and surface weathering.

4-14. Characteristics of Gullies—Cross Sections—Effects of Surficial Water Flow, Weathering, and Mass Wastage. Sections 4-9 to 4-13 did not include consideration of the effects on gully cross sections that could be attributed to surficial sheet water flow, weathering, and mass wastage.

These effects are important, particularly since they are, with the occasional exception of water flow, virtually always present. Although their effects are slow and more or less invisible, they are persistent and, over a long time, quite effective as landscape modifiers.

The processes of surficial water flow are relatively easy to understand. They come into being because rainfall exceeds infiltration capacity, creating runoff. This runoff, at least within the small areas associated with gully sides, is essentially rill-like in nature (Sec. 4-3) and its general effect is planation, abrasion, etc., i.e. *smoothing* and *softening* of the gully sides and slumps.

Surficial water flow is most important where

[6] Soil-mechanics *theory* demonstrates that there is no danger of a base failure (i.e., a failure as shown by the dashed line z z' of Fig. 4-2) unless the angle of slope, β, becomes less than 53°.

Table 4-3. Estimated Critical Heights Corresponding to Various Common Types of Real Soils

Type of material	Geological origin	Estimated heights, ft
A. Cohesionless materials		
1. *Clean dry* sands, gravels, and sand-gravel mixtures (rare in nature)	Occasional fluvially worked materials and wind-blown sands	0
2. *Clean moist* sands and sand-gravel mixtures (common in nature)	Fluvially worked materials and wind-blown sands; some residual sandstone soils	0.5–3
(*a*) Above with loamy topsoil developments (upper layers dirty and cohesive, lower layers clean)	Older, finer, or more feldspathic, and ferromagnesian sands, and sand-gravels; many residual sandstone soils	1–4 (see Note)
B. Cohesive "frictionless" materials		
1. Very soft to soft clays, clay loams, fine silty clays, organic clays	Lacustrine materials (recently deposited and exposed); glaciolacustrine materials; certain fluvial clays; certain ablation clays; certain residually weathered clays	3–8
2. Medium clays, clay loams, and fine silty clays	Same as above	6–15
3. Stiff to extremely stiff clays and silty clays	Desiccated or glacially loaded materials, exposed varved materials, other precompressed materials	6–15 (occasionally as high as 50 ft)
C. Materials having cohesion and friction		
1. Some silty clays	Lacustrine, fluvial, and glaciofluvial sediments	Variable, 10–30 feet typical
2. Clayey silts	Lacustrine, fluvial, and glaciofluvial sediments	
3. Clayey to silty sands and sand-gravels (dirty gravels)	Lacustrine, fluvial, and glaciofluvial sediments, plus superglacial tills and specific glaciofluvial material	
4. Sandy clays and silts	Lacustrine, fluvial, and glaciofluvial sediments	
5. Cemented sands, gravels, and clayey to silty sands and gravels, clays, silts, etc. (cementation caused by calcium carbonate, iron coatings, organically derived coatings, sodium chloride, siliceous coatings, puzzolanic coatings)	Most marine sediments; fluvial deposits in arid areas; lateritic soils; loessial deposits; most residual soils; many varieties of all soils	Extremely variable, 20–300 feet; heights 20–50 feet most frequent

Table 4-3. Estimated Critical Heights Corresponding to Various Common Types of Real Soils (*Continued*)

C. Materials having cohesion and friction (*continued*)

6. "Well-graded" mixtures	Most glacial tills (to some extent at least); many residual soils derived from conglomerates	Same as above
7. Semiconsolidated materials 8. Interstratified semigranular and granular deposits		May be high variable, 10-30 common if uncemented

NOTE: It will be noted that pits in so-called "clean" sands, gravels, and mixtures of the two are often observed to have nearly vertical faces 20 to 50 feet high, in apparent contradiction to these figures. Actually, there are many ways to account for this contradiction. These include the effects of compaction; the effects of occasional cohesive and semicohesive strata; the effects of slight residual or leached cementation films; the effects of strata contortion; and the extreme youth of the face. This latter is particularly important. The face is constantly being recreated by man. When it is left undisturbed for a year or two, it usually begins to assume the angle of repose, even when the above factors counteract the process. Particularly during dry spells, one can hear particles and segments of a pit falling all around. Of course, in the final analysis, there *is a divergence* between theory and reality.

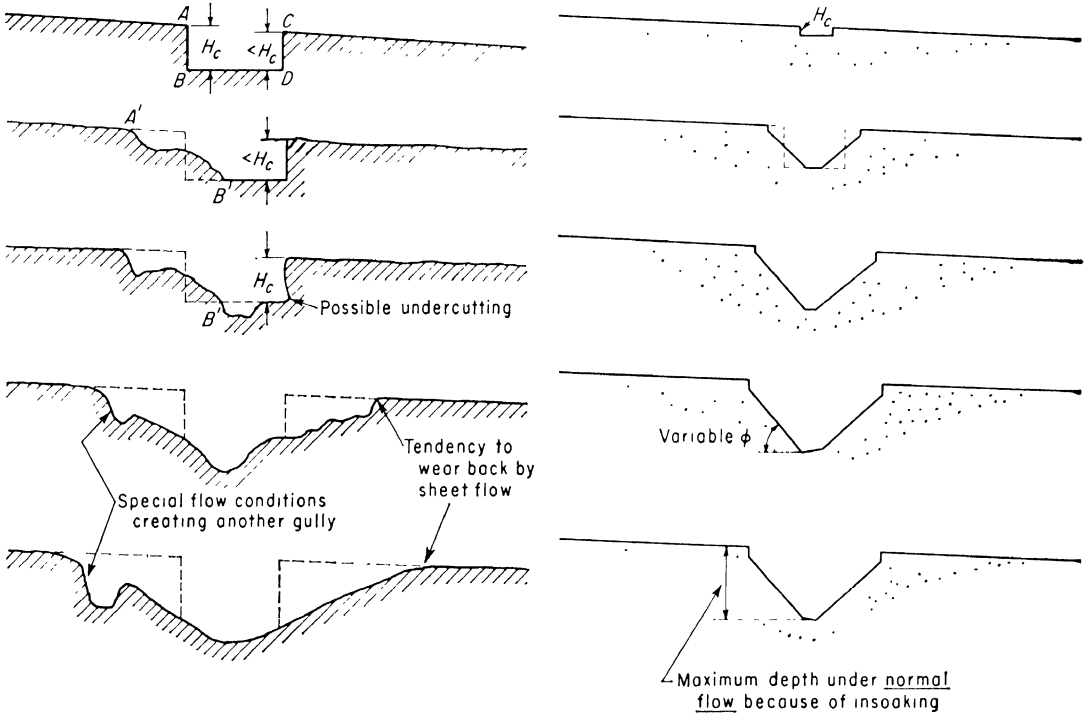
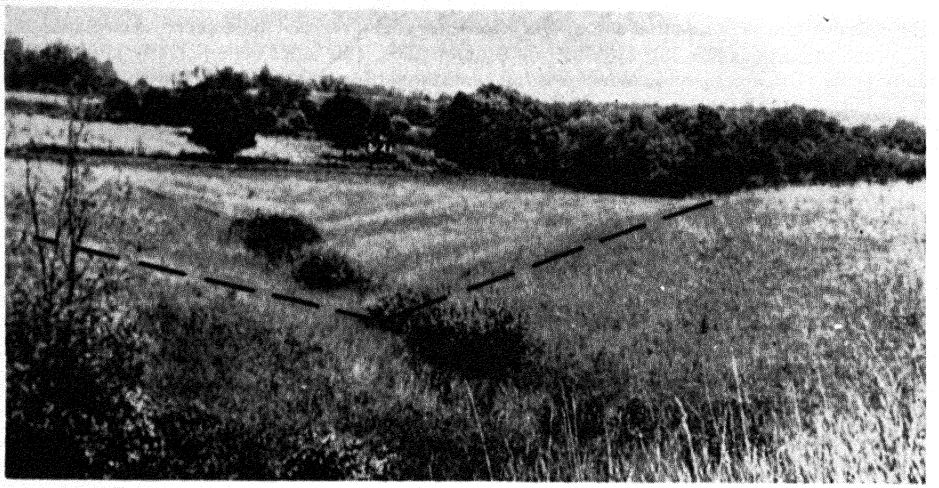


Fig. 4-5. A schematic representation of the process of gully development in cohesive and granular materials.

erodibility of the material is neither too great nor too small. Very porous materials, e.g., gravels, coarse to medium sands, and sand-gravels, show little softening due to surficial flow because runoff is both small and has insufficient carrying capacity to transport the component mineral particles. Porous but fine-grained materials having no cohesion, e.g., fine to very fine sands and coarse to medium silts, are very erodible because their relatively small-sized mineral components can be transported by even small amounts and velocities of water flow and there is little cohesion to prevent their removal. As a result, the surface of these materials may be roughened by surface water flow (sheet erosion).

Semipervious to impervious materials having varying amounts of cohesion are softened to greater or lesser degrees by rill action, particularly in those materials where grain size and cohesion tend to balance each other's effectiveness in terms of resistance to moderate amounts of runoff.

Physical and chemical weathering (Sec. 2-6) as well as the forces of mass wastage (Sec. 2-7) also *tend* to *soften* a given terrain composed of uncon-

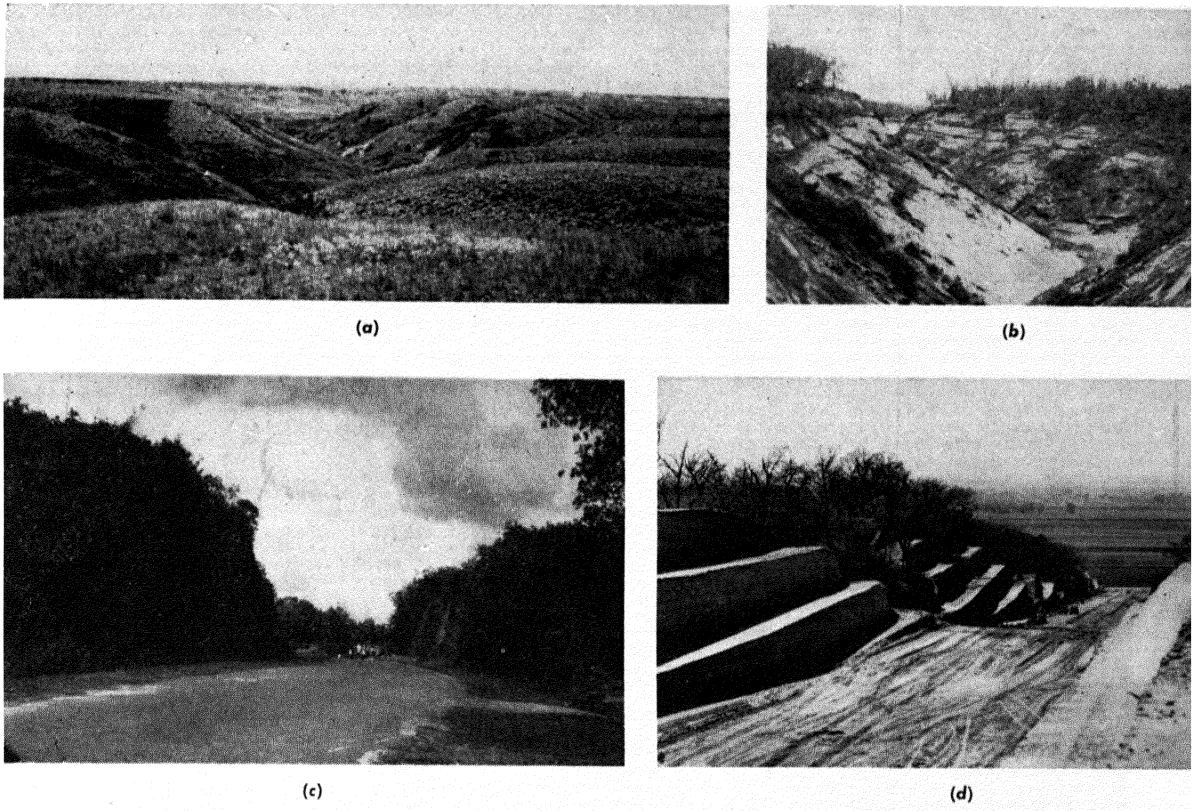


(*a*)



(*b*)

Fig. 4-6. Ground views of gullies in (*a*) clay and (*b*) intermediate soils. The gentle slopes in the clay and the U shape, abrupt head ends, and buttresses of the intermediate materials are apparent. (*Cornell University*.)



(a) (b) (c) (d)

Fig. 4-7. (a) V-shaped gravel gullies in the semiarid western United States; (b) a similar cross section in granular materials (note the angle of repose, the almost visible surficial rolling at the bottom, the slight vertical heights at the top, and the clogged channel at the bottom); (c) a vertical cross section in very highly decomposed laterite of Ceylon; and (d) a classical photo of very deep cuts (note the size of the cars in the background) in Iowan loess. (*R. E. Frost, U.S. Army, D. R. Lueder, Highway Magazine.*)

solidated materials (certain arid and arctic situations excepted). This effect is a result of long geological observation, though it would be difficult, if not impossible, to explain the process as a dynamic sequence.

The agents and processes of physical and chemical weathering and, as a result, certain forces of mass wastage such as solifluction and creep are more effective in fine- to medium-grained cohesive soils composed of minerals with diverse make-ups. These soils are the clays and "intermediates." The sands and gravels, usually predominantly composed of discrete—and inactive—particles of quartz, are much less susceptible to temperature-moisture changes and chemical processes.

In summary, surficial water flow, weathering, and mass wastage, all tend to soften landscape. This softening generally is least effective on very coarse to medium granular materials, and effective to variable but appreciable degrees on semipervious to semi-impervious materials. Certain highly erodible soils, subjected to rill erosion, are roughened by sheet erosion, rather than softened.

4-15. Characteristics of Gullies—Cross Sections—Bottoms. A gully cross section includes not only its sides but also its bottom.

The extent and shape of the bottom are related to a number of things: (1) nature of material forming the gully sides, (2) nature of material forming the gully bottom, and (3) nature of water flow.

The material forming the sides slumps to the bottom of gullies having depths greater than the critical height. The slumped material is worked upon by the water flowing along the gully bottom and has an effect of its own on the flow.

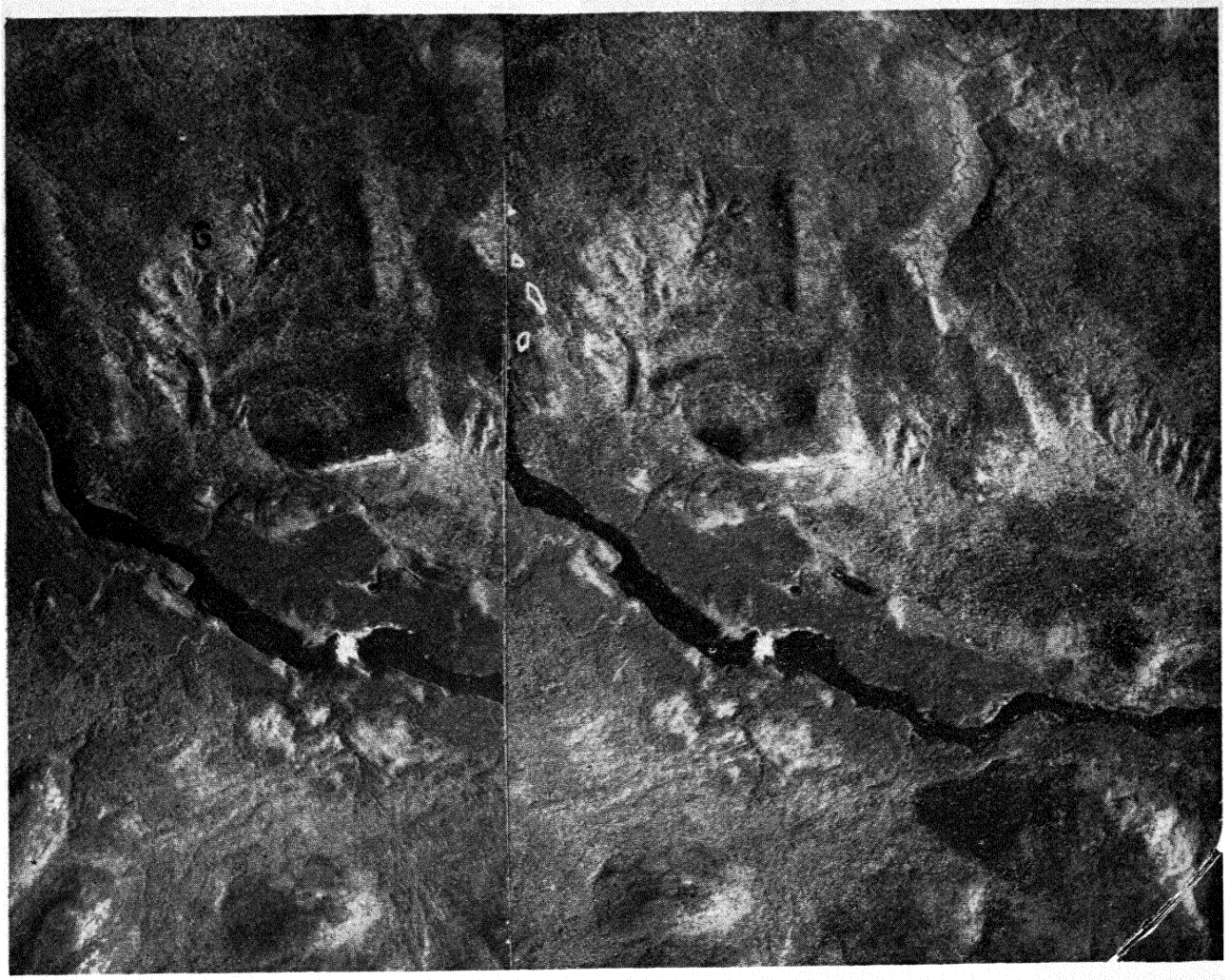


Fig. 4-8. This stereopair shows the characteristics typical of certain intermediate materials in a heavily forested area of Quebec. (*Photogr phic Survey Corporation.*)

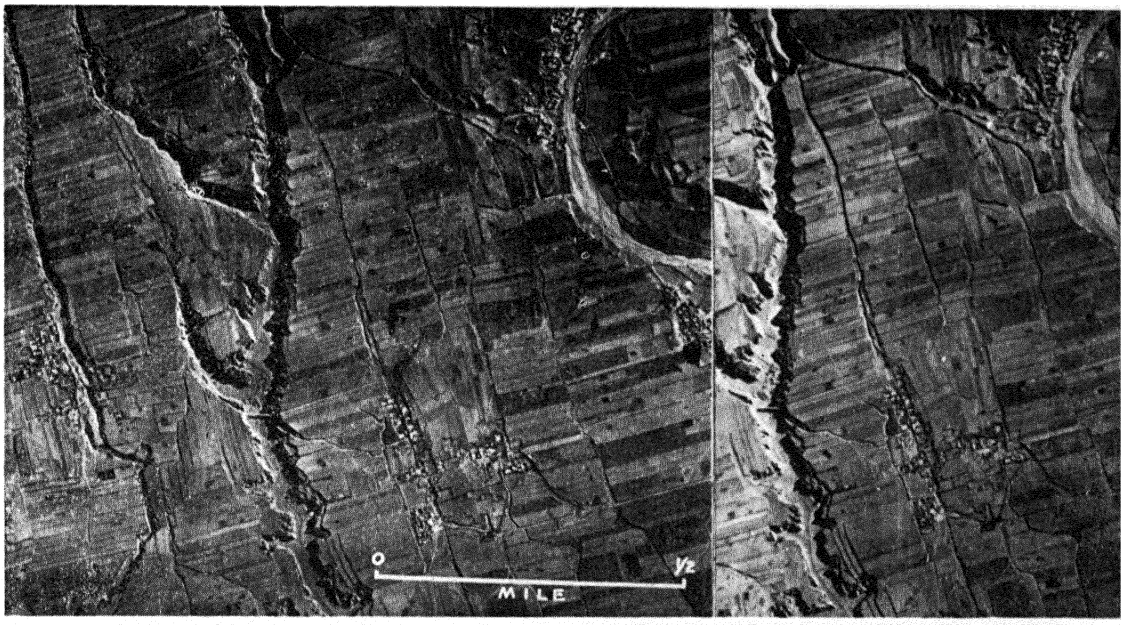


Fig. 4-9. A stereopair showing deep gullies in deep silty terraces of China. Note the footpaths *F* that are developing into gullies. This photograph was chosen by the Cornell group (43).

Coarse, cohesionless soils allow only narrow channels of flow along the bottom. This is due to the constant side slippage as angles of repose or critical heights are exceeded; the loss of flow volume by insoaking; and the relative difficulty associated with the transportation of coarse materials by diminishing, overloaded waters. As a result of these factors, gully bottoms in granular materials tend to be narrow.

Frictionless soils, because of their low critical heights, also tend to block the floor of their gullies. However, in such cases, the slumped material serves as an obstacle to undiminished and, in fact, an increasing, volume of water flow. The grain sizes are definitely capable of being transported by this flow, but cohesive forces tend to prevent their easy removal (Sec. 4-3). The flow is retarded—or at least deflected—to some extent. This retardation is aided by the constant load of detritus brought in along the sides and by the impetus of the sheet-flow rivulets themselves. The ultimate general result of all these factors tends to be a variable, vague, "soft" bottom.

Intermediate materials may be expected to have gully bottoms that partake of the characteristics of each of the above, and the net result might be a composite, even a flat, bottom.

The material forming the gully bottom is either the same as that forming the sides—a veneer or a continuation of the deposit—or it consists of a significantly different stratum. If the stratum is unconsolidated, the above remarks apply. If the stratum is semiconsolidated (hardpan) or consolidated (rock), broad flat or gently sloping planed bottoms may result.

The water flow has obvious effects upon gully bottoms that may counteract and obscure any tendencies discussed above. Examples are afforded by the distributaries developed in granular or semicohesionless deposits by the flash floods of arid regions. Unless the sides of these rapidly carved channels are maintained by cementation, they soon cave in. In any case, undermining will cause cave-in.

4-16. Characteristics of Gullies—Plan. The shape of gullies in plan should be related to the same factors that affect length, i.e., age, hydrology, and characteristics of materials.

Age may have an effect on both the shape of a gully system and an individual gully. All other things being equal, an older gully system should have more tributaries than a young one because of the longer opportunity for headward erosion at various side points along its greater length. In other words, an old gully system should have more tributaries than a young one. An older gully, also,

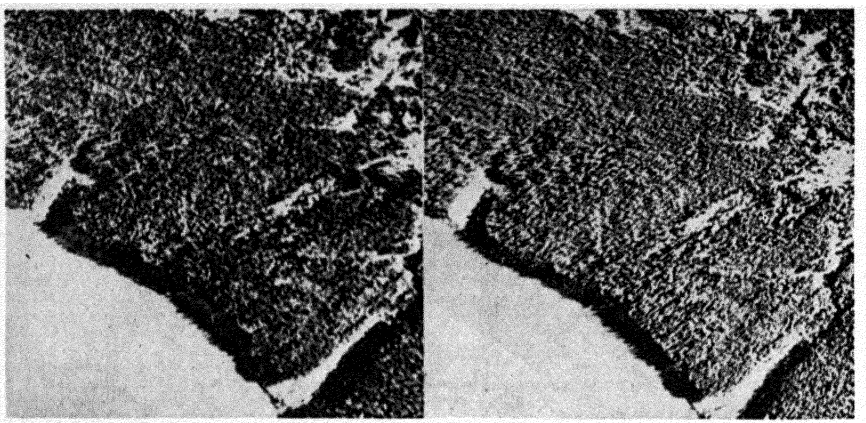


Fig. 4-10

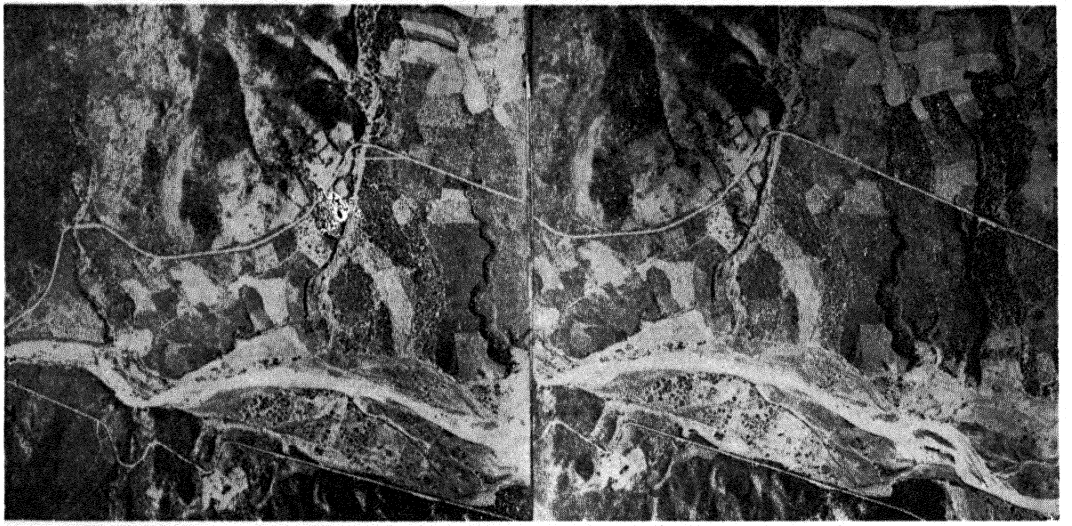


Fig. 4-11

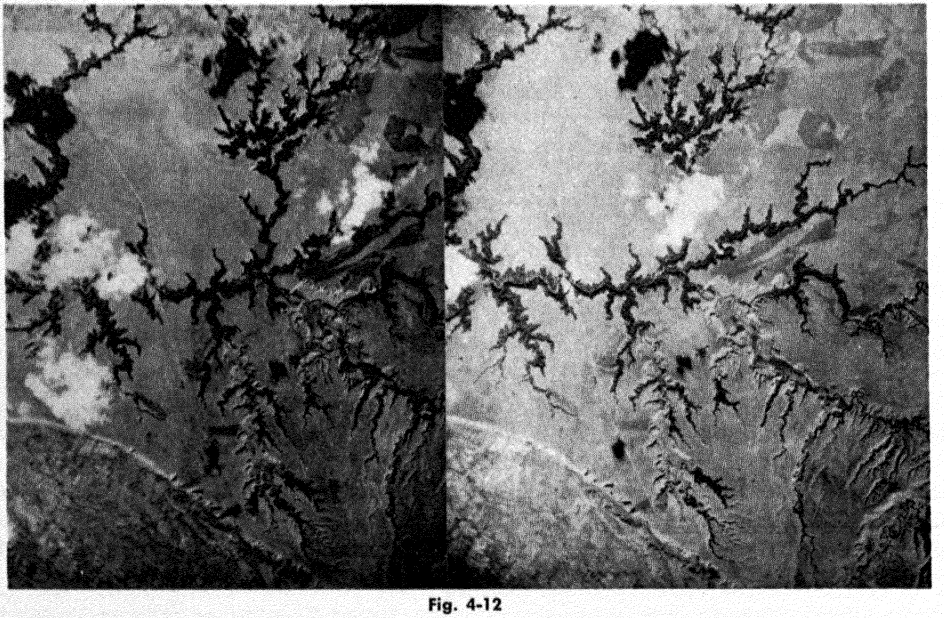


Fig. 4-12



Fig. 4-13. Stereopair of young gullies in uniform silty clays. Note the flowing plan, gradual gradient, and soft cross section. Note the tiny, vertical banks H_c at which the material is standing. *Also note the gradual tonal profiles* (Chap. 5) *between moist-organic and better-drained, less organic areas.* (*Canada. Photographic Survey Corporation.*)

Figs. 4-10 to 4-12 (*see facing page*). Stereopairs showing a typical gully developed in a certain type of gravelly-sandy material (Fig. 4-10), with its simple plan, steep gradient, V-shaped cross section; a type of sand-clay material (Fig. 4-11) with its rounded bottom and steep sides; and a partially cemented valley fill in the Philippines (Fig. 4-12). Note the steep sides and intricate plan. Compare this with certain similar photos of valley fill in Chap. 10. Also inspect other views of gullies in intermediate materials that are included in Chaps. 10, 11, and 12. Figures 4-11 and 4-12 were originally chosen by the Cornell group (43). (*U.S. Army.*)



Fig. 4-14. Stereopair of gullies developed in silty-clay lacustrine materials. The typical plan, gradient, and cross section are well shown. Note the bedrock outcrop *B* and the variety of tonal gradients (Chap. 5). Most of these tonal gradients are significantly affected by crop cover, as at *T*, and a search must be made for more normal gradients, such as those at *N*, to obtain practical information from the tonal gradient. (*Canada. Photographic Survey Corporation.*)

should have a different plan shape than a young one. In homogeneous soils, the shape should be smoother because of the softening and smoothing effects of long-continued weathering and water action. In nonhomogeneous soils, the opposite might well be the case.

The characteristics of water flow have an effect upon gully plan. In general, it may be said that flow of greater duration, volume, frequency, or velocity will have a tendency to create smoother gully shapes by virtue of greater effectiveness in removing or reducing local irregularities and obstacles. In nonuniform materials, the opposite may be true.

The characteristics of the materials in which a gully or gully system is formed have an effect upon its shape in plan. It appears obvious that permeable materials, all other things being equal, should permit the development of fewer tributaries than impervious materials. If this be the case, gully systems in granular materials should tend to be simpler than those in less porous deposits.

Texture and porosity are not the only physical characteristics that effect gully plan. Variations and extensive developments relative to cementation, consolidated and semiconsolidated occurrences (bedrock, hardpan), strata of different texture, etc., may also affect shape in plan.

In summary, it may be said that the number of tributaries displayed by a gully system is proportional (like length, width, and depth) to age, hydrology of water flow, and general erodibility of materials (primarily texture and cementation).

The shape of individual gullies within a system, i.e., intricacy, is probably affected by age and water flow but is also complicated by variations in the special characteristics of the materials undergoing erosion.

4-17. Characteristics of Gullies—Profile. The profile of a gully bottom has some significance with respect to an interpretation of the materials in which the gully has developed.

In general, both the nature of the profile and its significance as an indicator of materials are related to the previous discussions of critical heights and lengths. Porous, coarse granular materials, without cohesion, will tend to have steep evenly sloping profiles betwen the mouth and head ends of the gully. The head ends will have a sharp break. These reflect the effects of porosity, insoaking, negligible critical height, angle of repose, and the predominance of bed load. Semi-impervious materials, without internal friction, will tend to have long, gentle, evenly sloping, soft gradients betwen mouth and head ends. The head end may often grade imperceptibly into the surrounding terrain. Intermediate materials should have intermediate profiles, in terms of gradient, but should often have abrupt head ends, reflecting their greater critical heights at such points (Fig. 4-6*b*).

4-18. Special Characteristics Associated with Certain Types of Gullies. Certain types of gullies may

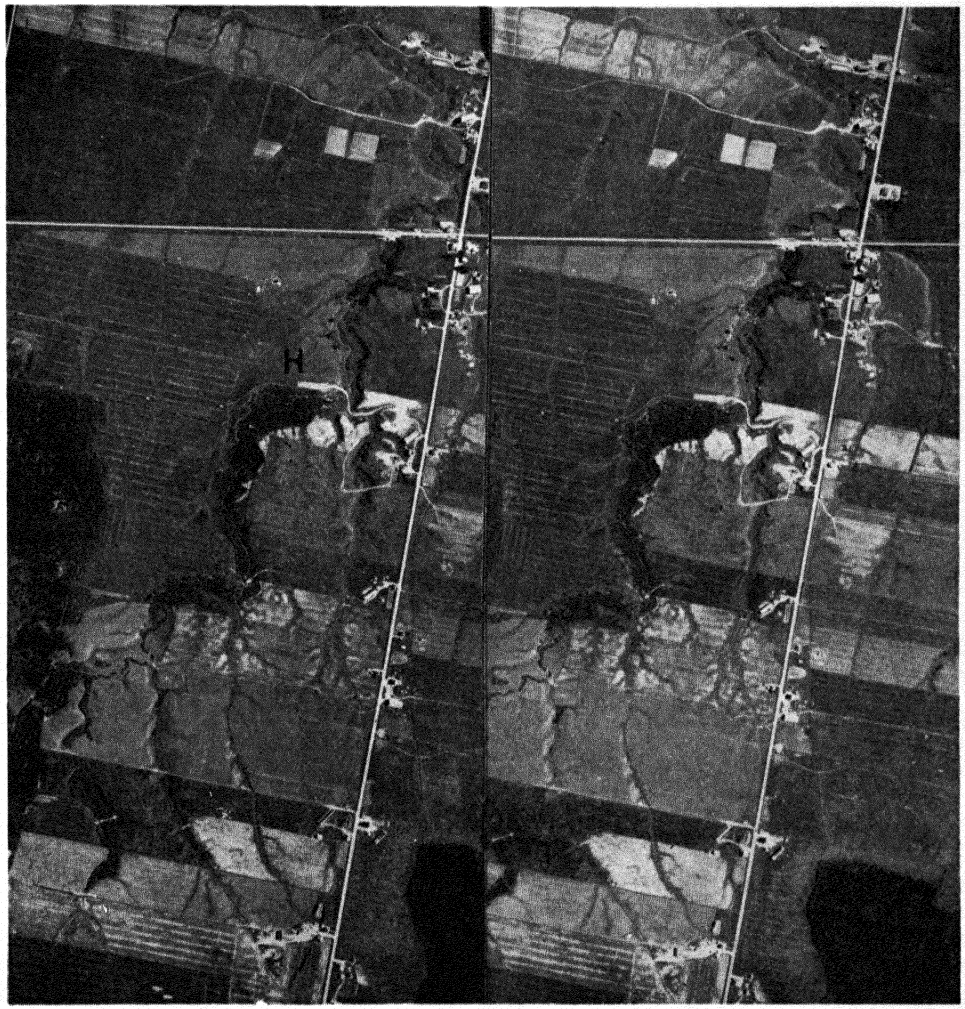


Fig. 4-15. A stereo view of gullies developed in stratified lacustrine materials having silty-clay surface textures. Note the plan, cross sections, and gradients. Also note that the material stands at a steep slope—and to appreciable heights—when it is cut deeply enough (*H*). This indicates the presence of modifying factors (different strata, cementing agents, high cohesion). This area includes many interesting manifestations of gully development. (*Canada. Photographic Survey Corporation.*)



Fig. 4-16. A stereopair showing large blowouts *B* in the sand hills of southern Ontario. Note the attempts at erosion control indicated by the planting *P* of small evergreen seedlings and the thicker plantings of the same. (*Photographic Survey Corporation*.)

have special characteristics associated with their development. One of these types is gullies eroded in loessial deposits. These gullies develop "pinnacles" and "buttresses" at their head ends and "catsteps" along their sides (provided the sides have weathered back enough through processes of slumping, surficial flow softening, and weathering).

The pinnacles and buttresses are remnantal loessial materials, in their natural (*in situ*) state, the surrounding material having been removed by erosion and collapse. They also are doomed to collapse and are therefore temporary features. Their existence reflects the peculiar characteristics of loessial deposits, and most particularly their high (comparatively) vertical porosity and critical heights. It may be deduced that certain intermediate materials, having similar characteristics, will also have similar features.

Catsteps are solifluction features, also characteristic of *slopes* in loess deposits. They repre-

sent the effects of minor heaving and slumping. They are not always present, even in loessial areas, and in all cases may be identified on aerial photographs only by careful inspection.

4-19. Observations of Gully Characteristics. A fair amount of information has been recorded concerning the characteristics of gullies developed in various types of materials. These include comments by Belcher (11), Frost (61), Frost and Woods (65), Parvis (146), Johnson (86), Stevens (183), and Holman and Nikola (79). Terzaghi and Peck (196) and Tschebotarioff (207) also discuss some vertical slopes in different materials.

The sum of these comments indicates that gully characteristics *do vary* and that the variations are closely related to characteristics of the soil in which they develop. The author's experience and observations support this indication. Some characteristics are qualitative rather than quantitative. Others may be approached through the semiquantitative techniques of soil mechanics.

4-20. Summary of Probable Gully Characteristics Associated with Erosion of Different Materials. Assuming that all other significant factors, such as age and hydrology, are constant, it is possible to predict the probable characteristics that will be associated with *young* gullies developed in various general types of materials. These are as follows:

1. Gullies developed in noncohesive materials having appreciable grain size and appreciable porosity
   a. Length—short
   b. Depth—variable but tending to be shallow or moderate rather than great
   c. Width—variable, but tending to be narrow
   d. Cross section—narrowly to medium V-shaped, occasionally with very low vertical sides at top, occasionally high and vertical when very young slopes have been created by man or violent flow
   e. Plan—simple and direct with few or no short, simple branches
   f. Profile—steep, uniform gradient with sharp knickpoint at head end
   g. Descriptive—short steep "gash," or "nick"
2. Gullies developed in cohesive materials having very small grain sizes, "no" frictional resistance, and low porosity
   a. Length—long
   b. Depth—variable but tending to be shallow or moderate rather than deep
   c. Width—variable but tending to be wide
   d. Cross section—variable but tending to be soft and gently sloping for all but the shallowest depths (less than 6 feet)
   e. Plan—smoothly curving, or at least nonintricate, with moderate to large number of similar branches
   f. Profile—gentle, fairly uniform gradient merging imperceptibly into the terrain at the head end
   g. Descriptive—"swalelike"
3. Gullies developed in intermediate soils having both cohesion and frictional resistance with variable grain-size distributions and porosities
   a. Length—variable but tending to long rather than moderate
   b. Depth—extremely variable but tending to be moderate (greater than 10 feet) to deep (greater than 20 feet) rather than shallow
   c. Width—variable but tending toward moderate
   d. Cross section—variably U, ⊔, or V shaped, the variation occurring toward the bottom
   e. Plan—intricate, with moderate to many branches of similar nature
   f. Profile—gentle, uniform gradient with abrupt head end
   g. Special—pinnacles and buttresses
   h. Descriptive—"troughlike"

This summary, of course, is the most general thing imaginable. In the final analysis, variations are many, and it must be left to the care, logic, intuition, and experience of the interpreter, supported by the results of research—as it becomes available—and selective field check, to derive the full benefit from gully analysis. In the ultimate analysis, it may be largely impossible to gain more *mapping* information from gully analysis than is summarized in the preceding sections. However, as mentioned in Sec. 4-21*a*, their value to other fields of earth science may be a great claim to attention. Figures 4-6 to 4-15 illustrate the appearance of gullies developed in various materials.

4-21. Importance of Gully Analysis to Effective Aerial-photographic Interpretation. There are many times when an interpreter has analyzed landform, surface drainage, gray tones, vegetation, and land use, but has been unable to come to a definite *specific* conclusion regarding the physical nature of the materials within an area. The reasons for his predicament are many: anomalous conditions;

counteractive conditions (Sec. 3-17); coincidental masking where vegetation masks key areas of probable indicative gray tones; pure lack or vagueness of evidence from the other elements.

In such cases, the interpreter looks eagerly for suitable gullies. If these can be found, they may reveal corroborative, supplemental, or deciding evidence that may allow him to reach a conclusion about the relative erodibility (texture, cementation) of the materials in the area.

They also are frequently valuable as indicators of, and depth to, subsurface changes (overburden to rock, existence of hardpan, one texture to another). They are, reciprocally, indicators of uniformity.

4-21a. Importance of Gully Analysis to Other Fields. In addition to its importance as an indicator of texture, cementation, uniformity of materials, and the associated value that such information provides to agriculture, engineering, etc., gully analysis has additional value to other types of study.

In accordance with the discussions of Secs. 4-6 to 4-8, the analysis of gullies may prove effective in evaluating the hydrology of an area or estimating the differences in age of the surficial materials that occupy it.

To the soil-mechanics fields, both theoretical and applied, gully analysis should be applied to the study of the stability of natural slopes. It is relatively simple to select and tentatively evaluate the nature of materials in a given area, the height of uncollapsed and probable collapsed gullies, etc. These can be checked in the field, described, sampled, and tested. The results, particularly if voluminous and analyzable through the medium of electronic or card-sort methods, should provide significant and practical data, not only for soil mechanics and engineering construction but for interpretation as well.

There are other ways in which gully analysis can be applied to soil mechanics, as well as similar applications to the studies of soil physics, reclamation, erosion control, etc.

4-22. Difficulties of Gully Interpretation—Necessity for Research and Experience. A great deal has been said on the subject of gully analysis in this chapter. An impression may have been given to the reader that such analysis is an effective, semiautomatic operation. Such an impression would be wrong. Gully analysis is not always effective, seldom semiautomatic, and almost never certain. It is far from perfect, not only from the standpoint of overlapping geometric characteristics (Secs. 4-6 to 4-20), but also because of extraneous factors.

Extraneous factors include the scale and quality of the photographs (scale, or magnification, must be large, and resolution good); the nature of vegetative cover (the gully should be completely visible) [7] and other superimposed counteractive effects of climate, age, and hydrology; the possibility of special and anomalous conditions within the eroding profile; and the lack of observational and research data.

This last factor is particularly important, and it cannot be said that full use is being made of gully analysis until such observational and research data have become available and have been digested.

In the final analysis, *successful gully analysis is a function of the background* (Sec. 1-12) *and particularly the experience and intuition of the individual interpreter* (Secs. 7-24 and 24-20).

OTHER EROSION FEATURES

4-23. Channel Scars and Cut Banks. Channel scars are the fossil indications of old stream flow. Cut banks are the most recent manifestations of current stream action. Both types of features may be used as indicators of qualitative facts regarding the nature of the terrain.

Channel scars may be accepted as indications of past fluvial history, and therefore texture, stratification, flood levels, etc.

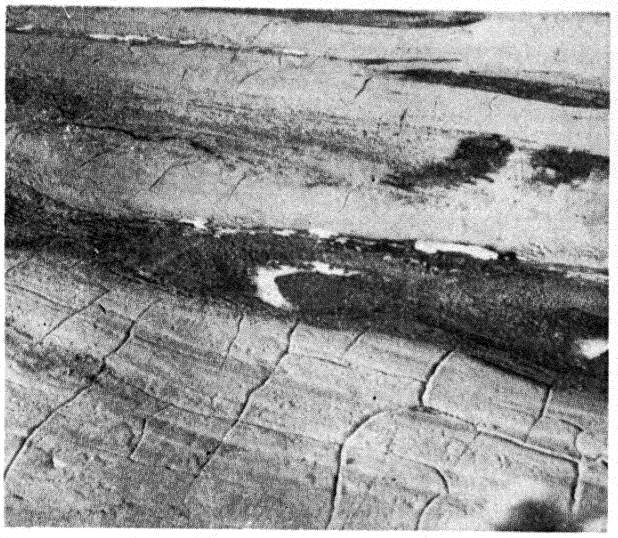
Cut banks may indicate the nature of materials in the same way as gully cross sections.

4-24. Blowouts and Yardangs. Blowouts are bare, shallow to moderately deep, dish-shaped features of wind erosion (Fig. 4-16) in sand. Obviously, they are indicators of sandy soils, usually fine- to medium-textured.

Yardangs are reported (44) to be wind-eroded features developed in fine-grained materials (semiconsolidated silts and clays?). If so, they are also indicators of texture. Unfortunately, the author has neither acquaintance with, nor photographs of, these features.

4-25. Various Thermal Forms of Perennially Frozen Ground. In those areas of the world above 48° of northern latitude, perennially frozen ground (termed, perhaps inaccurately, "permafrost") may

[7] For a case when gully analysis was successful despite cover, see Sec. 17-18.



(a)



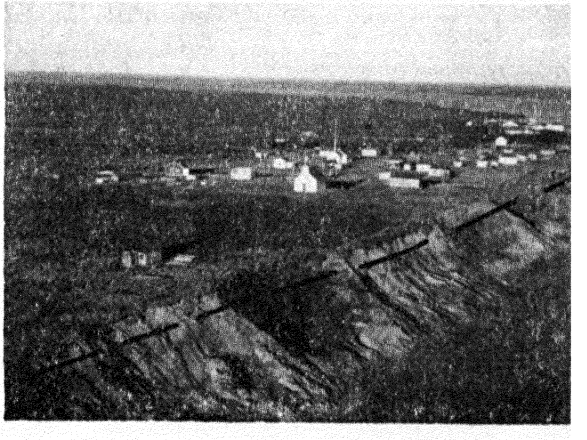
(c)



(d)



(b)



(e)

Fig. 4-17. (*a*) Oblique of four-sided thermal features on the sloping sides of beach ridges; (*b*) an aerial view of the same, with a part of the pattern that someone has outlined in black; (*c*) more conventional polygonal forms and (*d*) their general resemblance to mud cracks; and (*e*) an erosion scarp cut in a permafrost area of the Hudson's Bay area (the line indicates the climafrost limit and the weeping zone). A land cave-in is also apparent. This entire elevated plain, including the houses, overlies shallow permafrost. For more permafrost phenomena, see Figs. 4-18 and 18-9. [*Canadian and Alaskan Arctic.* (*e*) *D. R. Lueder.*]

be expected to be encountered. In the lower latitudes, occurrence may be sporadic. However, as more northerly areas are approached, occurrence becomes more widespread, until between 60 and 70°, it becomes continuous (except in Fenno-Scandia?). Permafrost probably also occurs in high mountains throughout the world, as well as in the Antarctic. In addition, fossil features appear to be present in many areas of the world that were previously cold and subject to perennially frozen conditions.

Permafrost is primarily a thermal phenomenon. Consequently, subject to the secondary regulating effects of other factors, it may occur at any place, at and to any depth, and in almost any form or pattern, provided the essential thermal conditions are present.

The other factors include the type of materials (textural gradation, aggregation, chemical composition, degree of induration); water regimen (depth to "water table," soil-moisture, etc.); topographic position; type of vegetative cover (insulation); geographic position; the activities of man; the nature of the climate (snow, clouds, humidity, evaporation, etc.); hydrology; and geothermal gradients.

The variety of thermal forms is great, and no complete and fully successful classification of them has been made. This situation will not be corrected here. Suffice it to say that they include:

1. Forms of level ground (polygons of various shapes, sizes, and center elevations, fissured polygons, stone nets, rings, circles and pits, soil circles, hummocks, pingos, pimple-mounds, Mima mounds, frost blisters, etc.)
2. Forms of sloping ground (polygons as above but with simpler shapes, soil stripes, stone stripes, terracettes, stone streams, solifluction stripes)
3. Thaw forms (beaded streams, thaw lake patterns, ridges and mounds, tilted terraces, sloping pond edges)

Some of these forms are illustrated in Figs. 4-17 and 4-18. Others appear in Chap. 15.

The reader may wonder why permafrost forms are considered as erosion features. The reasons are several. Invariably, such features are associated with changes in thermal factors and therefore are a direct effect of the forces of physical weathering. Usually, they involve a displacement, and promote the removal, of mineral material from the earth's surface. Finally, they are incipient to early stages in the modification of terrain that are, so to speak, temporarily prevented from becoming mature.

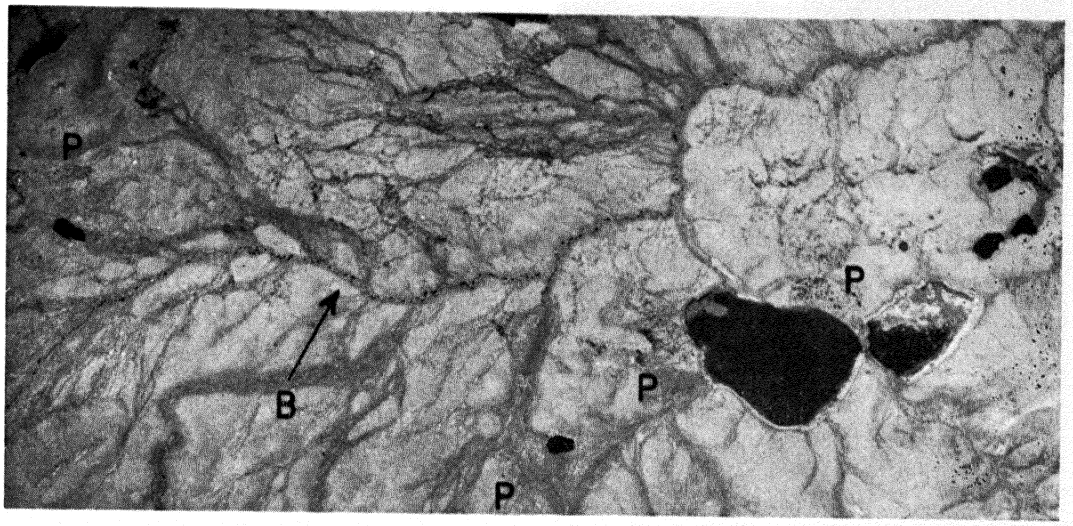
Polygonal forms are one of the most interesting, striking, indicative, and apparent (on air photos) of all thermal features. They are a form showing considerable variation and reflecting the combined operation of the variables and factors described above. In this respect, they do not differ from other natural phenomena, e.g., gullies, gray-tone profiles, soil profiles, etc., and it is surprising to find that some writers have attempted to oversimplify their formation, patterns, and significance, or at least overgeneralize by extending local phenomena over large and dissimilar areas. Washburn (217) mentions some 21 processes that have been used in the past to describe specific forms. Probably the majority of them are wholly or partly responsible for the forms with which they are associated.

Black (25) castigates various writers for disseminating erroneous information about polygonal forms, particularly with respect to their value as an indicator of detrimental permafrost. He flatly states that "polygons do not indicate that permafrost is present or even that it ever was present. Except for Rutton's theory, polygons generally indicate that certain disturbing forces are or have been operating in the soil or bedrock."

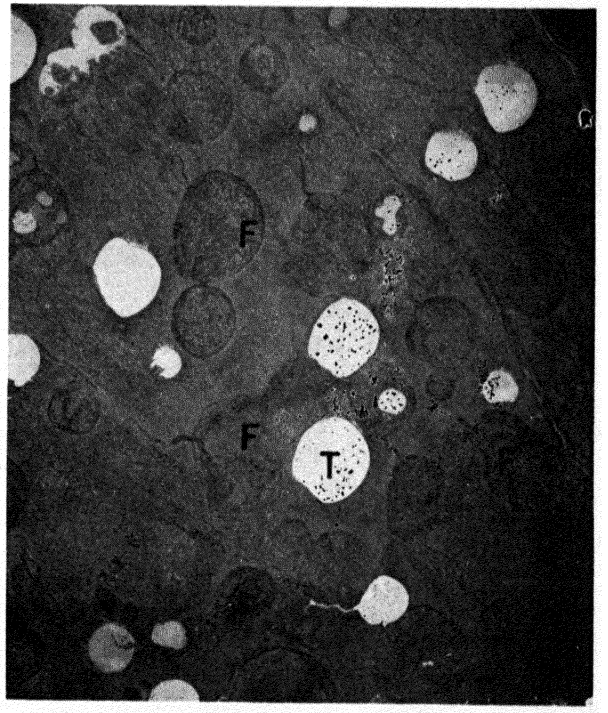
It should be evident that the visual identification of thermal features on aerial photographs will at least provide a warning regarding the possible presence of thermal phenomena (Fig. 18-8). As the significance of these phenomena becomes better known, such identification will become a true qualitative mapping tool, not only for permafrost, per se, but also for other terrain conditions. These include such items as textural gradation of soil, depth of seasonal-thaw (climafrost) moisture content, coefficient of thermal expansion, depth and width of ice wedges, type of vegetation, landslide potential, type of ecological communities, etc.

4-26. Miscellaneous Features of Mass Wastage. Sharpe (169) has prepared a rather complete classification of the features of mass wastage. While some of his types are of little interest to general terrain analysis, in the interest of completeness, his system is described below.

All features of mass wastage involve a certain amount of movement. This movement may involve either flow or slippage. In the former case, the flow is either imperceptible or perceptible (slow to rapid). In the latter, the movement is always per-



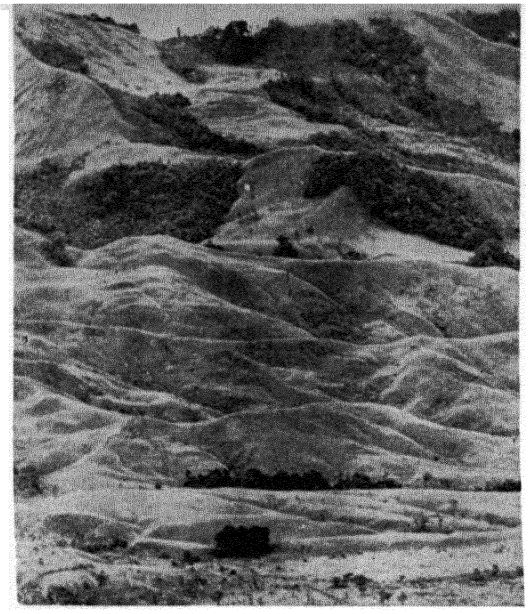
(a)



(b)

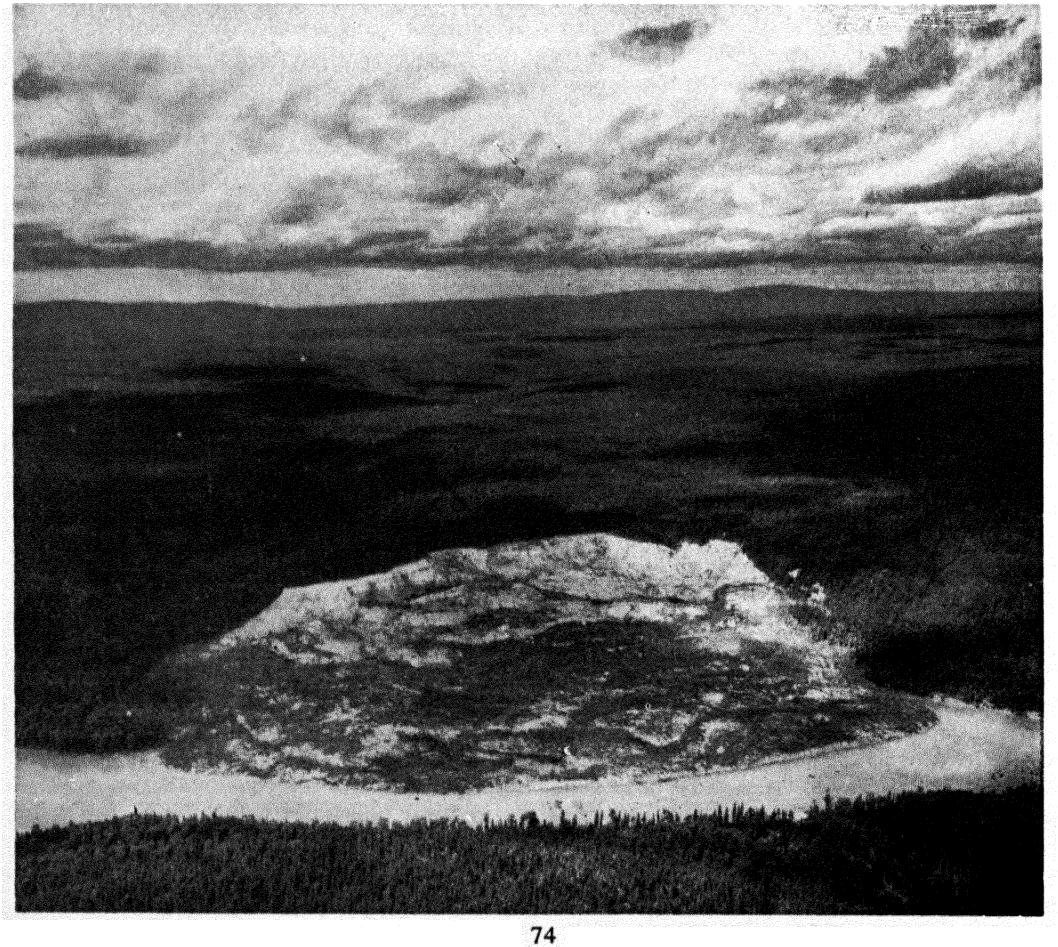
Fig. 4-18. Views of various thermal features, including (*a*) stream beads (*B*), polygons (*P*), and horsetail and anastomosic drainage and (*b*) thaw lakes. Note the coalescence of the frozen (*F*) and thawed (*T*) lakes. For other thermal features, see Fig. 15-4. (*Canada.*)

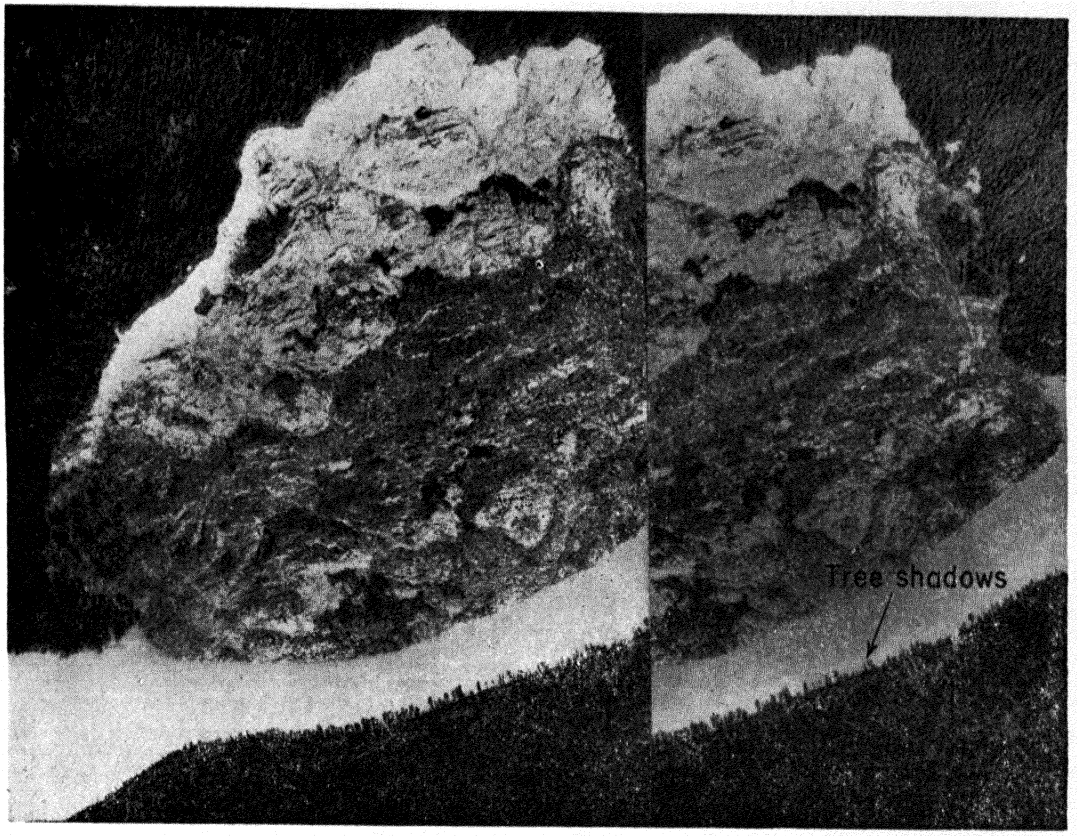
ceptible but may range from slow to rapid. The materials may involve pure ice; earth or rock plus ice; earth or rock with minor ice and/or water; earth or rock with considerable water; and pure water. Sharpe includes as flows such phenomena as glacial transportation, rock and glacier creep, solifluction, rock and talus creep, soil creep, debris avalanche, earth and mud flows, and fluvial transportation. As slips (popularly termed landslides), he includes slumps, debris slides, debris falls, rock-



(a)

Fig. 4-19. (*a*) A ground view of topography associated with land slippage; (*b*) an oblique of a very large landslide in virgin territory traversed by the Fraser River of British Columbia; and (*c*) a stereopair of the same. [*New Guinea, British Columbia.* (*b* and *c*) *British Columbia Government, Air Division.*]





(c)

slides, and rockfalls. Finally, he places subsidence in a separate category.

Various types of land slippages and related phenomena are depicted in Figs. 4-19 and 18-10*a* and *b*. Certain solifluction features (catsteps, Sec. 4-19) and thermal forms (Sec. 4-25) are illustrated at various points throughout the book. Both ice and rock glaciers appear in Chap. 12.

The value of old slippage scars to terrain analysis lies in their value as indicators of unstable conditions. Occasionally, they can be correlated with specific soil and drainage conditions, particularly if there is a previous experience record on the area.

4-27. Features Developed in Consolidated Materials. The various erosional features formed in consolidated materials (Sec. 4-2) are of relatively little value to terrain analysis.

Sinkholes (Sec. 16-19), of course, indicate the presence of soluble limestone, underground drainage, highly alkaline ground waters, and slumping.

Glacial features (including the grooves found in unconsolidated deposits) are indicative only of glacial action and, at present, have not been investigated to determine whether their shapes have special terrain significance (Chap. 12). Striae and grooves do indicate the *general* direction of glaciation.

Joints are of some importance to petrographic-petrologic identification (Secs. 16-9*a*, 16-17) and of considerable value in studying structural geology and completing mineral exploration (Chaps. 16, 19).

Buttresses, needles, etc., are of aid in predicting origin and composition of rocks (Chap. 16), as well as evaluating age and geomorphological history.

Felsenmeere is indicative of severe, thermally caused stresses in rock and may be associated with other thermal forms.

Illustrations of some of these features appear in the cited sections and chapters.

5 GRAY TONES (ALSO USE OF INFRARED, CAMOUFLAGE, AND COLOR FILM)

5-1. Definition of Gray Tones. Gray tones are often of great value in corroborating the interpretative conclusions reached through an examination of landform, drainage, and erosion. They are of particular value in estimating *variations in soil-moisture content; differences in surficial soil-organic content; general soil texture; general soil porosity; and boundaries between areas of different soil and rock bodies*. There is good reason to believe that they may be of value in studies of areal *soil evaporation, capillarity*, etc.

For the purposes of this book, a "gray tone" may be defined as *any density or shade between and including absolute white and absolute black that is registered by the terrain on an exposed non-color (panchromatic) aerial-photographic negative or the print processed therefrom.*

In certain interpretative cases, the importance of proper gray-tone evaluation to a successful interpretation is very great, and even dominant. Unfortunately, the correct interpretation of gray tones is often difficult and, because of lack of knowledge, uncertain. Gray tones registered by the terrain are affected by many factors, only a few of which have anything to do with the terrain itself. They comprise one element of the air-photo pattern that may be severely affected by the "foreign" factors mentioned in Sec. 1-1—which have so far been kept out of this book. Although proper photographic and processing controls and methods, combined with good equipment, have tended to reduce the effect of these foreign elements, their existence and nature should be recognized and understood by the reader.

To this end, the following pages list all the factors affecting gray tones. Those factors that are primarily related to, and indicative of, terrain conditions are then discussed, and their interpretation considered in some detail. Next, the predominantly foreign factors are given brief (summary) attention. Partly because their discussion is a summary, but also because the reader may be well acquainted with their ramifications, treatment of these latter factors is set in smaller type and may be omitted in a study of the more strictly interpretative aspects of gray tones.

Finally, because they are somewhat related, the characteristics and utility of infrared, camouflage detection, and color film are discussed.

5-2. Factors Affecting Gray Tones. Gray tones in aerial photographs reflect the aggregate effect of a great many factors. They are as follows:

1. Terrain factors (surficial topography and "texture"; soil, rock, and vegetative colors; and soil-moisture–organic content)
2. Technical factors (characteristics of materials and equipment, techniques of exposure, techniques of processing)
3. Meteorological and climatological factors (atmospheric haze, clouds, sun angle, season of the year)

5-2a. Aerial-photographic Negatives and Prints Are Really Infinite Assemblages of Individual Diffused and Integrated Exposures. Before discussing the terrain factors affecting gray tones, it is necessary to clarify the nature of such tones in terms of a given aerial-photographic exposure.

If one were to take a picture of an absolutely uniform material, under absolutely uniform conditions of lighting, and if one were to uniformly process the resultant exposed emulsion (also uniform), one would end up with a negative (and print) displaying uniform density (gray tone).

In actuality, photographs of such materials are seldom taken under such conditions. Most photographs expose the negative "emulsion" to different

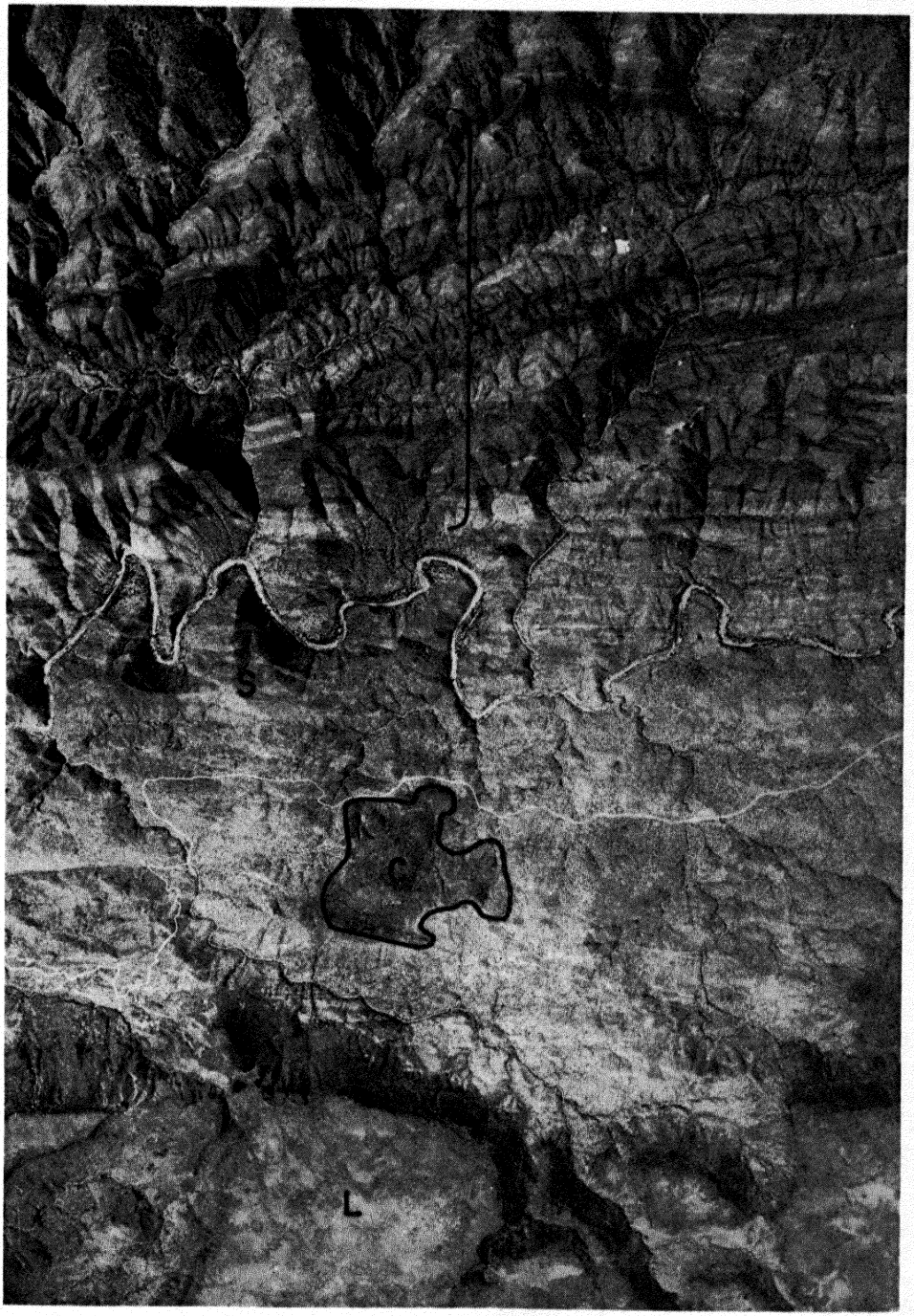


Fig. 5-1. This photograph illustrates the registration, on a panchromatic film, of rocks having different true colors. The color banding (bracket), outcrop *C*, and lava tone *L* contrast sharply with other deposits in the photograph. Also shown are shadow effects *S* that have similar tones in this picture. Usually, shadows caused by relief of this nature are much darker.

materials, having different textures and orientations of surfaces (Sec. 5-3) under different conditions of lighting and reflection. An "exposure," by definiton, is the product of *light intensity* impinging upon a sensitive emulsion and the *length of time* that it impinges. Therefore it is easy to see that a photograph, instead of being considered as a single exposure, should be considered as an assemblage—usually infinite—*of individual exposures, each one producing a different intensity of light over the same period of time.*

An aerial photograph is not different from a normal photograph in this regard. There is a tendency for similar materials, with randomly irregular surfaces, to diffuse and integrate and to appear as masses of equal tone rather than assemblages of individual tones. However, this tendency, which is really a function of distance from the camera, haze, and the characteristics of photographic materials, is counteracted by the larger area of the photograph with its greater number of integrated masses. The net effect is the same, namely, an assembly of individual exposures.

TERRAIN FACTORS AFFECTING GRAY TONES

5-3. Surface Topography and Texture. Surface topography refers to the general conformation of the land, the hills, valleys, swales, etc. Surface texture refers to the aggregate *microconformation* of the earth's surface, i.e., the roughening effect created by the entire complex of soil particles; rock fragments and outcrops; organic accumulations; water surfaces in their multitudes of depths and disturbance patterns; vegetation with its infinity of heights, shapes, orientations, and intermingling; and land use in its endless variety.

Surface topography may have two effects upon the intensity of light reaching the negative. One of these has to do with distance. All other things being equal, light intensity (therefore exposure and gray tone) is inversely proportional to the square of the distance from the emitting (or reflecting) source. In aerial photography, this effect may be largely ignored as insignificant for practical purposes.

The other possible effect of surface topography is largely theoretical. It has to do with the ideal angles of reflection of the sun rays. For any given sun angle, i.e., the sun angle at time of exposure, the topography of the land, depending upon its orientation with respect to the camera, and assuming a smooth surface, would reflect different quantities of light to the negative. However, the land does not have an ideal surface, and these ideal effects are changed by the surficial texture of the land to diffuse effects. As a consequence, differences in topography rarely have a significant effect upon the registration of gray tones. Of course, there are certain times when the effects are of moment, e.g., shadows and water-disturbance patterns.

Surficial texture has a much more important effect upon gray tones than topography. This should be fairly evident. The light rays striking an irregular, i.e., natural, surface are diffused. The amount and nature of the diffusion, and the amount and nature of the light reflected to the negative, depend upon the diffusing-reflecting character of the photographed surface. This general effect is emphasized, in aerial photography, because of the massing and integrating of natural surfaces within the photographic perspective.

There are innumerable types and combinations of surficial textural effects. These are illustrated throughout this book, but particularly in Part II and Chaps. 19 to 22.

5-4. Soil, Rock, and Vegetative Colors. Panchromatic film registers all wavelengths of the visible spectrum in terms of gray tones.

In so far as interpretation is concerned, it is sufficient to state that any aerial print containing separate areas having characteristics such that they display different massed (diffused) colors will register the areas in different shades of gray that are indicative of the mass wavelength modified by such surface-textural moisture, haze, etc., effects as may exist. Table 5-1 shows the effects of surface texture combined with color on *brightness*, but not on tone. It may be thought that colors are likely to be few in number and drab in aerial photography. In terms of specific areas, this belief may be correct, since most areas are characterized by relatively few colors. For nature, as a whole, it is wrong. The colors of nature include all shades of green (vegetation); green-blacks, and browns (rocks); browns, blacks, tans, and reds, plus all combinations of these (soils and rocks); whites and yellow-tans (aeolian and evaporite deposits); and occasional expanses of pinkish to purplish (rocks). Illustrations of some terrain differences, revealed by gray registrations of natural tones, appear as Figs. 5-1 and 5-2, throughout the various chapters of Part II, and in Chaps. 19, 21, and 22.



Fig. 5-2. This photograph shows the trace *T* of a sedimentary rock formation that is revealed almost solely by the gray registration of its natural color tone. Its topographic expression is almost negligible. There are many outstanding examples, throughout this book, of the panchromatic tonal registration of natural tones, particularly in Chaps. 3, 16, 19, and 22.



Fig. 5-3. An illustration of gray tones related to moisture content. Shown are the dark-gray tones caused by inundation of rice paddies in the area *W* from the canal *C*. Above the canal is a noninundated area *D*. Both areas have the same soil texture. Also shown are the tones of a very muddy irrigation "tank" *L*, and the bright-white tones of a sand bar *B* and sand-beach ridges. (*Ceylon. Photographic Survey Corporation.*)

Table 5-1. Brightness of Terrain Areas Having Different Colors and Textures (After Brock)

Surface and or type of terrain	Brightness, foot-lamberts	Relative brightness
Light-yellowish sand	2,400	100
Brown soil	1,100	45
Pasture grass	700	30
Streets and roofs of a nonindustrial town	700	30
Deciduous woods (summer)	600	25
Dark-green crops	560	23
Dark pine woods	300	12
Very light whitish sand (desert)	1,760	100
Open green grassland	630	36
Barren grassed area, brown and withered	690	39
Fairly open tree cover	630	36
Rich green grass near water	560	32
Dark-green woods	314	18

NOTE: The first seven items were "measured with a telephotometer, a very small angle of view, and refer to small areas picked out of the general landscape" (27). The last six items were "obtained with a standard Weston exposure meter having an angle of acceptance of about seventy degrees, the aircraft being at about 10,000 ft., solar altitude about eighty degrees, atmosphere very clear" (27).

5-5. Soil- and Organic-moisture Content. A little appreciated but highly important factor that affects gray-tone registration is the amount of moisture present in the soils and organic terrain that is photographed.

It can be shown on aerial photographs that *deep* bodies of *still, clear* water will register as very dark grays to blacks. Brock (27) confirms this and justifies it partially by saying that the bottoms are usually dark and/or the water is often slightly colored by impurities. He goes on to say:

> Unless the water is clear and shallow over a light-coloured bottom or turbid with light-coloured matter, or sending strong surface reflections upwards into the camera, it usually records fairly dark in panchromatic photographs. Pure water begins to absorb quite appreciably at the extreme red end of the visible spectrum and by about 1.4 microns a centimetre or so gives practically complete absorption. Natural water areas, even ditches only a foot or so in depth, record quite black in infra-red air photographs.

Conversely, deposits of *clean, dry* unvegetated soil, of practically any texture, and provided that they have no exceptionally dark or violent color and are not affected by specially adverse factors, will photograph as very light grays to white (Table 5-1).[1]

Between these two extremes, various mineral-water and organic-mineral-water mixtures will display shades of gray that do not solely reflect the effects of surface texture, natural color, processing, etc. In general, it may be said that the more moisture there is in an organic or mineral complex, the darker its gray tone will be. This fact has been noted by several writers on aerial-photographic interpretation and has been field-checked many times. Only a few quantitative measurements of the relations between moisture content and gray tones have been carried out (Sec. 5-14), and the fact must be accepted as general rather than specific. All observations and measurements to date, however, have indicated that the above conclusion is sound.

A proper interpretation of gray tones will separate those tones indicative of moisture content from tonal effects and will use them not only as indexes of moisture, but also as indexes of soil porosity and texture.

In this respect, moisture as a modifier of gray

[1] Even if adversely affected by other factors, these materials should be among the lightest relative shades.

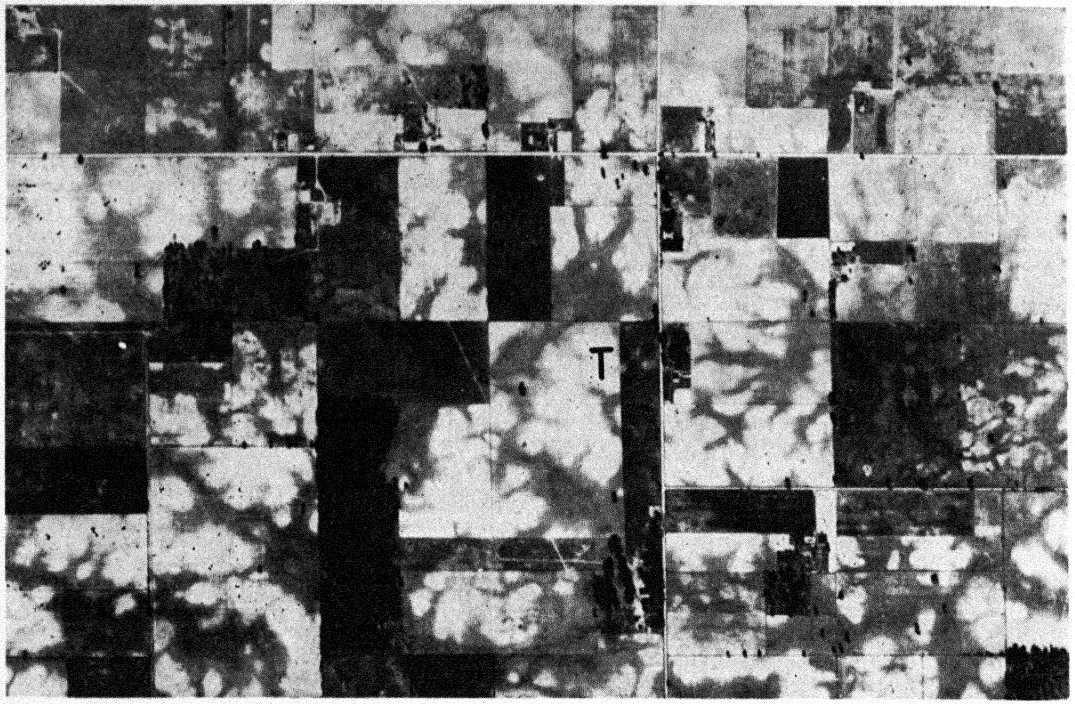


Fig. 5-4. Topographically correlated moisture-organic tones. Note the visually perceptible gradations in gray tones in the vicinity of T. For a discussion of this area, see Fig. 12-7. (*Indiana. U.S. Department of Agriculture.*)

tones is probably the most important factor affecting gray tones, simply because it can easily and quickly be put to practical use. While it may be thought that the separation of moisture-indicative tonal patterns from those due to other causes might be difficult, the opposite is true, as will be shown in the following sections.

Some examples of tonal patterns related to moisture content appear as Figs. 5-3 and 5-4. (Also see Fig. 24-12.)

INTERPRETATION OF GRAY TONES

5-6. Principle of Relative Tonality. The principle of relative tonality may be stated as follows: *When engaged in a practical interpretation of gray tones as indicators of natural soil-moisture content and seasonal variations; probable relative soil porosity; and probable general soil texture; the tones of significance must be considered in their relative rather than their absolute sense.*

As an example of this principle, consider an area in the humid-temperate climatic zone that has been photographed in the early spring. In most cases, such an area, particularly if it includes a variety of textures and elevations, will show both a great number and a great range of gray tones. These tones will indicate, to some extent at least, variations in field moisture. If measured by a microdensitometer, it may prove that there are, in essence, 15 fairly distinguishable *natural-moisture-indicative* tones ranging in relative density from 0.01 to 0.6.

If this same area is rephotographed in midsummer, it will probably be found that the tonal range, as well as the number of fairly separate absolute tones, has narrowed considerably. Microdensitometric measurements may now range from 0.01 to 0.2, while the distinguishable natural-moisture-indicative tones are 4 or 5 in number. In general, the area that appeared so interesting in the spring by virtue of its varietal tonal pattern, now appears dull, uniform, and drab.

The primary reason for this seems to be related to a withdrawal of moisture from all elements of the terrain and their consequent drawing together,[2]

[2] The same effect can be partially caused by proper variations in materials exposure and by processing techniques, but the moisture effect is normally superimposed upon this effect.

the more pronounced masking effect of low summer growth together with their associated spectral effects, and the lack of visual and/or photometric acuity or differentiation.[3]

In this second case, small differences in tonality will reflect essentially the same possible porosity and textural differences that were originally indicated by large differences. During the summer an area of perennial, spring-fed, sidehill seepage that originally had tones well within the range of those present might well display the darkest tones in the photograph.

Two examples of relative tonality are illustrated by Figs. 5-5*a* to *d*.

The effect of tone subduing and the application of tone relativity must be expected in all areas where wet and dry seasons exist, where variations in processing exist, etc., or, in short, on all prints. Its probable effect must be evaluated when completing any interpretation.

5-7. Special Features of Moisture Gray Tones. In addition to their tonal values moisture gray-tone patterns have special aspects that are often of significance in making a proper interpretation. These include (1) boundary characteristics (shape, topographic correlation, sharpness) and (2) shape of tonal profile.

5-8. Boundary Characteristics—Shape. In Sec. 5-5, it was stated that gray tones indicative of field-moisture (and organic) contents were relatively easy to separate from those due to other factors such as surface texture. One reason for this statement is related to the *shape* of such tonal patterns.

In so far as shape is concerned, it may be said that gray tones indicative of field moisture almost always have *irregular shapes that ignore all aspects of the terrain except topography*. Thus they can be separated from the other most common cause of gray-tone variation, land usage and its surface-textural modifications, which usually have regular or semiregular boundaries between tones.

Of course, vegetative types have irregular boundaries (which are often related to moisture differences), but such tones are due to the surface texture of vegetation and are easy to distinguish. Also, they seldom have real topographic correlation.

[3] The same number of separable tones may be present, but indistinguishable to the human eye, and very close to each other even on a densitometric scale.

5-9. Boundary Characteristics—Topographic Correlation. As mentioned above, gray tones indicative of field-moisture contents are generally, but not always, related to the topographic expression of the terrain. Inspection of various terrain areas, through the tridimensional medium of stereoscopic examination, will reveal that the darker field-moisture tones are *generally* coincident with the lowest areas while the lighter tones tend to occur upon hills, ridges, and interstream areas in general.

This poses an interesting question. Inasmuch as water runs downhill and collects in the lows, does it not carry with it particles of upland soil (possibly of different color) and organic matter which also collect in the lows and which, presumably, also change the gray tones; i.e., are not the field-moisture tones also reflective of a certain aggregate effect caused by organic accumulation and actual color change?

The answer to this question must, in general, be "yes." However, this does not necessarily complicate matters. What the interpreter sees, and indeed is looking for, is the condition of terrain relative to field moisture, soil porosity, and soil texture. Since all these are affected drastically by the accumulation of fines and organic matter, it can be said that they tend to emphasize field-moisture–organic differences rather than obscure or complicate them.

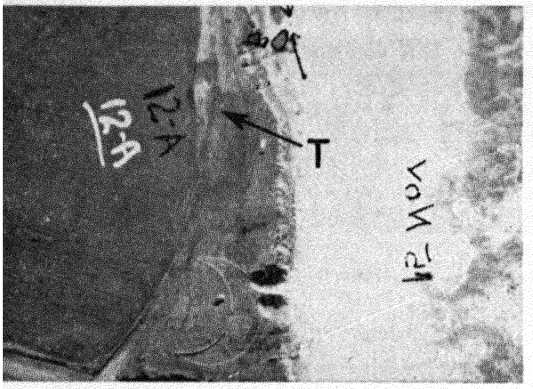
In certain instances complications may arise, and it is then necessary to interpret more carefully, possibly with an examination of the gradients between adjacent tones.

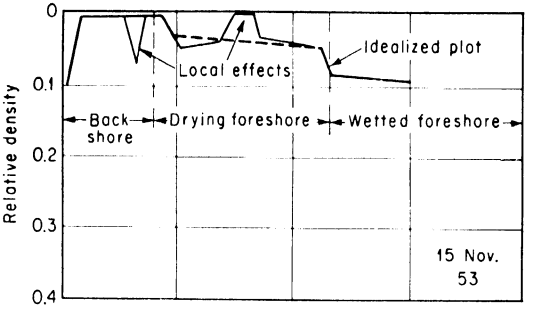
5-10. Capillarity of Natural Soils. Before discussing the sharpness of tonal boundaries and the shape of tonal profiles, it is necessary to review some physical observations on soil capillarity. It is a well-investigated fact that materials having different textures also have different capillary potential. For soils, Terzaghi and Peck (196) state that the height of capillary rise may be roughly expressed by the equation

$$h_c = \frac{C}{eD_{10}} \tag{5-1}$$

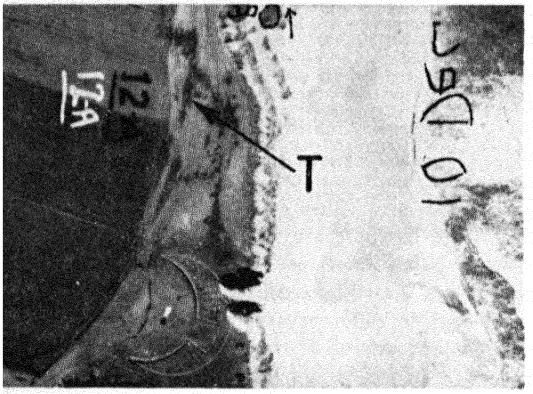
where D_{10} is the effective size of the soil in centimeters, e is the void ratio, and C is an empirical constant depending upon the shape of the grains and their surficial impurities.

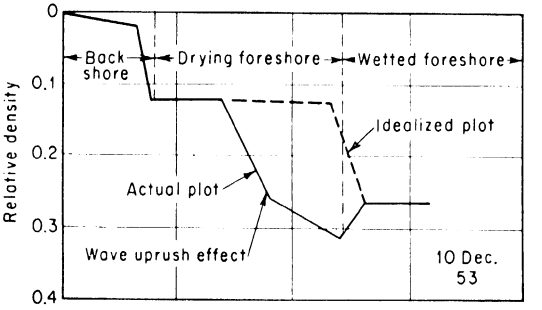
Therefore, if two soils, one composed completely of sand sizes and one composed completely


12-A
T
12 Nov 53

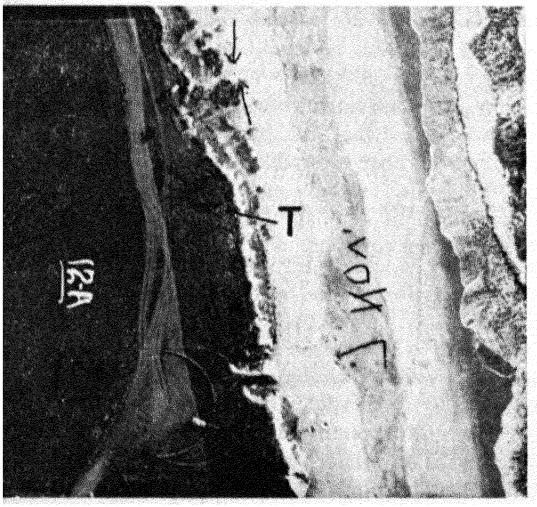

Relative density
0
0.1
0.2
0.3
0.4
Back shore
Drying foreshore
Wetted foreshore
Idealized plot
Local effects
15 Nov. 53

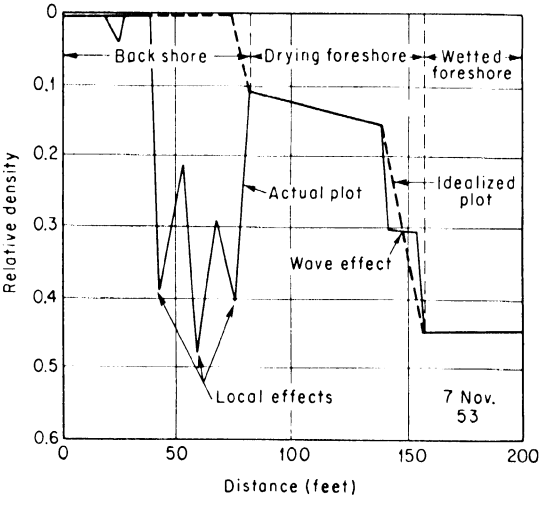
(a)


12-A
T
10 Dec 53

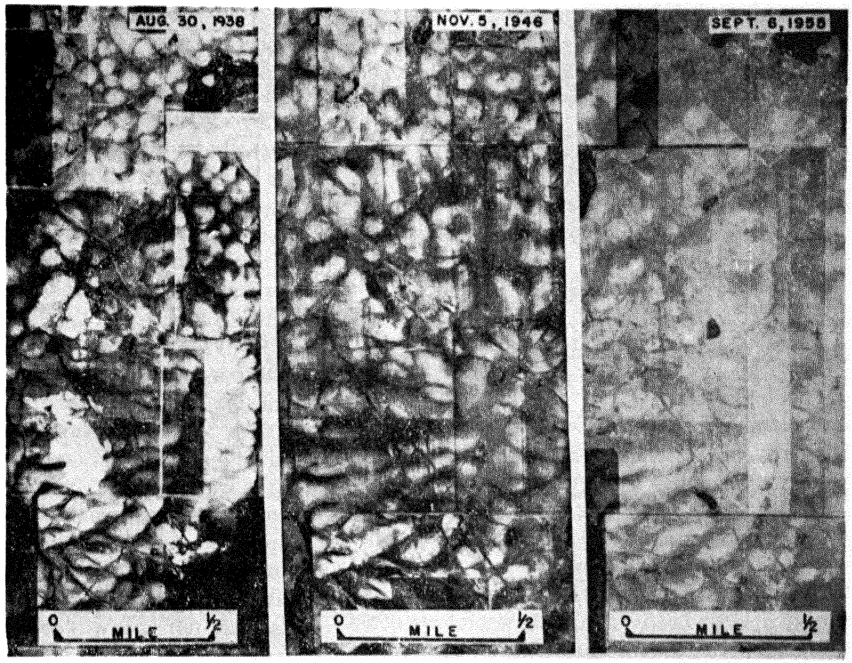

Relative density
0
0.1
0.2
0.3
0.4
Back shore
Drying foreshore
Wetted foreshore
Idealized plot
Actual plot
Wave uprush effect
10 Dec. 53

(b)


12-A
T
7 Nov 53


Relative density
0
0.1
0.2
0.3
0.4
0.5
0.6
0
50
100
150
200
Distance (feet)
Back shore
Drying foreshore
Wetted foreshore
Idealized plot
Actual plot
Wave effect
Local effects
7 Nov. 53

(c)



(*d*)

Fig. 5-5. These photographs and actual averaged microdensity plots show the effect of relativity. Only the horizontal letter *T* and the ranges of relative densities have significance. Note the expansion in the range of relative densities—and gray tones—proceeding from (*a*) to (*c*). Yet moisture-indicative tones *T* exist in all three photographs and indicate the same condition. However, their absolute tone has varied. In one case, they are close to the darkest tones; in another, they are in the middle; and in a third, they are toward the lighter end of the range. Figure (*d*) is a composite photograph showing the same effect, probably complicated by processing. [*United States.* (*a*) to (*c*) *U.S. Navy;* (*d*) *courtesy of J. D. Mollard.*]

of silt and clay sizes, are placed so that appreciable portions of their sloping surfaces extend above the water table, it may be expected that the sand will have a *narrow zone of capillary action* and the silty clay will have a *broad* zone. The capillary action within this zone will vary for both soils because the interconnected chains of voids that are partially responsible for capillarity have varying sizes from point to point. In both cases, however, the bottom portion of the zone of capillary action will *tend* to be a *zone of capillary saturation* caused partly by upward capillarity, partly by lateral and downward capillarity, and partly by simple gravity flow. The upper zone will be a *zone of varying capillary moisture,* the amount and extent being a function again of variable pore diameters, without the supplemental effects of downward flow.[4] Part of this upper zone will be occupied by air, or mixtures of air and water vapor in transit to the surface (Fig. 5-6).

The theoretical and actual height of capillary rise in natural soils is not the only factor that is required to describe capiliary action in soils. It is necessary to consider also the rate of capillary rise.

Most writers and investigators have touched upon rate to some extent. Terzaghi and Peck (196) say that the maximum height of rise within 24

[4] After rains and downward percolation, the boundaries of these zones change in elevation. The zone of varying capillary moisture, for example, always extends to a greater height if the soil mass has previously had a higher water table. "Thus, high percentages of saturation are common in fine sands and silts at heights above free water that are considerably greater than could be similarly saturated by capillary rise" (193).

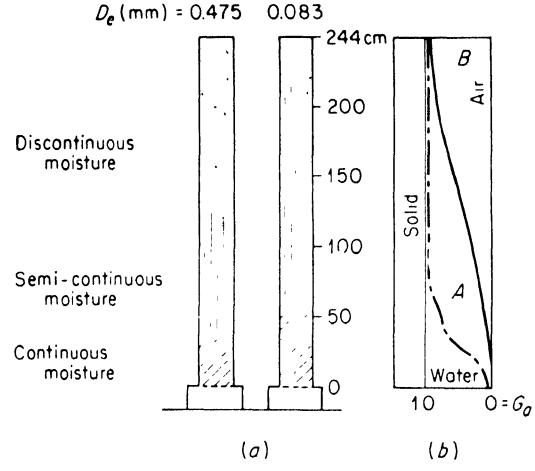


Fig. 5-6. Soil moisture in two different samples of sand after drainage for 2½ years in the laboratory. [*From Terzaghi and Peck* (196).]

hours, i.e., the greatest rate of rise, for uniform quartz powder occurs at a grain size of about 0.02 millimeter (around a medium silt size in most grain-size classifications). Baver (9) mentions the work of several investigators, among which was Wollny (224*a*), who concluded:

1. That capillary openings ranging between 0.05 to 0.1 millimeter in size (coarse silt to very fine sand) conducted water most rapidly
2. That capillary movement attained a minimum at 2.0 millimeters (boundary between gravel and sand)
3. That the rate of capillary rise was faster in a column of sand particles having mixed sizes than one having uniform sizes

Baver also mentioned Moore (134), and Bodman and Colman (26). All these investigators found that the rate and quantity of capillary movement were a function of grain-size distribution; also that they depended upon the moisture content of the source of capillary water.

Moore is cited as showing that the capillary conductivity is a maximum at or near saturation, decreasing rapidly as moisture approaches the moisture equivalent and remaining constant as reduction continues. According to his measurements, grain size also has an effect such that the capillary permeability is lowest for sand and highest for clay. Furthermore, Moore found that the capillary permeability became zero, i.e., moisture films became discontinuous, at values of soil-moisture content that varied from 5 per cent for sand to 26 per cent for clay. Bodman and Colman confirmed these observations.

5-11. Evaporation in Natural Soils. As mentioned in Sec. 5-10, capillary permeability becomes zero when the moisture content reaches some percentage that varies with the soil, but is lowest for sands and highest for clays. Beyond the vertical point where such moisture contents exist, upward capillary movement of water does not occur. Upward movement can take place only in the vapor state, from a point of high vapor pressure to one of low vapor pressure.

Vapor pressure is affected by variations in soil moisture and temperature, with temperature appearing to be the more important factor. In general, it may be said that moisture will move upward in the vaporous state from a zone of high temperature to one of low temperature, i.e.; maximum vapor movement will occur when the subsoil is warmer than the surface soil (early mornings during the summer; cool dry spells during the summer; fall and winter while the ground is unfrozen; etc.). An opposite movement of water vapor should occur during normal warm summers. Smith (177) is cited by Baver (9) as having found that vapor movement was also affected by the state of the soil, being small in natural clays but high when the clays were fragmented.

When water rises through a soil column by capillarity and continues its rise by vaporous transit, it ultimately is affected by evaporation. The rate of evaporation is affected, according to Baver (9), by temperature, relative humidity, wind velocity, the degree of saturation with soil moisture (in turn affected by depth to water table), particle gradation, state of aggregation, and color of soil. All other things being equal, the rate of evaporation is proportional to temperature, wind velocity, darkness of surficial soil layers, amount of soil moisture, and depth to water table. It is inversely proportional to relative humidity and dominant particle diameters.

5-12. Downward and Lateral Movement of Water in Natural Soils. At the top of the zone of varying capillary moisture, capillary permeability becomes zero and capillary rise is no longer possible. Yet moisture occurs between the upper limit of the capillary zone and the surface of the ground. This moisture is discontinuous and occurs as films surrounding points of contact between individual mineral grains. Because of this it is called "contact moisture" and the zone in which it occurs is called

the "contact-moisture zone." Moisture in this zone occurs because of three effects:

1. Remnantal capillary moisture from previous conditions of high water table
2. Condensation of upward- or downward-moving water vapor
3. Downward and lateral movement of infiltrated precipitation or runoff by gravitational and/or capillary forces

The third effect is of considerable interest. Regarding the effect of gravity alone, Terzaghi and Peck (196) say:

In the laboratory the drainage of sand under the influence of gravity continues for years at a decreasing rate, even if the sand is fairly coarse. [Figure 5-6] represents two samples of sand 2½ years after the start of drainage. In both samples the air-space ratio increased quite rapidly with increasing elevation above the water table [as shown in Fig. 5-6]. Furthermore, even at the end of 2½ years, the average air-space ratio of both samples was still increasing.

In the field every process of drainage by gravity is accompanied periodically by an inflow of water from rain or melting snow and ice. The effect of the recharge on the average moisture content of a drained soil in the field depends not only on the amount of recharge and evaporation, but also to a considerable extent on details of stratification. Furthermore, experience indicates that the air-space ratio for a drained soil in the field is practically independent of the elevation above the water table, whereas in drained laboratory specimens it increases consistently in an upward direction [as shown in Fig. 5-6].

Baver (9) says that

. . . data were presented to show that the percolation of water through a soil column was definitely a function of the amount and size of the larger pores. The interpretation of this relationship to drainage problems would imply that the ability of soils to drain naturally, as well as their need for artificial drainage, are correlated with the noncapillary porosity or air capacity . . . the character of the pore space is a much more reliable index than texture for judging drainage needs. These results also point out the fact, which has been repeatedly emphasized in the discussions on soil structure, that the air capacity of soils is not necessarily related to total porosity.

About downward movement by capillary forces, Baver says:

The movement of capillary water downward takes place under the combined influences of the gravitational-potential gradient (Grad ϕ) and the capillary-potential gradient (Grad ψ). If evaporation is prevented at the surface, such downward movement will continue until the soil is drained or until equilibrium is attained with an impermeable layer or a saturated water table.

And about lateral movement,

. . . lateral or horizontal movement of water takes place under the influence of the capillary-potential gradient only . . . [it] is slightly less than downward movement.

It should be evident to the reader that the various aspects of downward and lateral drainage in soils will affect their gray-tone patterns.

5-13. The Concept of Boundary Sharpness and Tonal Profile. Experience in the observation and close examination of gray-tone patterns that appear on aerial photographs will reveal, to the careful observer, that the sharpness of gray-tone patterns varies. In some areas, the break between dark and light tones is sharp, or at most goes through one or two *visually different* tones. In other areas, the change from light to dark shades is gradual, and definite boundaries between different tones cannot be ascertained. Some of these variations in sharpness may obviously be related to overriding differences in surface texture (Sec. 5-3). However, others seem to bear some relation to the texture of the soil.

This apparent relation is not only an intriguing one, but it is also supported by logic (Secs. 5-6 and 5-10 to 5-12). The relation may be termed the "concept of boundary sharpness and tonal profile." This concept is difficult to put into words, but the following represents an attempt to do so. If the intensity of a gray tone is partly proportional to the amount of moisture present in a soil, then the degree of sharpness and the shape of the tonal profile between nearby dark and light natural tones should bear some relation to the capillary permeability and conductivity; the vapor-evaporative condition; the degree of recent surficial wetting or downward percolation; and therefore to the texture, depth to water table, or other physical characteristics of the soil upon which the tones occur.

Admittedly, the above statement is complex. But so is the concept that it is trying to present. To illustrate by example a very simple case, consider two soils, one composed completely of medium silt and clay sizes and the other of medium sand sizes. Let these deposits comprise two topographically identical knolls, and let their bases intersect the water table. Further, assume that it is summer,

with a downward vapor-pressure gradient, and that there has been no precipitation for an appreciable period. Under these conditions, assuming similar vegetative covers and sun-angle exposures, the two soils should display different degrees of sharpness and shapes of tonal profiles between tones. Because of low capillary permeability, the zone of capillary activity in the sand should be narrow. That in the silt, because of high capillary permeability and conductivity, should be wide. Therefore the sand knoll should display a sharp boundary and abrupt profile of tones between its wet and dry areas. The silty-clay knoll, contrarily, should display an indefinite boundary and a tonal profile with a gradual gradient.

Of course, the above is an ideal case and would seldom be duplicated in nature. To add to this scarcity, there are all the permutations and combinations involving texture, structure, capillarity, vapor gradients, evaporation, winds, precipitation, color, vegetative cover, sun angle, exposure, etc., compounded by all the additional permutations of negative and print exposure and processing. When one thinks of this imposing list of complicating factors, it is quite reasonable to suspect that the concept of sharpness and tonal profile is of academic interest rather than practical value.

Such may be the case. In truth, not much work has been done to indicate one way or the other. However, it has been the author's experience that nature has a way of integrating series of complicating factors, smoothing out minor divergences, etc., so as to make similar situations comprehensible and interpretable (e.g., in the regime of rivers and their analysis as presented by Blench). Such may be the case in this instance. There have been some instances where an examination of boundary tonal profiles has proved of deciding importance in estimating soil profiles. These instances have had no quantitative data involved. Rather, the interpretations depended upon interpretative intuition, logic, and experience. Partly because of these instances, the author is loath to accept the contention that tonal profiles are of no practical value. However, there is additional reason. This has to do with certain elementary measurements that were made in connection with beach sands.

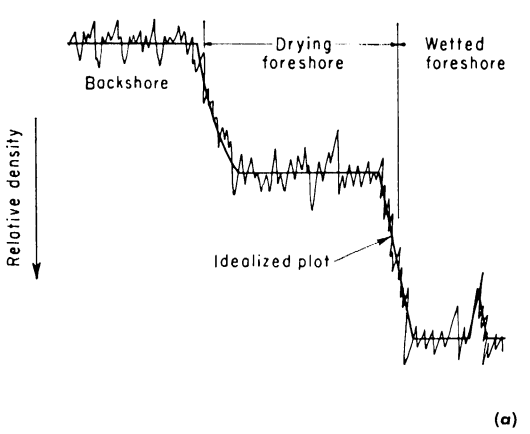
5-14. Results of Densitometric Measurements of Moist Sands of Various Textures. Some years ago, the author (108) had the opportunity of performing densitometric measurements on recently wetted beach sands having varying textural gradations and predominant sizes. The conditions under which this research could be conducted were fairly good for the observation of natural phenomena.

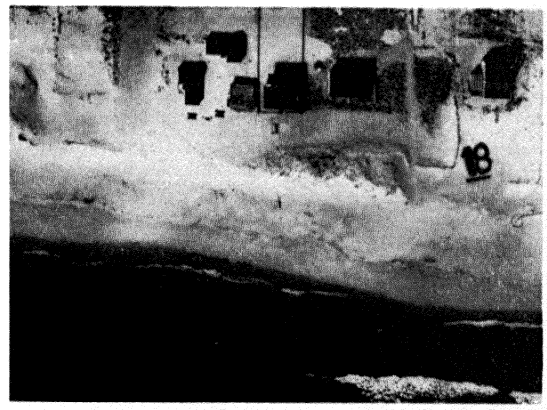
To begin with, it was believed intuitively that, all other conditions being equal, a beach composed of coarse sand would have different tonal profile characteristics than one composed of fine sand. It was realized that, because of tidal fluctuations, wave changes, slope variations, and debris accumulations, the patterns would be subject to some variation, but that by proper interpretation, the typical pattern for various grain-size classes could be distinguished. Several factors were more or less equalized between various beaches and observations. No vegetative cover required consideration. The soil texture was limited to sand sizes. For all intents and purposes, after the Cardex analysis of some 500 samples, the grain-size distribution could be assumed to be of similar shape (though at different positions on the gradation chart). The soil composition was almost completely quartz and/or feldspar. Slopes, and therefore reflection and upwash, varied between relatively narrow limits. Photographs could be selected so as to eliminate radically different sun angles. They could also ensure that measurements were taken after falling mid-tide. Winds and evaporation were relatively constant. Water tables were at relatively uniform distances below the highest point on the beach. Finally, the beaches were bounded by two zones of relatively constant characteristics, one being the almost completely dry backshore and the other being the almost completely saturated lower foreshore.

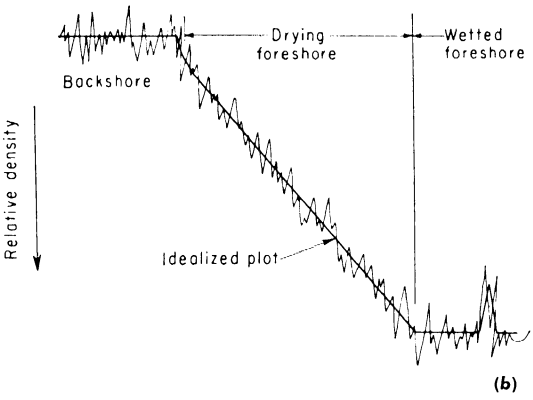
The original method contemplated for investigation involved simultaneous execution of aerial photography, physical profiling, and material sampling on a variety of beaches. This was to be followed by controlled development of the aerial films to something approaching a constant gamma and by measurement, with a transmission microdensitometer, of the tones across the beach parallel to the physical profile.

This ambitious program broke down for a variety of reasons, and many compromises and revisions had to be made. Further, the usable quantitative data were reduced severely from that expected. However, results were sufficiently good to provide some data of value.

This study definitely indicated that the gray tones appearing on the drying foreshores of sand beaches were indicative of the surficial moisture







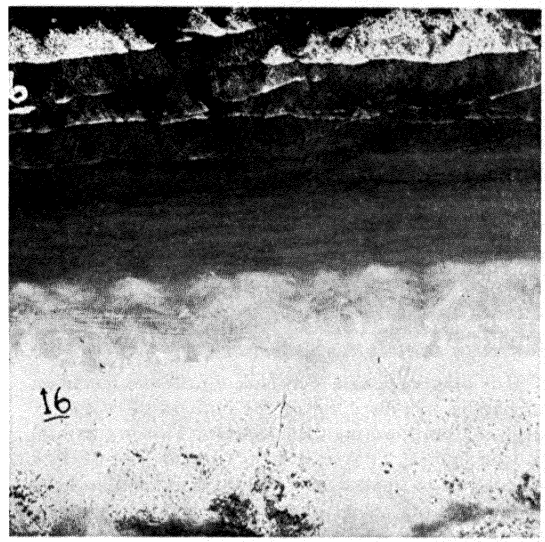


Fig. 5-7. Idealized typical microdensity plots for coarse and fine sand beaches with aerial-photographic views of same. The numbers on the photographs have no significance. These idealized plots are subject to many types of local and vertical variations (Fig. 5-6).

content and predominant grain sizes occurring on the beach. It further indicated that the tonal profiles for beaches composed of coarse material (D_{50} greater than 0.5 millimeter) were quite different from those for beaches composed of fine materials (D_{50} less than 0.5 millimeter) (Fig. 5-7).[5] Finally, it indicated that the gray-tone pattern was independent of physical slope on coarse-grained beaches, but that the rate of tone darkening increased proportionately to the physical slope of fine-grained beaches (Fig. 5-8).

[5] Actual microdensitometric records showed an irregular jagged variation on either side of the idealized lines. The trends and special points, however, were unmistakable.

5-15. Visual Acuity. Visual acuity is a definite factor to be considered in the evaluation of tonal profiles (average gradient and shape).

It is fairly easy to accept the fact that the *normal* eye is incapable of discerning all the variations in density that are recorded by the *average* negative. Brock (27) says that the contrast sensitivity of the eye (ratio of an incremental change in brightness to the original brightness) remains virtually constant at 0.02 over a wide range of absolute brightnesses (25 to 400 equivalent foot-candles), but that the contrast sensitivity of the photographic emulsion can theoretically be much greater, and actually substantially so. (He also mentions that

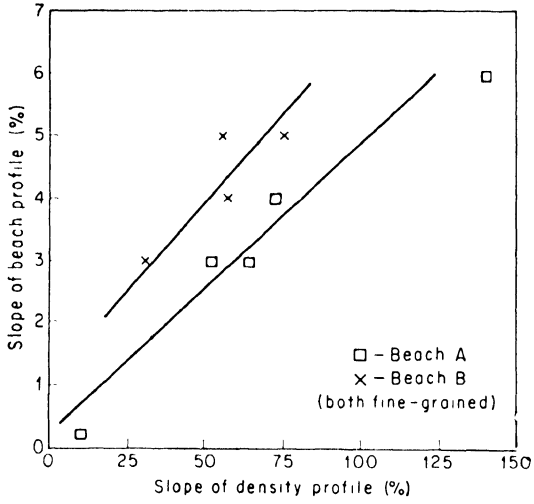


Fig. 5-8. The relation between slope of microdensity profile (drying foreshore) and the physical slope of the same for fine-grained beaches. It will be seen that processing and other factors being equal (grain sizes varying within a narrow range), the physical slope affects the total gradient. On coarse beaches, such a correlation was not found.

the detail being sought must be large relative to the grain structure of the developed emulsion.)

Brock also makes the following statement of interest to the reader on the evaluation of tonal profiles:

It is often supposed that haze affects the definition of photographs by diffusing the outlines of objects as distinct from lowering their contrast. This is a natural misconception, because it is so easy to confuse lack of contrast in small details with lack of sharpness. To some extent, of course, the contrast and the sharpness of photographs are interlinked because a contrasty reproduction will have a steeper density-gradient at the boundary of any image, but apart from this it has been shown experimentally that a reduction of contrast under conditions which cannot possibly affect definition always conveys the impression of a reduction in sharpness. It has also been shown experimentally that haze does not affect sharpness of definition in the true sense.

This effect was noticed frequently in the aforementioned beach studies, when the outer limits of the tonal ranges were close to each other. A similar effect is probably involved in the seasonal subduing of tones (Sec. 5-6).

5-15a. Combined Effect of Various Factors—Necessity for Research. As was mentioned in Sec. 5-13, the various permutations and combinations of the factors that affect tonal registrations and profiles are virtually infinite. With proper, electronically registered research data and programs, it may be possible to determine the effect, or probable effect, on gray-tone patterns of any given combination, to determine the range of variation caused by given factors, with all others constant, etc., and thereby to arrive at the truly significant causes and effects that are associated with tonal patterns.

Following this, the relation between tones and terrain conditions must be determined, correlated, analyzed, and fed into the computers.

Finally, it may be possible to arrive at a most probable solution, in terms of terrain conditions, for any given general tonal pattern, provided that proper data are available on the factors affecting gray tones and the factors affecting moisture.

This procedure might be academic, or it might not be, particularly if rapid, widespread investigations of evaporation, capillarity, texture, precipitation, etc., could result. However, it is also possible that a dependence upon the integrating and compensating actions that are typical of nature (Sec. 5-20), combined with well-planned densitometric and field research, would make the procedure unnecessary, and still yield a substantial amount of usable and valuable information.

In any case, variations in tonal profiles *do* exist, and appear in many illustrations of this chapter, as well as throughout the book, notably in Chaps. 3, 4, 9, 11, 13, and 14.

TECHNICAL FACTORS AFFECTING GRAY TONES

★ 5-16. Characteristics of Materials and Equipment. Certain characteristics of materials and equipment have significant, but complex, effects upon the rendering of gray tones. These characteristics, for materials, may be listed as follows:

1. Of the negative (shape of the characteristic curve, speed, gamma, latitude, resolving power, wavelength sensitivity, uniformity, and composition of the "emulsion")
2. Of the paper (virtually identical with those of the negative)
3. Of processing solutions (chemical composition and deplenishment)

The characteristics of equipment that have significance are:

1. For the camera (quality of lens with regard to image formation)

2. For the processing equipment (factors affecting time, temperature, and intensity)
3. For the contact printer (type of light, adequacy of contact)

Because of their complexity, the included summary treatment of these factors may be insufficient. For the interested reader further elucidation will be found in references such as Brock (27), Mees (123), Clark (35), and Dutton (54).

The characteristic curve of a given emulsion can be obtained by exposing small segments of it to various degrees (usually by varying intensity of light while keeping time constant), processing the negative, measuring the densities of the various differently exposed segments, and plotting the densities against the logarithms of exposure. It must be remembered that the curve is strictly characteristic only under the test and processing conditions that obtain during the above procedures. A typical characteristic curve appears in Fig. 5-9. It can easily be accepted that, since such curves are affected by the conditions of exposure and processing, and also by the composition and uniformity of emulsion, then gray tones, the reciprocal, in effect, of densities, will also be affected.

Certain convenient constants expressive of emulsion characteristics are derived from the characteristic curve. These do not inherently affect the rendering of gray tones by themselves. Rather, they reflect the fact that such rendering is affected by the conditions of exposure, processing solutions, processing techniques, and character of emulsion.

"Speed," in the broadest sense, is a term expressing the reaction of a given emulsion to light. It is defined by Brock (27) as the "reciprocal of the exposure required to bring the emulsion to some chosen point on the characteristic curve, such that an *acceptable* [italics added] photograph is obtained when the darkest tone of the subject is reproduced at that point."

Howlett (81) recommends that the speed be measured at an exposure corresponding to 0.9 of maximum resolving power (Fig. 5-9). Since both resolving power and sensitivity of emulsion to light have an effect upon the registration of gray tones, speed may be considered a general criterion of such registration.

"Gamma," or "contrast," refers to the slope of the straight-line portion of the curve (Fig. 5-9). It indicates the range of densities, and hence of gray tones, that is associated with a given range of exposures. It is apparent that the lower the gamma, the more compressed is the range of densities that reflect exposures on the ground, i.e., the less the contrast and fine detail between individual tones.

"Latitude" may be defined as that range of exposures, i.e., range of light emissions from the ground (since time is constant), that can be accepted without voiding the standard of reproduction. The standard of reproduction in aerial photography is resolution of fine detail.

Emulsions having broad latitudes are likely to have unsatisfactory ranges of resolving power. Conversely, small latitudes may not satisfactorily reproduce wide ranges of tones. Large latitude and high contrast are incompatible in aerial photography.

"Fog" refers to an inherent weak density, chemically originated, that appears in the toe of the characteristic curve where the light energy has been largely ineffective. Large amounts of fog increase general density and reduce contrast between the darker tones of the subject.

"Resolving power" refers to the ability of the negative emulsion to reproduce a degree of definition, usually expressed in lines per millimeter, at the plane of the photographic image. Resolving power depends upon many things. These include the contrast of the subject, characteristics of the lens, the nature of exposure, the type of developer, the nature of the wavelengths emitted from the subject, and the nature of the emulsion itself. The net effect of a low resolving power is a loss of detail and a probable effect on tonal gradients (Sec. 5-13).

"Wavelength sensitivity" refers to the comparative response of a given emulsion to wavelengths of various frequencies. It varies in accordance with the physicochemical nature of the emulsion (in terms of the grain-size distribution and type of the halide particles) and the amount and nature of the energy-absorbent dyes. Naturally, ground features emitting different mass wavelengths will be registered in different gray tones by emulsions having different wavelength responses.

Since wavelength response and resolving power, as well as the features of the characteristic curve, are

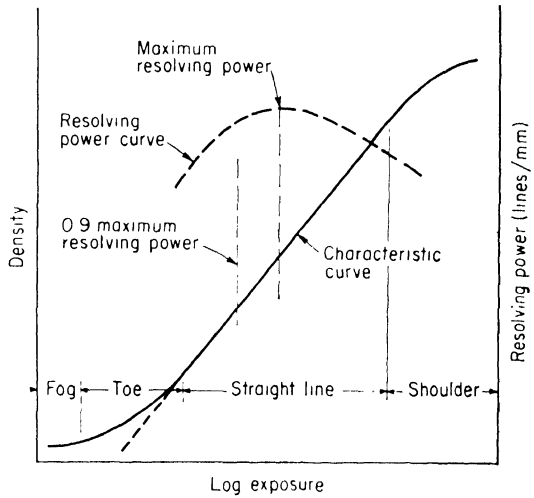


Fig. 5-9. A diagram showing the nature of the characteristic and resolving power curves, together with certain criteria of emulsion behavior that are derived from it.

related to the composition and grain distribution of the negative emulsion, this composition becomes of some moment in terms of its effect upon gray-tone registration. Obviously, the uniformity of composition and distribution must also have an effect. Finally, the size of the grains, i.e., the "graininess" of the emulsion, has a separate effect upon gray-tone patterns. Increasing graininess decreases perception of detail, particularly between areas of moderate to low contrast. Consequently, it has an important effect upon the nature of tonal boundaries (Sec. 5-13).

The characteristics of printing paper that affect the rendering of gray tones are analogous to those of the negative. Some important differences may be mentioned. Papers are slower than negatives. Their curves are different, usually more rounded. They can produce, for any given grade, only a fraction of the tones registered on the negative. They flatten out the tones at the top and bottom of the curve and exaggerate those in the mid-portion. They have an effect upon resolving power. The texture of the printing paper has an effect also upon the shape of the tonal profile. Matte and semi-matte papers cannot faithfully reproduce the same range of tones as glossy, glazed paper.

The loss of reproducibility in print emulsions, compared with negative emulsions, is a very serious thing to interpretation of tonal variations. The negative records the values in accordance with its characteristics and other factors. The print is capable of reproducing only a fraction of the tones recorded on the negative, without losing resolution and detail, and even these tones and resolutions are reproduced differently! Of course, this does not always have to be a limitation, and during the Korean War use was made of the fact that proper papers would emphasize the tonal gradations at one of the ends of the characteristic curve. Thus, details in shadow or snow, normally invisible, could be made visible.

The chemical composition of developing, fixing, and washing solutions has an effect upon the shape of the characteristic curve of the finished negative and print, and therefore upon gray-tone registration. These effects are exceptionally complex.

The image quality of the camera lens has very important effects upon resolving power, above and beyond those ascribed to other factors (see above). These effects are quite complex and variable, depending upon the type of lens, aperture, etc., and should be studied in other references. However, lenses do affect tonal gradients and the differentiation of tones having small area. Brock (27) discusses the combined effect of lenses and subject contrast on resolution:

"The importance of object contrast should be remembered when applying the results of resolution tests to actual air photography. If a lens is found to have an angular resolving power of, say 1:2,000 for detail of contrast 0.2, it will resolve from 20,000 ft. details 10 ft. apart on the ground if their contrast with their surroundings is 0.2, but much smaller objects will be seen in negative if their contrast is high enough. White objects on a black background, for example, will be resolved if they are about 5 ft. apart. Conversely, objects of lower contrast than 0.2 will only be seen in the negative if they are larger and more widely separated than 10 ft. It should also be remembered that single objects will often be recorded at sizes smaller than the limit of resolution for two adjacent objects. As the camera gets farther away from an object, its image in the negative at first gets smaller in accordance with the laws of geometrical optics, but eventually a stage is reached at which the patch of light is the smallest that the lens will give. If the camera continues to recede, the size of the image remains about the same, but its contrast with the background diminishes, since less flux enters the lens to be concentrated in the luminous patch. The distance at which the object finally vanishes in the negative depends mainly on its contrast with the background, though the contrast of the emulsion also has some influence. The shape of the image at this stage is mainly determined by the characteristics of the lens and bears little relation to the shape of the object, but it will be recorded in some fashion from much greater distances than might be expected from the resolving power as determined on Cobb or line test objects. As an example of this kind of effect, negatives taken from 10,000 ft. with an 8-in. lens will often show the white broken lines painted on roads for traffic control at corners; the individual white patches are of the order of 3 in. wide, while the ground resolution from 10,000 ft. with an 8-in. lens is approximately 2 ft. for black and white lines" (Fig. 23-1).

It must also be mentioned that the nature of the lens has an effect upon the relative amount of illumination reaching the edges of the negative, as contrasted with that reaching the center (where illumination is at a maximum).

The processing equipment for developing, fixing, and washing, whether it be of the tray, rocker, rotary, spool, etc., type, has an effect upon the shape of the characteristic curve, since it affects, in both an absolute and a relative manner, the pattern of effective time, temperature, coverage, and intensity with which the processing solutions reduce and otherwise modify the energy-charged silver halide crystals, thus revealing the latent image.

The type of light, whether parallel or diffused, has some effect upon contrast and resolution, and hence gray tones. However, this effect is relatively minor unless the negative is unusually thick.

Bad contact between negative and print, during contact printing, regardless of its cause, reduces that resolution which it is possible to obtain in the negative.

★ **5-17. Techniques of Exposure.** The techniques of exposure have some effect upon the rendering of gray tones (densities) in the photographic negative. These effects are related to (1) movements of the image and (2) nature of the exposure.

Image movements are caused by forward movement of the aircraft, its pitch and roll, and vibration within the aircraft body itself. According to Brock, "the three types of image movement acquire different relative importance under different conditions of flying and photography." These different conditions are related to the height of the aircraft, the lens used, the frequency of irregular movement, the speed of forward motion, and the time of exposure. The irregular movements (vibration and pitch degree roll) are usually combined because both increase in importance with height, while the effect of forward motion is constant regardless. The net effect upon gray-tone patterns of an improper evaluation of, and compensation for, image movements is a loss in resolution.

It should be obvious that exposure has considerable effect upon the shape of the characteristic curve. Not only does the time component of exposure have an effect upon resolution, but the amount of total illumination reaching the sensitive emulsion has a proportionate effect upon the amount of energy reaching the active silver halides, and hence the latent image and density procurable after processing. This total illumination must also be changed to compensate for lens properties, such as those mentioned in Sec. 5-16, that vary the exposure over the area of the negative.

Brock (27), in his usual admirable fashion, mentions the factors that should be taken into account in selecting an exposure:

1. Regular variations in the quality and density of daylight (distance of sun, solar altitude)
2. Irregular variations in the quality and density of daylight, due to haze, mist, clouds
3. Altitude of aircraft
4. Nature of terrain

Most of these are discussed to some extent in the following sections because, in affecting the selection of exposure, they automatically have an effect upon patterns of gray tones.

One of them—aircraft altitude—is not mentioned hereafter, and it must be said that altitude at the time of exposure not only has an effect upon resolution, but also two separate effects. One of these is the related distance of haze penetration (Sec. 5-20). The second, and less obvious, is related to scale. As Brock says, "With reduced scale the mean brightness of the image tends to rise irrespective of any increase of haze, because many of the smaller shadows tend to vanish, and within larger shadowed areas the reduction of scale produces an averaged brightness."

These effects have apparent results in terms of tonal variations.

★ **5-18. Techniques of Processing.** After a film has been exposed, it bears no visible image. Nevertheless, the light-sensitive grains of silver halide have been irrevocably affected by the energies of light emission, and they bear the invisible scars as the "latent image." These scars can be revealed only through chemical processing, i.e., the chemical reduction, fixing, and washing of the film. Not only the composition of the chemical solutions for these processes and the characteristics of the equipment used to bring the film in contact with them (Sec. 5-16), but also the technique and skill of the processor, must affect the amount and nature of the chemical reduction, and thus development of the latent image. Certainly, the time of development will have an effect, as will adequacy of fixation and reduction. Consequently, these factors also affect the available densities on the developed negative that ultimately are registered on a print as photographic gray tones.

The same remarks apply to the processing of prints. In this connection, the narrow range of gray tones that can be registered by the paper and the different characteristic curves, as well as the texture of the paper (Sec. 5-16), is of some significance, and it might be said that, for research on the terrain indications of gray tones, it would be best to use negatives or positives rather than prints.

METEOROLOGICAL AND CLIMATIC FACTORS AFFECTING GRAY TONES

★ **5-19. Regular Variations in the Nature of Daylight.** The distance that sunlight travels on its way from sun to earth varies from day to day and season to season. It might have a slight effect upon the gray-tone patterns of the same area taken at two different times of the year (other things equal). It might have a greater effect upon the selection of exposure. However, it is claimed that the difference between winter and summer sunlight is less than 10 per cent. This may be considered negligible for normal aerial-photographic purposes, although it may have significance in specialized investigations.

The solar altitude, contrarily, may be of considerable importance to tonal patterns. The solar altitude is a function of geographical location, time of day, and the sun's declination. It affects the angle at which the sun's rays traverse the atmosphere (primarily the troposphere), and therefore both the quantity and quality of light that reaches the terrain and is reflected into the camera lens.

The net effect imposed upon the registration of gray tones by differences in the quantity and quality of daylight may be easily imagined. One thing of fair importance, for example, is the fact that shadows are illuminated by skylight and nonshadowed areas by sunlight. Therefore, as the proportions of these change (as

they do with changes in solar altitude and thickness of air mass), so do the tonal proportions of the shadows.

★ 5-20. Haze (Mist, Fog) and Clouds. The natural atmosphere is never absolutely pure and clean, but always contains some quantity of minute particles of foreign matter in normal or Brownian suspension. These suspended particles are called "aerosols."[6]

Aerosols may consist of both solid and liquid matter. The solid matter may consist of minute to fairly large inert particles of volcanic efflata, sand, domestic and industrial fire ash, salt crystals of various types from the sea, playas and tidal flats, and organic particles. Actual organisms such as molds, spores, and bacteria may qualify. In many cases, these particles act as nuclei for the condensation of water films. Sulfur trioxide (a combustion product of coal) and salt crystals are particularly active in this regard. Brock concludes that haze is largely and generally a mixture of inert dust particles and droplets of salt solution.

Naturally, being in suspension, aerosols are responsive to air currents and migrate around the world in accordance with such currents.

The aerosols, in their various concentrations, are responsible for the phenomena known as haze, mist, fog, and even clouds.

A good description of the general photometric effect of haze on aerial photography is provided by Brock (27):

"A beam of light passing through the atmosphere suffers a certain attenuation by the loss of the scattered radiation. In general the attenuation will be greater for longer paths and higher concentration of scattering particles. With no absorption there is no loss of energy, and all the scattered light reappears after repeated rescattering as a general diffuse illumination of the medium. In photographing over long ranges or from great altitudes the light reaching the camera from the ground is appreciably attenuated. Even more important is the effect of the light scattered upwards from the haze, as this plays no part in image formation and merely lowers the contrast of the scene. Suppose we have two objects on the ground, of different brightnesses, B_1 and B_2. Their contrast is expressed by $B_1 B_2$. Both suffer the same proportional reduction in brightness when seen through the haze, and the same amount of general light is added to each. The apparent brightness ratio when viewed through the haze is therefore $(AB_1 + h)/(AB_2 + h)$. So long as any light is scattered upwards, this expression will be smaller than B_1/B_2, and it tends to unity, i.e., to zero contrast, with increasing scatter."

[6] For some interesting data, see Middleton (128), who also discusses past investigations of aerosols to some extent and describes extremely clever experiments by Dessens in which he used microscopic spider-web filaments (10^{-6} centimeter) for capturing and observing haze particles.

Excellent discussions of haze effects are provided by Brock (27), Middleton (128), Bullock (29), and Tupper (208). Most of these presentations treat of details beyond the scope of this chapter. The chief interest here is the effect of haze upon tonal patterns. In general, the effect is a loss of contrast, or, as Brock says, "a reduction of the effective brightness range of the subject, which not only makes the larger details difficult to see but inevitably lowers the resolving power and makes some details disappear altogether. Both of these effects are relatively more serious in the darker tones of the subject, and although loss of contrast can be offset by appropriate photographic techniques nothing can be done about the lowered resolving power." (See also Sec. 5-15.)

Haze not only affects gray tones as they appear in the print, but also the density gradient between tones, whether the boundaries be sharp or gradual in nature (Sec. 5-13).

Clouds, according to various investigators, seem to have the general effect of increasing the tonal brightness in existing shadowed areas and deepening the tone of previously unshadowed terrain within their own cast shadow. Because aerial photography is seldom taken with cloud cover, it may be considered to have little significance to gray-tone patterns except in special cases.

★ 5-21. Effects of Season on Terrain. In addition to the effects of season on sun distance and angle, there are certain direct effects that it has upon the terrain itself.

The apparent direct effects are related to changes in the tonal qualities of the vegetative ground cover and the appearance or disappearance of snow.

The not-so-apparent direct effects are related to seasonal changes in the average surficial moisture content.

The appearance of foliage in certain seasons, and disappearance in others, or changes in foliage types, colors, textures, reflectance, emission, etc., are simple facts. In this book, discussions, references, and illustrations of greater or less pertinence occur in Secs. 5-3, 5-4, 5-22 to 5-26, and 19-13 and Chap. 22. The subject of gray tones as an indicator of natural soil-moisture-organic content and of the qualitative effect on them of seasonal change is discussed in Sec. 5-6.

COLOR FILM

5-22. Nature of Color Film. There have been, and are, many types of aerial color film manufactured throughout the world: Kodacolor Aero Film for Reversal, Anscocolor, Agfacolor, to name a few. Of all these, the one that seems to receive the most use, almost exclusive in the Western Hemisphere, is Kodak Ektachrome Aero Film

(prior to 1950 known as Kodacolor Aero Film for Reversal). Tarkington (191) has discussed this film and some of its characteristics that affect interpretation.

Kodak Ektachrome Aero Film (High Contrast) is an incorporated-coupler, multilayer, or monopack, type of color film which is reversal-processed by the customer to yield a positive color transparency. In a multilayer, or monopack, type of film, three emulsions are coated on a single film base, the emulsion next to the film base being sensitive to red light, the middle emulsion sensitive to green light, and the top emulsion sensitive to blue light. The red-sensitive emulsion layer has incorporated in it a chemical compound, known as a coupler, which reacts with certain developing agents in the oxidized state to form a cyan dye, the middle layer has incorporated in it a coupler which yields a magenta dye with the same developing agent; and the top layer has incorporated in it a coupler which yields a yellow dye with the same developing agent. . . .

The colors produced, therefore, by the type of color film just described are some combination of the three dyes formed in the film during processing.

His dissertation indicates an important fact about color photography, namely, that, at present, it does not reproduce hues and saturations (i.e., the spectrophotometric characteristics of objects photographed) either as they actually occur or as they are interpreted by the human eye:

The spectrophotometric characteristics of all colors reproduced by this type of color process are the sum of the spectrophotometric characteristics of the quantities of the three dyes formed by the process for the particular color in question. There is no direct simple relationship between the spectrophotometric characteristics of the color formed by the process and the spectrophotometric characteristics of the color of the object photographed.

. . . It is important, however, for interpreters to understand the limitation of color photography in reproducing the spectrophotometric characteristics of objects and to realize that determining the spectral characteristics of a color photographic reproduction of an object does not constitute a necessarily unique identification. Perhaps the simplest procedure to follow in determining the usefulness of color photography in identifying or distinguishing objects is to photograph the objects with the color process that is to be used. In this way, all the factors which affect the photographic reproduction of colors—and there are a number of factors not discussed here—will be taken into consideration. If differences between objects are evident in the photograph, these differences can be enhanced by the use of filters and also by further photographic manipulation.[7]

The inaccuracy mentioned by Tarkington is further complicated by atmospheric haze, which changes hue and saturation even beyond that extent attributable to the sensitivity of the various color layers.

5-23. Use of Color Photography—General. In recent years, a controversy has developed concerning the comparative usefulness of aerial color versus "black-and-white" photography in terms of their applications to engineering and resources mapping. This debate has been highlighted by the emergence of some opinion that seems to recommend the general, all-purpose use of color photography as a substitute for black-and-white.

It must be admitted that aerial color photography, properly used for certain specific purposes, can be of great value to the aerial-photographic field. However, in the author's opinion, this fact does not justify the dissemination of an erroneous conclusion to the effect that color photography has already (early 1958) reached a state of development and usefulness where it can replace panchromatic film for general and indiscriminate use.

The contrary is true, and the following two sections discuss some of the reasons.

5-24. Practical Use of Color Photography—Procurement, Processing, and Handling. The time, during any given day, that is suitable for securing satisfactory color photography is much less than that for obtaining panchromatic, being in the approximate, average ratio of 1:2. The lesser time available for color photography is a function of the slower exposure speed, smaller exposure latitude, and, to some extent, the rendition of tones on color film.

The practical result of this lesser available time for color photography is that, for any given scale and suitable photographic day, the amount of aerial coverage that can be completed in color is substantially less than that which can be completed in panchromatic. Since most aerial-photographic contracts involve certain per diem charges that are independent of time in the air, it would seem obvious that color photography of any given area at any given scale would be considerably more

[7] The latter is far from being an objection, since the registration of color by various people's eyes is certainly not constant. However, it is difficult to avoid reference to this "practical" standard.

expensive than the same product in panchromatic.

In addition, and particularly in humid and tropical areas where diurnal topographic and climatic factors generate appreciable haze, the number of days during which good color photographs can be obtained is small indeed. In some areas, e.g., Venezuela, only 2½ hours per month may be expected as compared with 7 hours for black-and-white.

Again, the practical effect of this limitation is a substantial and unpredictable increase in the amount of stand-by charges accrued by color photography in comparison with those accrued by panchromatic.

The exposure of color film is critical. Altitude and haze effects must be properly evaluated. This is not always easy, particularly with respect to haze. In addition, if high-quality color rendition is desired, requirements for slow shutter speed, wide-open aperture, low altitude, and an excellent lens are automatically assumed.

The practical effects of these requirements are an increase in costs and decrease in efficiency, due to the imposed limitations on personnel and equipment; the decreased latitude that can be allowed for field operations; and the tendency toward image movement that accompanies low-level, slow-speed, large-aperture exposure.

It might be mentioned that the wide-angle lenses generally required for aerial photography have a "hot spot" in the center. In panchromatic photography it is possible to compensate for this with a chromalized filter, but in color photography it is not. The practical result is often a condition whereby the corners of color photographs appear dark, while flare causes deterioration in color rendering. (Modern camera lenses have done much to minimize the "hot spot" effect.)

It should also be emphasized that except in certain areas of the world, high-level, small-scale photography is usually unfeasible with color photography because of haze effects, while such photography can be taken with panchromatic film. Since high-level photography has the lowest cost per square mile and the widest coverage per unit of time and is a normal reconnaissance technique, color photography loses a wide range of usage by virtue of its inability to service this need.

Processing and Handling. As might be expected with a three-layer emulsion, the processing of color film is quite critical and requires great care. Hence, there can be less latitude in both field and base operations.

Color film requires more care in handling and storage than panchromatic. It should not be kept on hand, unexposed, for as long a period, and hence requires more frequent purchase. It is also more susceptible to fungus growth. The practical result is an increase in laboratory costs and a decrease in laboratory efficiency as compared with the processing of black-and-white materials.

Finally, duplicates of color transparencies are far more troublesome to make than are prints from panchromatic film, and color prints, at the moment, are practically unobtainable.[8] The net result is a slowdown in use due to lack of sufficient sets of prints.

Further, dyes in color film have a tendency to fade when continually exposed to daylight or any other light source rich in ultraviolet frequencies.

5-25. Practical Use of Color Photography—Photogrammetric Operations. It may be possible to prepare adequate black-and-white diapositives from color transparencies to allow accurate topographic mapping by photogrammetric methods. However, to the best of the author's knowledge at the time of publication, evidence that this possibility is an accomplished fact is insufficient. Until the body of such evidence is greater, he must admit to being dubious that such a process is, as yet, both feasible and satisfactory.

In any event, panchromatic film will do the same job, but better and at less cost. Therefore the only reason for using color photography in such activities is that based upon its *extra value* for *other uses*, such as interpretation. In the following section, it will be pointed out that such extra value is immediately apparent in only certain instances.

5-26. Practical Use of Color Photography—Interpretation. Both panchromatic and color photography can be used effectively to conduct photographic interpretation. The point of discussion in this section is whether color photography is better than panchromatic for such a purpose.

The author must admit to the opinion that the *general* answer to this point of discussion is "no."

The author has not used color photography to a great extent. He has used panchromatic for years. Perhaps his opinion is therefore somewhat slanted. However, he has not seen many cases of *ordinary* application where the job that can be done with color photography cannot be as well, or

[8] This does not mean to say that the production of color prints may not soon become practicable. See Sec. 5-26.

better, accomplished with panchromatic film. Perhaps the results are related to the fascination that colors have for the human brain. One becomes lost in the colors and neglects significant details. The colors have a tendency to disguise the detail. Panchromatic pictures, on the other hand, provide no distraction to the interpreter and force him to use his head in addition to his eyes.

Of course, this disadvantage must be added to those above-mentioned ones associated with expense, exposure, processing, and handling during interpretation.

There are special applications where color photography can be very valuable to interpretation. These include the following:

1. In geological mapping (Sec. 16-11)
   a. Where extreme detail concerning variations in rock types, colors, and contacts are required (particularly in arid regions, where even high-level color photography is possible, and in forested regions where the ground can be seen through the trees). This type of mapping includes mineralization studies and, if expense is an object, should be confined to localized areas chosen from panchromatic interpretation.
   b. Where expense has no significance.
2. In geochemical and geobotanical studies (Chap. 22)
   a. Where the probability of color significance is high.
3. In forestry studies (Chap. 22)
   a. Where extreme detail of differentiation or special facts, e.g., location of disease-stricken areas, are sought. These applications are particularly enhanced in areas of selective and progressive seasonal change and if consideration is given to such color-film variants as Aero CD (Sec. 5-28).
4. In specialized ecological studies (as above).
5. In detailed land-use studies where differences in growth patterns at the time of exposure are of significance (Chap. 21).
6. In certain river, harbor, and coastal studies where water and current variations may be expected to be reflected in terms of tonal variations (Chap. 18).
7. In certain military studies (Chap. 23).

It will be noted that the above list includes very little in the way of engineering applications. No doubt, however, these applications will increase in both number and effectiveness. It may therefore be wisest to subscribe to the statement of Brock (27):

> Air photographs in colour can be exceedingly attractive to look at, and their fascination is apt to obscure the fact that they may convey no more information than a good monochrome, and sometimes less. It is not suggested that there is no place for colour in air photography; a really satisfactory process, giving paper prints in unlimited numbers with the same ease as black and white, and requiring the same camera exposure, would obviously be invaluable, but there is no such process as yet and no likelihood of one appearing. As things stand at present colour photography has definite disadvantages, and in general it can only be used for special tasks under favourable conditions.

It must be understood that such research and experimentation are being carried out on the use and improvement of aerial color film. For example, there is now available a Kodacolor film from which colored prints may be obtained directly. This is a negative material, and, by using it, most of the difficulties encountered with transparencies can be eliminated. If this material proves to be satisfactory in practice, it will represent a substantial step forward in the use of color. The new Veljay method may also be the awaited answer.

Because of continuing research, and its results in terms of products such as the above, the remarks of this section must be considered to indicate the current, commercial status of color use, rather than the future, or theoretical, status. Consequently, the statements given are subject to change, although it is the author's opinion that procurement, exposure, and interpretative disadvantages of color film will be with us for a long time.

INFRARED FILM

5-27. Nature and Use of Infrared Film. The infrared portion of the spectrum extends from about 0.75 to about 100 microns. Emanations from this portion are invisible to the human eye. Some photographic "emulsions" can be made that are sensitive to a small part of the infrared, say, 0.75 to about 1.3 microns. Aerial infrared film, because of considerations related to stability and "speed," has even less latitude and is generally fairly sensitive to a range of wavelengths between 0.75 and 0.9 micron. In addition, it has sensitivity to the entire visible spectrum.

Infrared film has two major characteristics that

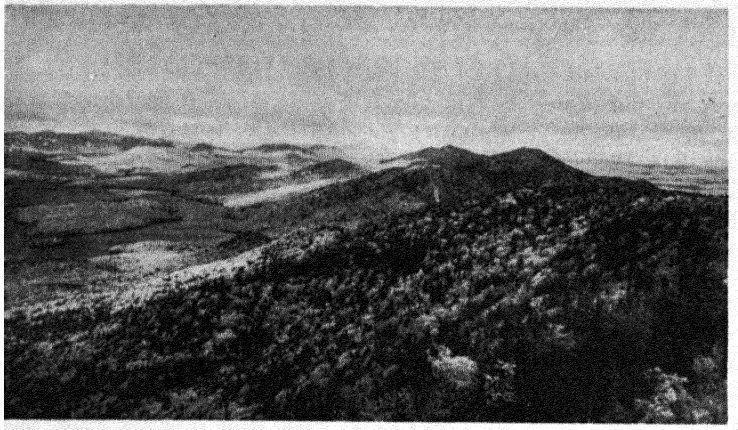


Fig. 5-10. An infrared oblique showing the effect of chlorophyllic reflection in rendering green vegetation light gray to snow white. See also Fig. 5-11.

Fig. 5-11a. This shows normal panchromatic rendering of roads (*R*), muddy water (*W*), and clean water (*C*), green trees, dry soil (*D*), and sun reflection on water (*S*).

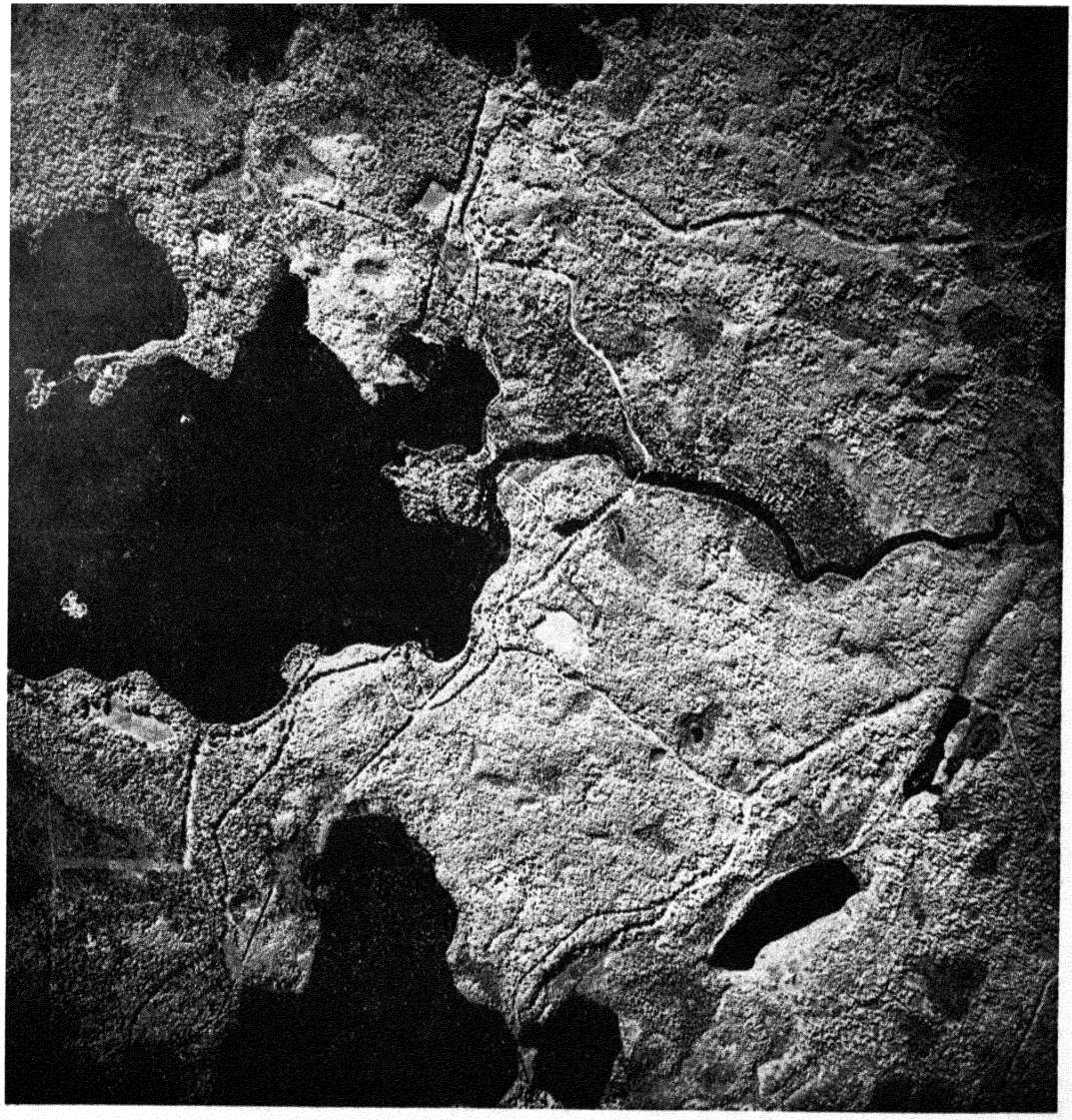
(*a*)

are of interest to aerial-photographic interpretation. These are associated with unusual tonal rendering and increased haze penetration.

Infrared film gives a very light rendering of green vegetation (the "chlorophyll effect"). In all cases, the rendering is lighter than that of panchromatic film, and in some cases (Figs. 5-10 and 5-11), certain vegetation may be as light as snow. All green vegetation contains chlorophyll. This chlorophyll has an effect upon spectral reflectivity.

Fig. 5-11b. This photograph, in infrared, shows the same area at a different scale and illustrates the chlorophyll effect, as well as the dark rendering of water. (*Wisconsin.*)

(*b*)



The typical curve of reflection density versus wavelength shows that maximum reflectance in the visible spectrum occurs in the middle green; minimum reflectance in the low red; and a very high emission in the low infrared. This emission is much higher than in any portion of the visible spectrum.

Green vegetation reflects only a small proportion of incident light even in its area of maximum reflectance. Further, this area of maximum reflectance does not correspond with that of maximum panchromatic sensitivity. As a result, green vegetation is rendered in dark tones on the panchromatic air photo (while dead vegetation—brown, yellow—registers light). In the infrared zone, green vegetation reflects a considerably greater amount of incident light, and on infrared film, this corresponds with an area of high sensitivity. Consequently, on infrared film, green vegetation registers light.

Various types of green vegetation, including flowers, fruit, leaves, grass, shrubs, etc., photograph light in infrared. However, the spectral emissions of different types, in different physical states, may be said to have slightly different light registrations on infrared. Curves for various types are included in Clark (35), Bäckström and Welander (4), and others. One exception to the general rule is the registration of coniferous needles. These, for some reason, are rendered *dark* on the infrared film. Brock (27) concludes that the reason is the physical configuration of the needles.

Water is also rendered dark by infrared (Sec. 5-5), and shadows are emphasized, though detail within the shadowed area is lost.

The haze penetration of infrared film is superior to that of panchromatic, but according to Clark and Brock, much less so than is commonly believed. Brock cites the work of Rayleigh, Middleton, Foitzik, Harrison, Hurlburt, Hugon, and Mohler to show that for conditions of fog or dense haze, scatter is almost independent of wavelength and that infrared photography would increase a visual range of 1 mile to only 1.1 mile, whereas an increase to 8 miles would correspond with good visibility. As he says:

> This is not to say that infra-red photography is useless, but merely that it will not increase to any striking extent the range at which average-sized objects as distinct from natural features can be recorded. In practice there is always some gain in clarity by using light of longer wavelength, even in heavy industrial haze, but it is not spectacular, and has to be balanced against the lower resolution due to larger lens apertures and/or slower shutter speeds necessitated by the deeper filter or by the lower sensitivity of infra-red film.

Further, Brock points out that the *apparent* improvement in clarity that is exhibited by infrared photography is due to the chlorophyll effect whereby the contrast between chlorophyll-bearing and non-chlorophyll-bearing material is enhanced:

> In general, then, the "haze-penetration" of infra-red photography is most frequently due to enhanced contrast in the subject caused by the unusual rendering of water and green vegetation. The effect is no less useful for being spurious, but if it is not understood, the possibilities of infra-red cannot be appreciated at their true value. The greatest improvements in "haze penetration" are to be expected when photographing well-grassed terrain, especially in early summer when the green is at its brightest, and most saturated. There is always some improvement even over completely built-up areas, but it is not possible to predict just what infra-red will do or when it will be worth using, since this is ultimately a matter of opinion and must be based on personal experience. The improvement over smoky industrial cities is sometimes rather greater than might be expected from the visibility, due possibly to small-sized combustion particles in the haze, but the photographs of such areas on infra-red film on a hazy day never approach in quality those taken on panchromatic film on clear days. If clear photographs are required of a hazy industrial area the best policy is to wait for clear weather and use panchromatic film.

In view of the above discussion, the value of infrared would seem obvious. It may be used, under favorable atmospheric circumstances, to enhance the contrast between chlorophyllic and nonchlorophyllic substances; to emphasize shadows, "map detail" such as roads, canals, etc., and coniferous or deciduous foliage; to differentiate between some types of deciduous foliage (Chap. 22); and to emphasize water areas and shallow-water–mineral boundaries. Most of these applications are highly specialized and have only limited application. As Brock says of infrared, "it is too valuable to abandon, but not good enough to use."

CAMOUFLAGE DETECTION FILM

5-28. Camouflage Detection Film. Within the past seven or eight years, a new film, called CD Ektachrome Aero Film, has been produced by the Kodak Company. CD film differs from conventional color film (Kodak Aero, Sec. 5-22) in that the top layer, usually sensitive only to blue light,

Table 5-2. Probable True Colors as Rendered on CD Aero Film (After Bennett)

Color on CD film	Probable true color of subject	Probable magnitude of infrared reflectivity
Red	Blue or black	Some
Brown to black	Blue or black	None
Magenta	Green	Some
Blue to bluish purple	Green	None
Yellow	Red, brown, deep orange	Some
Green	Red, brown, deep orange	None
White	White or yellow	Some
Cyan	White or yellow	None

has been replaced by one sensitive only to infrared radiation.

It is obvious that this substitution will reproduce features of the terrain in accordance with a system of false colors that is above and beyond the "normal" color distortion of most color films (Sec. 5-26). This system of false colors is related not only to the fact that one important part of the emission spectrum—the blue—cannot be recorded by the film, but also to the fact that various colored objects emit different patterns of infrared energy. It might also be mentioned that visually similar colors may have quite different infrared emissions.

Bennett (16) has indicated the probable colors registered on CD film, as well as their *probable* true color and extent of infrared reflectivity (Table 5-2). It has been pointed out that slight variations in CD rendering do not necessarily indicate similar variations in infrared reflectivity. This is due to the variety of factors that affect rendering, among which are lighting conditions, time of day, season, type of lens, and processing techniques. Section 22-15 records further data on the CD rendering of specific features.

Brock (27) suggests methods whereby special color processes could be used to exaggerate certain kinds of detail.

Colwell (38) has reported on some extremely interesting studies in which panchromatic, color, and CD films were used comparatively.

6 MISCELLANEOUS ELEMENTS

6-1. Explanation of Miscellaneous Elements. In accordance with the dictionary definition, miscellaneous elements of the aerial-photographic pattern consist of diverse things, are heterogeneous, have various qualities, and deal with diverse subjects. They cannot be further described, both satisfactorily and concisely and also in a collective sense, except by saying that *they are the aggregate of all features appearing upon the photograph that may be conveniently separated from the patterns of landform, surface drainage, erosion, and natural gray tones.*

It would be quite logical to discuss each of the miscellaneous elements under a separate chapter heading, rather than discuss them in a single chapter, as is done herein. The latter treatment has, however, been chosen for two reasons: (1) Separate-chapter treatment would assign an importance to each of the elements that usually is not deserved in comparison with that of the four major elements. (2) Separate-chapter treatment would lead to excessive length.

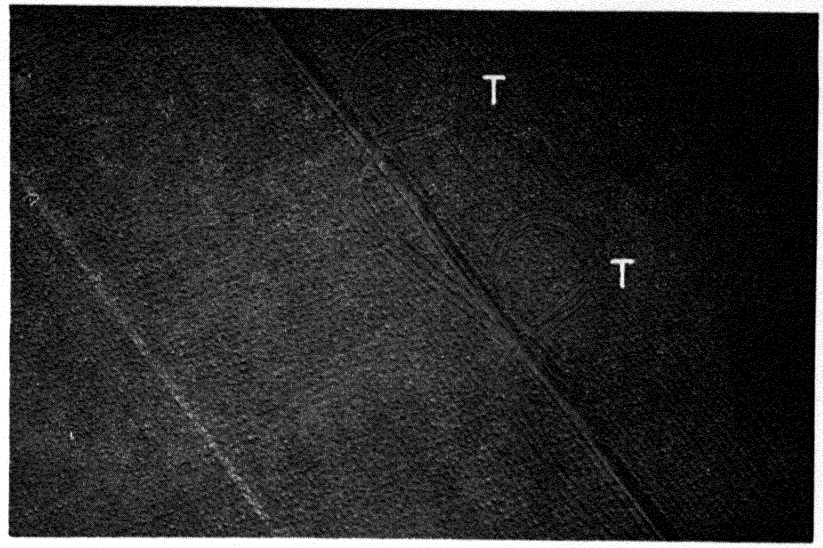
The first reason is one implication of the words "conveniently separated." The separation and convenience are often arbitrary, but they are based upon a generalization that the significance of a miscellaneous element to proper interpretation of qualitative terrain conditions is *usually* less than that of two or more major elements. *Occasionally*, a miscellaneous element has dominant importance, but this is not the rule.

The second reason is also important. A complete treatment of some of the miscellaneous elements, e.g., vegetative features and patterns, would involve such variety that it would truly be "exhaustive." The features, patterns, and significance associated with the other elements approach equal variety.

For these reasons, this chapter is brief, being largely devoted to general discussion.

(a)





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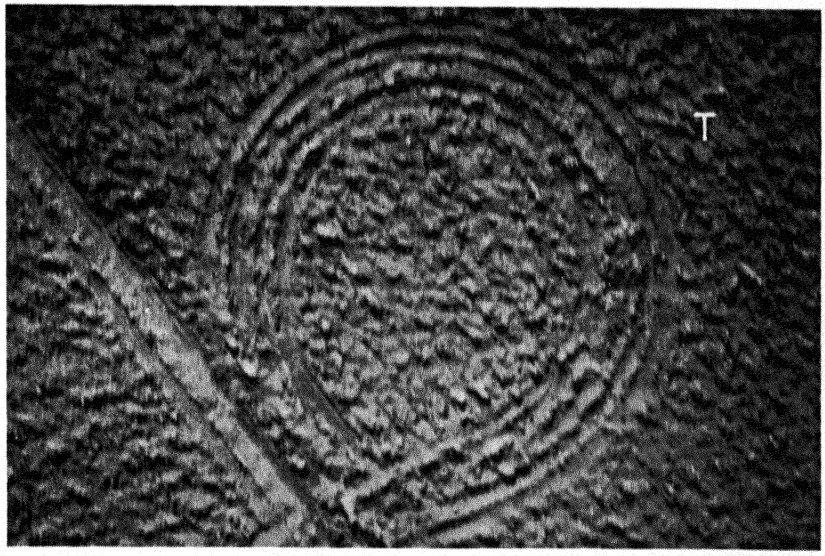


(c)

Fig. 6-1. Examples of the detail attainable with very large scale aerial photography. The pictures show cultivation furrows, dead furrows (for drainage), and tractor tracks T. The scales are approximately 1:720, 1:500, and 1:125.

6-2. A Listing of Miscellaneous Elements. The miscellaneous elements may be listed (classification would be difficult) as follows:

1. Vegetative features and patterns
2. Cultural features and patterns
3. Natural slopes
4. Boundary characteristics
5. Fourth-order topographic features or patterns
6. Microterrain features and patterns that are not topographic

6-3. Vegetative Features and Patterns. Vegetative features and patterns refer to the complete vegetative complex as it is developed upon the land. This includes both natural and cultivated

vegetation, although the latter often may be more properly considered as a part of the cultural features and patterns.

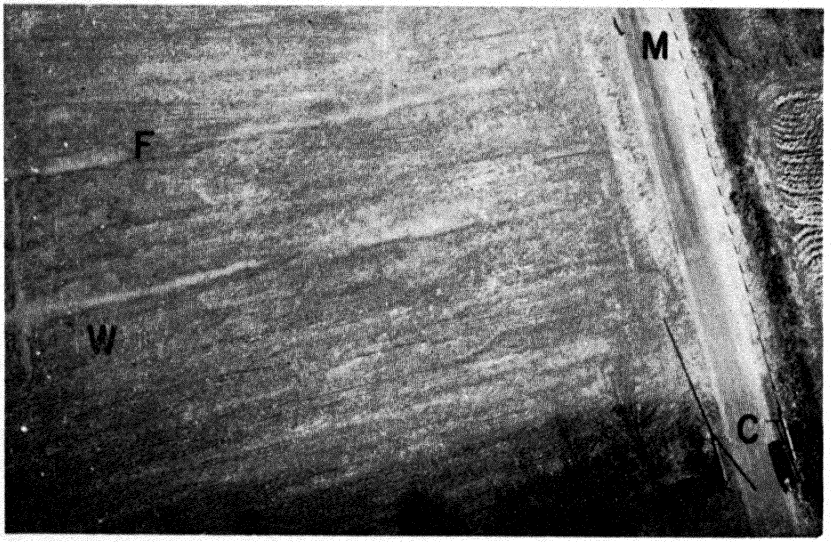
Considering the broad variety of grasses, shrubs, and trees and their permutations in terms of association, tolerance of conditions, selective and broad response to terrain positions, climatic factors, soil characteristics, and water conditions, it is easy to see that, even at normal air-photo scales, the variety of vegetative features, patterns, and significances is truly infinite.

This infinity does not mean that an examination of vegetative features and patterns is valueless. The contrary is true. Definite selectivities and pattern associations do exist, in all climates, but most particularly in extreme ones such as the subarctic, tropical, and arid (Chaps. 15, 21, and 22). These associations are of great aid in evaluating practical terrain conditions of many types: general patterns of climatic normality may be studied and their gradations related to gradations in terrain conditions; absence or presence of specific species may indicate the absence or presence of general terrain requirements, etc.

A general knowledge of botany, ecology, and forestry is desirable for the effective interpretation



(a)



(b)

and use of these associations. A further knowledge of normal regional vegetative features and patterns, as well as of the factors affecting their presence, absence, variation, and development, is of even greater value.

Unfortunately, such knowledge is seldom at hand for most terrain specialists, and as a result, much of the interpretative value of vegetative details is undoubtedly being lost. In time, however, this condition should improve.

Chapters 15, 16, 19, 21, and 22 illustrate and discuss some examples of vegetative details and their significance.

6-4. Cultural Features and Patterns. The case for cultural features and patterns is almost identical with that for vegetative details. There is an infinite list of permutations involving land use and disuse, as related to natural terrain qualities of topography, soil-rock characteristics, water conditions, and climatic factors, *complicated by considerations of tradition and economy as interpreted by man's understanding and developed through his ingenuity.*

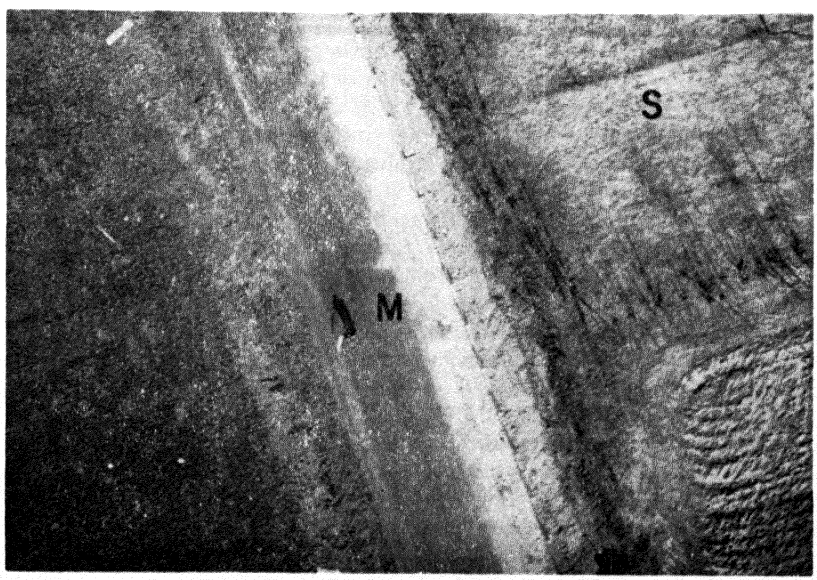
It appears obvious that a proper interpretation of cultural features and patterns will provide selective and general qualitative terrain information of a practical nature and will also give a better understanding of those portions of the complete air-photo pattern that are reflections of tradition, ingenuity, or climate, rather than terrain conditions. Such interpretation depends upon a regional knowledge of culture and cultural practices that should be greater than is normally the average.

Illustrations and discussions of cultural patterns appear throughout the book.

6-5. Natural Slopes. The slopes of materials in their natural angle of repose, or their temporary state of stability, often have great significance in interpreting predominant textures, extent and type of stratification, etc. Much of the significance of slopes to interpretation is related to the theories and observations discussed in Chap. 4 for gully cross sections. Admittedly, this is imperfect and requires more research, observation, revision, and supplementation. Nevertheless, an *experienced* interpreter can often gain extremely valuable clues from an evaluation of natural slopes in both their repose and freshly eroded states.

6-6. Characteristic Boundaries. It has been observed, either definitely or tentatively, that certain types of materials have characteristic boundaries.

A characteristic boundary may be defined arbi-



(c)

Fig. 6-2. These photographs demonstrate the effectiveness of very large scale photography. Among the details shown are footprints *F* in the soggy soil, standing water *W*, a man *M* (the author), a car *C*, and cornstalks *S*. Scales are approximately 1:750, 1:500, and 1:325. For more large-scale examples, see Chap. 22.

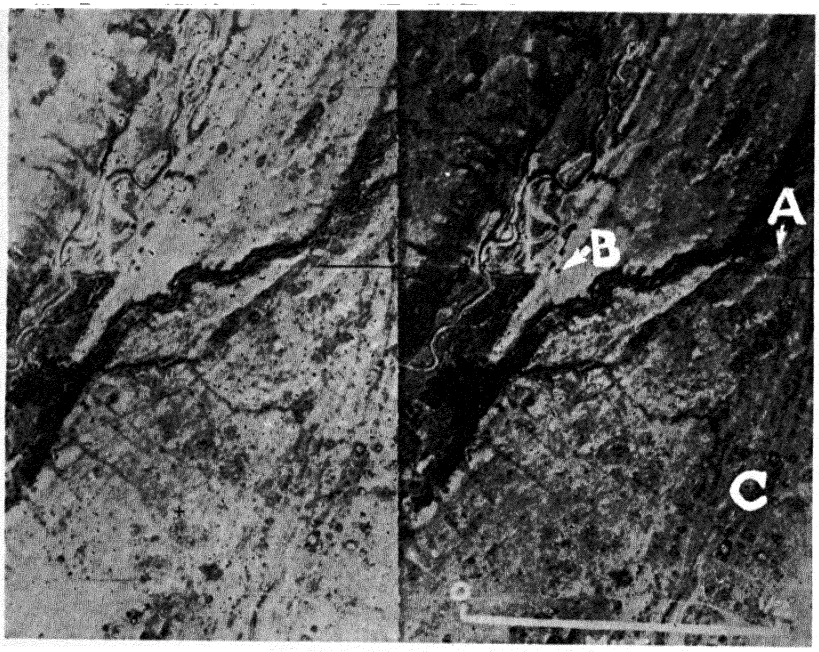


Fig. 6-3. A stereopair in a glaciated plain. The small dots *B* and *C* surrounded by trenches are huge boulders. The trenches were reputedly made by buffaloes scratching their backs. This has no practical significance today, but argues for the ingenuity of the buffaloes. *A* indicates a usable boulder accumulation. (*J. D. Mollard selection.*)

trarily as *one having a habitual, typical aspect that is intimately related to the physical characteristics, or formation, of the natural materials on one or both sides of the boundary.*

Characteristic boundaries may be of a planimetric-topographic nature, a tonal nature, or a combination of both.

Characteristic boundaries having a planimetric-topographic nature are those whose shape (macro- or micro-) and vertical aspects have significance to an interpretation of the materials on one or both sides of the boundary. They are almost completely confined to consolidated rocks, particularly of the igneous variety where the conditions of injection, extrusion, rate of cooling, etc., have an effect upon the degree of viscosity, type of crystallization, etc. Occasionally, the sharp break in topography at the boundary between two types of consolidated or unconsolidated materials may be properly considered as a topographic boundary characteristic.

A few examples of characteristic boundary having a planotopographic nature are illustrated in Chap. 16 under the headings of igneous extrusives (basalt, rhyolite, lava), certain metamorphics (serpentines, slates), and one igneous intrusive (granite). It is probable that other types of consolidated rocks also have characteristic boundaries.

Characteristic boundaries of a tonal type do not mean differences in absolute or relative tonality between dissimilar materials. Such differences, for any given pairs or patterns of tonality, may occur in connection with a variety of materials. Consequently, they are not significant and, in any case, may be evaluated in terms of the discussion of Chap. 5.

A characteristic tonal boundary implies typical gradients and/or shapes of tones and tone patterns. Tonal boundaries—at least to the writer's knowledge—are best developed in unconsolidated materials. A discussion and illustration of them are included in Secs. 5-13 to 5-14.

6-7. Fourth-order Topographic Features or Patterns. Sections 2-23 to 2-26 discussed the various orders of relief, and it was shown that the von Engeln system of classification recognized three orders, of which the smallest, the third order, encompassed topographic features of comparatively

low degree and permanence, i.e., individual hills, valleys, cliffs, depressions, etc.

This classification, and this lowest order, may be satisfactory for geomorphology, but not for practical interpretation. There is quite a distinction, e.g., between the relief orders of a valley, a sinkhole, a remnantal oxbow lake, a lava pocket, and a basalt surficial vesicle or blister; or between a tall cliff, a small cut bank in alluvium, a beach ridge, a bar, and a braided channel scar. In each case, the latter four features may be considered third-order forms by general definition, but are smaller than the more common examples of such forms. Further, the latter features often are repetitively arranged on the surface of some definite land form or rock type and, being genetically related to its formation and characteristics, aid in both its identification and analysis.

Since the entire classification of relief orders is arbitrarily designed for convenience, the writer suggests the concept of fourth-order relief forms (or patterns): *relatively small to exceedingly small features having definite topographic expressions that are usually, but not always, genetically related to the composition and/or formation of the material or landform in which or on which they occur, often repetitively.*

It seems apparent that a recognition and analysis of such forms are invaluable to proper air-photo interpretation. Numerous examples appear throughout Part II.

6-8. Nontopographic Microfeatures of the Terrain. There are many and varied features of the terrain that are not, except in the smallest way, topographic, but are nevertheless visible on aerial photographs. These features have wide variety, including such items as the visible indications of insect activity, animal activity, buried bedding planes and structures, sand drifting, age mottling, chert occurrences, variable overburden conditions, etc. These features are difficult to categorize, but to the interpreter who knows, or is able to adjudge, their significance, they are important in evaluating or outlining specific and general terrain conditions.

6-9. Summary Regarding Miscellaneous Elements. Miscellaneous elements, being of infinite variety and associated with regional, formational, climatic, human, and animal factors, are almost impossible to classify. Nevertheless, they are of great value to terrain evaluation in many specific and general ways. Usually, to interpret them properly, the interpreter must have specialized knowledge, regional experience, or intuitive appreciation. As a result, their recognition and effective use must be the result, not only of formal training, but also of geographically broadly based practice and field activities. They should be used with caution.

7 BACKGROUND—TRAINING, EXPERIENCE

7-1. General. It is the purpose of this chapter to discuss background. The discussion considers various departments of knowledge that contribute to the effective use of interpretation by the professional man who recognizes its value in whatever terrain field he may be specializing. Experience is briefly discussed. Lastly, an opinion is given concerning the nature of the training that is desirable for specialization in terrain analysis.

The interpretation of individual elements and their proper combination can be accomplished only through professional capability. The interpreter must be able not only to recognize the infinitely variable, significant characteristics of the air-photo pattern, but also to reduce them to a logical and reasonable whole.

Interpretative theories provide the basic tools. Background, in the form of academic knowledge, photo experience, and field experience, provides the supplemental, or "polishing," tools.

While proceeding through the chapter, it will be noticed that an academic background is considered necessary in *different* fields of earth science, even though a degree of specialization in a single field is definitely productive of better interpretative information for that field. The words "different fields" imply the author's conviction that interpretation should not be compartmentalized—like some organizations where specialists labor obscurely in specialized divisions of specialties only to bring forth the harbingers of further specialization. Such compartmentalization, while it may have justification in some scientific fields, has none in the interpretative field. Rather, it defeats the very idea—that of assembling all the terrain elements, correctly interpreting their significance, and combining them in a recognizable and dependable set of conclusions. It also defeats a further real objective of aerial-photographic interpretation: *the gradual evolvement of the true terrain specialist.* This latter person is one who, through the necessity of acquiring a sufficient background for interpretation, and through long experience in exercising that background, with aerial photographs in different areas and climes, has attained a truly integrated knowledge of the land—a true approach to ecological understanding.

7-2. Various Departments of Knowledge. The departments of knowledge that will be considered in this chapter are the geological, soil, botanical, meteorological, and coordinative sciences.

7-3. The Geological Sciences. The geological sciences comprise a rather broad field of interest that may be divided into two broad classes and a number of subdivisions or specialized subjects.

1. Natural and theoretical geology
   a. Physical geology (petrology, lithology, petrography, mineralogy, structural geology, sedimentation, geomorphology)
   b. Historical geology (paleontology, stratigraphy)
2. Applied geology (economic, mining, engineering)

Physical geology is concerned with the materials and features of the earth, together with their methods of occurrence, in all their natural and theoretical connotations.

Historical geology is concerned with the history of past events in terms of their sequence (stratigraphy) and life (paleontology). It must, of necessity, include all the facts and principles developed in physical geology, but extends them into its own field of interest.

Applied geology is concerned with the occurrence of, exploration for, extraction of, and other practical significance of minerals and rocks having either economic value or engineering pertinence.

It includes all the principles developed by both physical and historical geology, but adds its own compendium of information and experience.

To the aerial-photographic interpreter, a knowledge of physical geology, in its various subdivisions, is of utmost importance (Chaps. 9 to 16). Knowledge of historical geology is of little importance, and that of applied geology is of frequent importance (Chaps. 19 and 20). Physical geology only will be considered in the following sections.

7-4. Petrology (Lithology, Mineralogy, and Petrography). Petrology is a fairly broad study having to do with the origin, occurrence, composition, and classification of rocks. Occurrence is of considerable importance. Lithology is an equivalent term for the similar study of unconsolidated materials (both terms imply, in addition, a study of the rocks and of materials as they occur *in situ*, i.e., their sequence, gradation, partings, etc.). The definitions are rather arbitrary, since petrology can include unconsolidated materials (sedimentary petrology) and lithology can be applied to rocks. However, in the interests of simplicity, the above separation seems reasonable.

A knowledge of these subjects is of great value to an interpreter, for a number of reasons. Primarily, they give him a classification system within which to frame his interpretation. Secondly, they provide a means, once he has established origin or landform, of predicting and uniformly describing the characteristics of the materials composing the terrain. Thirdly, their subject matter provides an aid in completing his selective field check.

Mineralogy and petrography may be considered as the laboratory branches of petrology and lithology. Mineralogy deals with the crystallographic, physical, and chemical properties, as well as the classification, of minerals, while petrography deals with the classification of rocks according to their mineralogical and chemical composition and properties. Both of these provide the scientific basis for petrology and lithology and are therefore of some importance even to the interpreter. However, their importance is relatively slight, and a general knowledge of their subject matter and jargon may be considered sufficient.

7-5. Structural Geology. Structural geology is concerned with the stress-strain and formational relations of rocks, the special surface and subsurface features formed by various combinations of stress and strain in rocks, and the significance of visible linear strain and formational indications (faults, joints, bedding, etc.) to a prediction of subsurface conditions.

Much of the topography evident on the surface of the earth is the result of stress and strain on rocks of varying composition. If the features can be related to a type of stress-strain phenomenon, it is often possible to predict, with considerable accuracy, many significant, practical terrain characteristics that would not otherwise be easily evaluated. Such a prediction can often be checked or extended through an aerial-photographic examination of the surface-drainage pattern (Chap. 3), or vice versa, an otherwise meaningless drainage pattern can be explained.

The great importance of structural geological knowledge to any interpreter, and particularly to those concerned with the problems of geological mapping, economic geology, ground-water exploration, and engineering geology, can easily be understood.

7-6. Sedimentation. Sedimentation is concerned with the origin, dynamics of transportation and deposition, and manner of occurrence in nature of unconsolidated and consolidated sediments. Petrology and lithology are concerned with the origin of the discrete particles comprising the deposits and their description or classification in place. Geomorphology describes the formation of landforms in an over-all way. Sedimentation is concerned primarily with the processes by which the materials composing the landform arrived at their position.

A knowledge of sedimentation is of value to the interpreter for the same reasons as those listed in Secs. 7-4 and 7-5. It is of particular interest to terrain specialists who utilize aerial photographs in the solution of engineering problems. Representative problems in applied sedimentation are discussed in the book edited by Trask (202).

7-7. Geomorphology. Geomorphology has often been defined as the science that is concerned with the manner in which landforms are created and destroyed (but see Reference 212).

As discussed in Chap. 2, a knowledge of landforms and their formation is of exceedingly great importance to the interpreter or terrain specialist in any field. Once a landform has been identified, many of the dominant practical characteristics of the materials comprising it, as well as the general practical characteristics of the landform, can be easily inferred. *For the interpreter, a knowledge of*

geomorphology is unequaled in importance even by knowledge of petrology.

7-8. The Soil Sciences. The soil sciences, like geology, embrace a wide field of studies and may be divided into two classes and several subdivisions: (1) natural and theoretical soil sciences (pedology, soil physics, soil chemistry, theoretical soil mechanics) and (2) applied soil sciences (agronomy, applied pedology, applied soil mechanics).

The natural and theoretical soil sciences are concerned with the observance, recording, explanation, and classification of natural phenomena dealing with the soil, as well as the development of theories to explain, extend, or predict existing phenomena in compatability with the basic laws of the universe as they are currently understood.

Applied soil sciences are concerned with the variances between the idealities of theory and the realities of nature, as well as the means whereby these variances can be circumvented in utilizing the natural facts and theoretical hypotheses to achieve sound practical results.

7-9. Pedology. Joffe (85) defines pedology as "the science dealing with the laws of origin, formation and geographic distribution of the soils *as a body in nature*" (italics added). In further explanation, he says "Pedology teaches that the soil is a distinct body in nature consisting of definite parts, each one possessing chemical, physical, and biological properties of its own. The parts are closely related and interdependent."

Although there is no justification for a detailed discussion of pedology in this book, because of its importance to interpretation, a discussion of some of its concepts appears essential.

The rock that forms the earth's shell is covered almost everywhere with a mantle of unconsolidated material. This mantle, which may be thick or thin, was developed either from the solid rock of the shell, at its immediate location, or was developed at some other location and then transported by wind, water, and glaciers to its present location. In either case, the unconsolidated materials were derived from the rock by the mechanical and chemical forces of weathering (Sec. 2-6).

These ubiquitous weathering forces that created the unconsolidated mantle by acting on the rock also continue to act upon the mantle they created. However, as might be expected, their continued action (particularly of the chemical type) is most effective near the surface and progressively less effective with depth. The result of this variation in continued action is the development of a mantle composed of highly altered materials at the surface and unaltered materials at some depth below the surface, with certain variations and transitions existing between. The vertical section between the surface and a point lying a short distance within the unaltered materials below is called the "pedological soil profile" (Fig. 7-1). This section may have a depth of only a few inches. More commonly, it extends to 3 or 4 feet. In some areas it goes beyond these depths.

Inspection of the pedological soil profile will show that it is divided into layers, or "horizons" (horizons is preferred because it implies transition). Each of these horizons has rather distinctly different physical, chemical, and practical properties. In general, it may be said that the horizon nearest the surface (termed the *A* horizon) has a relatively high organic content but, through hydrochemical leaching, has a relative deficiency of fine-textured particles (clays and colloids). The underlying *B* horizon has, usually, a relatively low organic content, but also has, through accumulation of leached products from the *A*, a relatively high percentage of clay- and colloid-sized particles. The next layer, called the *C* horizon, is that transition zone between the *B* horizon and the completely unaltered base material. The *C* horizon and the completely unaltered material below it are often jointly termed the "parent material," or "subsoil," by pedologists (Fig. 7-1).

It is obvious to any casual observer that soils are not alike. It became further apparent to pedologists that soil profiles were not alike, though groups of soils in similar climatic regions showed great profile similarities. Consequently, they began to study and analyze their similarities and differences. They came to the conclusion that a number of fundamental factors had the greatest effect upon the character of the soil profile. These were *parent material, climate, time, topographic position,* and *biotic environment.*

The effect of parent material is easy to understand. It is the material from which the soil profile develops. Since it may show innumerable variations, so also may the soil profile. In other words, the character of the soil profile in terms of texture, stratification, heterogeneity, etc., is a function of the parent material, *assuming all other factors constant.* Other factors, of course, are not constant. For example, the effect of parent material becomes less and less as time passes and weathering pro-

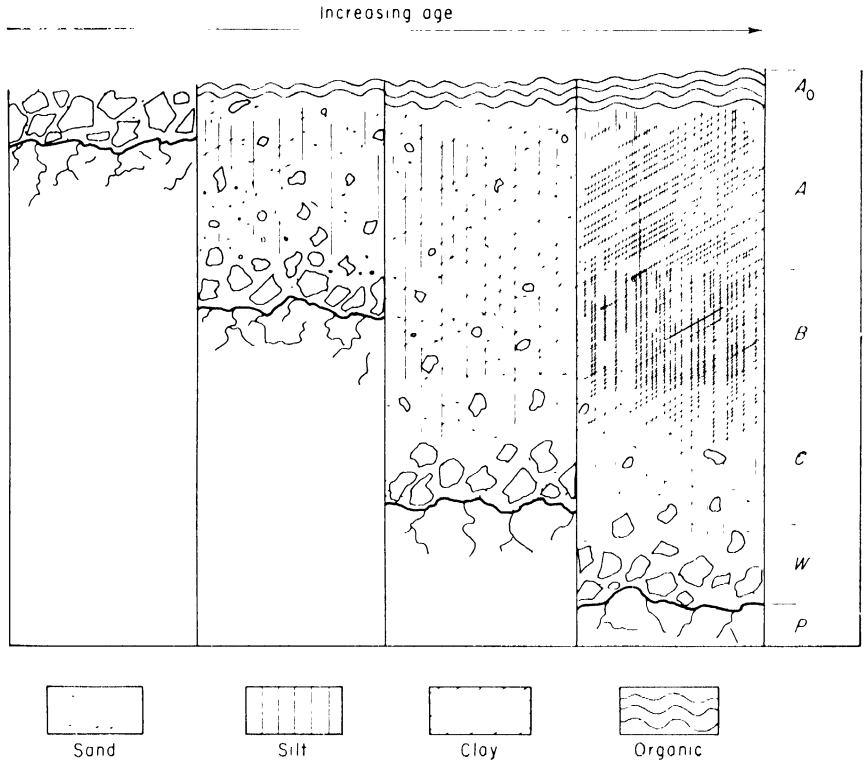


Fig. 7-1. A schematic representation of profile formation.

gresses. Also, each of the other basic factors is always operative.

Climate is operative. The intensity and nature of weathering action depend upon climate. In arid climates, because of water scarcity, chemical weathering is greatly reduced and physical weathering predominates, resulting in a tendency toward coarse soils. In humid regions the opposite is true.

Time is operative. All other things being equal, it may be said, in general, that an old soil has a deeper and better-developed profile than a young soil. The character of young soils seems to be related more to the character of the parent material, while that of an old soil shows more of the climatic-weathering effects. As Joffe (85) says, "Thus most soils are acquiring, some slowly, some rapidly, the characteristics induced by climate . . . and are losing at a corresponding rate their original geological features."

Topographic position is operative. The weathered materials on a steep slope will tend to be continually washed away by surface runoff, exposing the parent material. Weathered material in gently sloping areas will tend to undergo deeper and more pronounced development (if not waterlogged).

Lastly, biotic environment is operative. The presence of organic materials, in combination with moisture, results in their decay and releases a great variety of humic acids that have much to do with the intensity of chemical weathering. Obviously, the amount and type of material available for decay have a significant effect upon profile development.

It is easy to see that these five factors, in simultaneous operation, produce a great complexity of soil profiles. Pedologists are concerned with these complexities in terms of these factors. Through considerable study, analysis, and observation, they have determined that the soil profiles can be grouped into several categories, each one possessing typical and similar characteristics and complexities. These categories, generally, are termed climatogenic soil types. The specific climatogenic types go by names such as podzols, chernozems, laterites, etc.

Pedology is not just a theoretical or observational science. It has practical manifestations, which will be considered briefly in Sec. 7-12.

With the exception of physical geological studies in petrology and geomorphology, there is no subject that can be of greater aid to the interpreter than pedology. By applying the principles of pedology to his interpretations he can supplement or extrapolate his conclusions to a point where, in favorable instances, he can even predict rather detailed profile characteristics and physical constants in a remarkably accurate manner.

7-10. Soil Physics and Chemistry. Soil physics and chemistry are concerned with the pure interrelationships, more or less divorced from the pedological viewpoint, among the solid, liquid, and gaseous phases of a given soil in all their scientific, chemical, and physical aspects.

From the standpoint of the professional specializing in the use of aerial-photographic techniques, soil physics and chemistry are chiefly of value as "nice to know" background information. In one respect, however, soil physics is of great importance to everyone. This aspect is related to the mechanical composition of the soils, i.e., their "texture," or "gradation" of grain sizes.

Texture, or gradation, comprises the fundamental soil characteristic. *There are few scientific or practical soil properties that cannot be related, either directly or indirectly, to this major characteristic.* Consequently, a knowledge of this *soil-classificatory* aspect of soil science is of great value to the interpreter in formulating, presenting, and evaluating his analysis of the photo pattern.

7-11. Theoretical Soil Mechanics. Soil mechanics, as a whole, may be defined (196) as the study of theories of soil behavior under stress, based upon radically simplifying assumptions, and the application of such theories to practical soil-engineering problems in the light of knowledge concerning the physical properties of real soils. Generally, the first portion of this definition is considered to be within the province of theoretical soil mechanics, while the latter portion lies within that of applied soil mechanics (Sec. 7-14).

One application of theoretical soil mechanics to interpretation was demonstrated in Chap. 4 in connection with the analysis of gullies. It seems apparent that similar applications can be found, and the basic approach used, in many facets of aerial-photographic interpretation and that, reciprocally, interpretation and analysis can provide immense amounts of data for the digestion, reflection, and use of soil-mechanics specialists.

7-12. Agronomy. Webster's New International Dictionary defines "agronomy" as "the theory and practice of field-crop production and soil management." Typical of its subject matter are some of the chapter headings of the book by Lyon and Buckman (113). These include supply and availability of plant nutrients in mineral soils; organisms of the soil; organic matter of mineral soils; soil and water and their plant relationships; soil-moisture losses and their control; the soil reaction—soil acidity and alkalinity; liming the soil; the nitrogen economy of soils; fertilizers and fertilizer practice; and methods of fertility maintenance for mineral soils.

This applied branch of soil science is mainly agricultural in character. It is of little use, because of its detailed and specialized nature, to interpreters other than those specializing in agriculture and land use. For the latter, a knowledge of agronomy is of great importance.

7-13. Applied Pedology. Pedology being a natural and theoretical science, applied pedology is its practical arm. The results of theoretical studies can be gleaned for those elements of information that have practical meaning to specific endeavors dealing with the land. Names can be coined to cover these applications, such as agropedology, engineering pedology, and pedobotany, but the term "applied pedology" is probably as good as any.

In agriculture, pedology and agronomy should go hand in hand because they deal with the same subject, the soil as a medium for crop growth. Unfortunately, there has been in the past, and there still persists in some quarters, an attempt to separate the two rather than combine the applicable and valuable data of both.

Because of this persisting tendency toward separation, applied pedology may be considered as the pedological, or "soil-profile," viewpoint on such subjects as moisture, air, fertilization, land usage, land productivity, and soil classification, while agronomy may be considered as the more or less detached physicochemical consideration of the plowed layer. The combination of the two would properly be the "edaphology" of Lyon and Buchman (115).

The term "engineering pedology" was, to the best of the author's knowledge, first conceived and used by the Purdue group. Writing on this

aspect of pedology, Belcher (11) made an excellent presentation, a brief extract from which follows:

Regardless of geographic distribution, soils developed from similar parent materials under the same conditions of climate and relief are related and will have similar engineering properties which in comparable positions will present common construction problems and produce like pavement performance. . . .

Because of their individual properties, these parent materials produce a soil pattern that is related to their texture, slope, ground water conditions, and origin. This can be termed "the principle of the recurring profile."

. . . When a soil profile recurs, as it does in comparable positions within a parent-material area, the soil pattern will also occur. This is the link between the soil pattern in the airphotos, the soil profile, and the related soil problems. Thus, by the proper sampling of a given soil area the results may be used to determine soil characteristics in other areas having a similar pattern in the airphoto without respect to distance.

In the author's opinion, Belcher's dissertation is a classic. It should be studied by all soils engineers and interpreters, not only for its general discussion of interpretation, but also because it explains a basic interrelationship among engineering, pedology, and aerial-photographic interpretation.

Of course, pedology can be applied to botany, ecology, and forestry in a manner similar to that described for agriculture and engineering.

7-14. Applied Soil Mechanics. In Sec. 7-11 it was said that theoretical soil mechanics utilized the concept of ideal masses to develop mathematical theories or working hypotheses of soil behavior under stress. Applied soil mechanics revises these theories to accord with experience and judgment as revealed by the variance between the assumed and actual properties of real soils.

A knowledge of applied soil mechanics is of benefit to the engineering specialist in aerial-photographic interpretation and is of some value, as a general background, for most interpreters. In general, however, it is a subject of supplemental, rather than primary, value.

7-15. The Botanical Sciences. These sciences are concerned with plant life in its most comprehensive detail. Similarly to geology, they may be separated into natural, theoretical, and applied botany.

Except to the botanical specialist, most of the botanical sciences (forestry and phytogeography possibly excepted) are of relatively slight use to interpretation. This is not because plants are unimportant to terrain analysis. The converse is true (Sec. 6-3). Rather, it is because most of the botanical sciences are concerned with individual plants rather than the relations between plant groups and terrain conditions. Ecology, in its proper connotation, is concerned with such relationships. However, in the author's opinion ecology is less a botanical science than a coordinative science directed toward botany, but applicable to other earth sciences.

7-16. The Meteorological Sciences. The basic meteorological sciences, excluding various subdivisions, are meteorology and climatology. Meteorology is concerned with the study, observation, analysis, theorization, and prediction of movements and changes in the circulation and state of the atmosphere. Climatology is the study, observation, analysis, theorization, and prediction of the collective state of the atmosphere at a given place or over a given area within a specified period(s) of time, i.e., climate.

A study of meteorology is of only slight significance to one engaged in the analysis of terrain variations (Sec. 7-19). Climatology, contrarily, is of great importance. The basic differentiation between pedological soils—and, consequently, soil profiles—is due in great degree to climatic differences (Sec. 7-9). The climatic regime affects the rate, types, and intensity of weathering. It has a significant effect upon the types, and some of the characteristics, of landforms developed in a given region. It affects the complete ecological complex, including hydrology. In view of these widespread effects, it is evident that a working knowledge of climatology is of great help in evaluating the terrain characteristics of a region.

7-17. Coordinative Sciences. A number of important studies or sciences may be classified under this heading. These include civil engineering, hydrology, geography, ecology, geobotany, geochemistry, geophysics, and aerial-photographic interpretation.

It is a characteristic of these studies or sciences that, although they are concerned with characteristics of the terrain, they are less concerned with a specific aspect of it than geological, soil, botanical, and meteorological sciences. Rather, they have a tendency to consider the terrain in all its aspects, in the *aggregate,* as a *coordinated unit.* These studies, consequently, must be based upon

a knowledge of geology, pedology, etc., but must also go beyond them in an attempt in evaluate the land as a whole—either practically or theoretically—but definitely as a whole.

7-18. Civil Engineering. This very old and broad profession may be defined as that body of practice, based on theory, empiricism, experience, and application, derived from a wide variety of scientific fields, that deals *economically*, *efficiently*, and *effectively* with the materials, resources, and terrain of the earth in such a way that they can be controlled, overcome, or exploited to provide benefits for mankind.

In general, the field of civil engineering may be divided into (1) *theoretical studies and research* (mechanics of solids, fluid dynamics, properties of materials, soil mechanics, hydrobiochemistry, hydrology, geodesy, cartography, geoastronomy); (2) *applied studies on artificial materials primarily* (structural design, materials inspection, control and testing, hydraulic engineering); and (3) *applied studies involving natural materials and the terrain to a large degree* (highway, railway, pipeline, airport engineering, town planning, water supply, materials supply, certain types of hydraulic engineering, drainage engineering, soils and foundation engineering, hydrology, engineering geology).

It is the third category that can most use the data derived from aerial-photographic interpretation. All categories, except category 2, can provide useful data to air-photo interpretation. In fact, it can be said that, next to geography, civil engineering provides the best *general* background for interpretation.

7-19. Hydrology. Hydrology is defined by the American Society of Civil Engineers (2) as that science which "encompasses the behavior of water as it occurs in the atmosphere, on the surface of the ground and underground." Generally, hydrology considers the behavior of water under five headings. These are precipitation, infiltration, runoff, evaporation and transpiration, and ground water.

The value of hydrological knowledge to terrain specialists—and particularly its value to specialists who utilize aerial-photographic techniques to accomplish their objectives—is considerable. Such knowledge enables them to interpret erosion drainage and vegetation features that might otherwise be obscure. The hydrology of a region sometimes has more effect upon the land-use pattern than the climate, and a knowledge of hydrological probabilities and possibilities hereby aids in their interpretation. Finally, hydrology is of practical significance to so many fields of endeavor dealing with the land that its study may be considered almost a requisite for sound operations in these fields.

7-20. Geography. Geography is concerned with all the features, natural and man-made, that comprise or have an effect upon the earth's surface and men's activities upon it (rocks, soils, hydrology, vegetation, climate, topography, landforms, minerals, settlements, agriculture, manufacture, transportation, etc.). Moreover, geography is concerned with the economics, interrelationships, causes, and effects related to these items. It attempts to classify, study, analyze, and theorize upon them in a systematic manner designed to produce a practical result in terms of planning, predicting, rebuilding, and improving human development.

In the absence of a formal or self-acquired background in the various subjects covered by the preceding sections, a course in geography will provide the best "short-term" (but excessively generalized) background for aerial-photographic interpretation. With such a background, however, geography may be classed as a "nice to know" subject chiefly of value for its consideration of the types, reasons, and effects of land-usage practices.

7-21. Ecology. It may be said that ecology is a very broad science, encompassing consideration of all terrain information together with its analysis in terms of effects upon, and by, living things.

Ecological knowledge, as it is currently known, is generally of only minor value to most specialists dealing with aerial photographs—largely because of numerous uncertainties, lack of generalities, and excessive academicism. There are exceptions (Chap. 15), and more will come into being with time.

Contrarily, aerial-photographic techniques provide an exceptionally valuable tool for the investigation of ecology and botany, particularly in arid regions, and will, no doubt, be more and more widely used in the future (Chap. 22).

7-22. Geochemistry, Geobotany, and Geophysics. These coordinative sciences use the results developed by any scientific field to support and aid the expansion of knowledge in their own specific interests, i.e., the broad and specific patterns, and other

manifestations, of chemistry, botany, and physics as they occur on, under, and above the surface of the earth.

Each of these sciences includes a fascinating body of knowledge, which is, however, of relatively little present use to the aerial-photographic interpreter. Interpretation, contrarily, can be of great use to the geochemist, geobotanist, and geophysicist (Chaps. 19, 20, and 22). Ultimately, interpretation and these sciences will become mutually contributive.

7-23. Aerial-photographic Interpretation. Aerial-photographic interpretation may also be classified as a coordinative science. In other ways it may be considered a technique to be used by other sciences. However, in a fundamental way it may be considered as a true science in every sense of the word.

Webster's New Collegiate Dictionary has the following entry under science:

> 1. Knowledge obtained by study and practice. 2. Any department of systematized knowledge. 3. Art or skill;—chiefly humorous or sporting; as, the *science* of boxing. 4. A branch of study concerned with observation and classification of facts, esp. with the establishment of verifiable general laws, chiefly by induction and hypotheses; as, mathematical *science*. 5. Specif., accumulated knowledge systematized and formulated with reference to the discovery of general truths or the operation of general laws. 6. Esp. such knowledge when it relates to the physical world;—called also *natural science*.

It is certain that interpretative knowledge is gained by study and practice, but then, as per item 3, so is boxing knowledge, and boxing is really a skill.

However, interpretation represents an actual department of systematized knowledge, that of the integrated aerial-photographic patterns displayed by the earth's surface and its component materials in their innumerable manifestations.

Further, it is obvious that interpretation is concerned with the observation and classification of facts since the air-photo pattern is a *factual* representation. Also, interpretation involves the erection of verifiable general laws, e.g., erosion cross sections, and it utilizes induction and hypothesis to reach its conclusions.

The same reasoning applies to item 5 of the definition, while it is apparent that the knowledge accumulated through interpretation relates to the physical world. For these reasons, it seems proper to classify interpretation, in terms of its systematization, body of knowledge, and hypotheses, as a *natural* science as well as a practical technique.

7-24. Experience. A qualified aerial-photographic interpreter must have experience of three types:

1. *Photo experience*—the evaluation of air-photo patterns, of similar landforms as they develop in different climatic regions and in response to variations in local factors
2. *Field experience*—the correlation of repetitive photo details with actual significant field details.
3. *Professional experience*—a certain amount of practical or working knowledge in the field for which interpretation is conducted

The author knows no adequate way to emphasize the importance of experience. Take a man eminently qualified from the standpoint of academic training and give him some photos to interpret. Frequently he will be lost, or, having no experience, will either waste the photo perspective or abuse it by interpreting facts that are not interpretable. He has no photo experience. He may be able to pick out obvious facts, but he is unacquainted with the innumerable manifestations of photo details and has not that indefinable concatenation of intuition, caution, visualization, and sense of significant detail. This only comes with time and practice.

This defect is emphasized when different regions are examined. Regional knowledge can be of tremendous importance to successful interpretation, particularly in fields that are affected by the human equation.

Even a man who is a good interpreter in terms of academic training and photo experience may not be a good practical interpreter. The air-photo perspective, while it supplies much information, does not supply it all, nor is it always possible to obtain the desired elements of information from the most careful initial interpretation. A *selective field check* must be made. This should be initially *planned upon the air photo* to take every advantage of repetitive patterns, existing cross sections, specially indicative elements, etc. (Chap. 24). Further, when executed in the field, the interpreter should be able to correlate his field observations with their photographic manifestations, as well as concentrate upon those things that are of importance, either theoretically or practically. The author has seen people given a perfectly adequate initial interpretation with a selective field check plotted upon it. Such people will spend several

days in the field and will return with largely useless, erratic, or unexpandable information, and moreover with clusters of insignificant check points of their own choice substituted for those previously plotted upon the photographs. They have absolutely no conception of the part that should be played by field check in successful interpretative mapping. Until they gain such a conception, their efforts are largely useless.

Lastly, professional experience is of obvious importance. No one would ask an agriculturalist to design a hydroelectric installation. The same implied rule applies to interpretation. However, it can be said that professional experience is not as important, in some cases, as the foregoing experience. Because of the common basis in fundamental earth sciences, interpreters in one field can often function successfully, to a point, in another field.

7-25. Résumé on Background. As stated in Secs. 1-12 and 7-1, and as developed in this chapter, aerial-photographic interpretation is both a *practical technique* for evaluating the qualitative characteristics of the land and a *natural science* of systematizing and studying these techniques and erecting general laws regarding them.

Interpretation is not a job for a technician, but is an art. It requires not only training and experience with photographs, and in the field, but also a broad and diversified background of academic knowledge in certain sciences. The most important of these sciences are petrology, geomorphology, pedology and applied pedology, certain aspects of civil engineering, and hydrology.

7-26. Training of a Terrain Specialist. The author has been queried by students and others concerning his idea of the studies that should be taken to prepare for aerial-photographic interpretation. Actually, it seems better advised to inquire concerning those studies that are important in preparing oneself as a "terrain specialist" or "earth specialist" based upon a maximum use of aerial-photographic interpretation as a technique and discipline. The author's ideas follow.

The first part of any preparation as a terrain specialist must be a thorough grounding in the basic sciences and arts that comprise the first two years of most scientific curricula. These studies should include *mathematics* (advanced algebra, analytical geometry, calculus, differential equations, least squares, and statistics); *physics* (theoretical, experimental); *chemistry* (physical, inorganic, organic); *geodesy and surveying* (ground); *economics* (emphasis on economics of working regions and countries); *history* (emphasis on the development of civilizations and modern history); *sociology* (emphasis on community and region); *literature* (general survey, selected classical and modern general); and *drawing and cartography.*

It should be the purpose of these two years to provide a thorough grounding in basic sciences, qualitative studies, and practical techniques, all having a wide variety; promote development of the "well-rounded person"; and develop firm habits of logical and incisive thought founded upon the disciplines of mathematics, physics, chemistry, and surveying.

The second part of the preparation should include two years of comprehensive studies in the most important basic earth sciences, coordinative sciences, and aerial-photographic techniques: *physical geology* (basic mineralogy-petrography, petrology, geomorphology, sedimentation); *pedology* (theoretical and applied); *soil physics and chemistry; soil mechanics* (theoretical and applied); *climatology; hydrology* (theoretical and applied); *photogrammetry* (basic and advanced); *hydraulics and hydrodynamics* (theoretical and experimental); *materials of construction; mechanics;* and *aerial-photographic interpretation* (basic, advanced, field, and research).

It should be the purpose of this period to promote the concept of the terrain as an integrated topographic-geological-soils-water unit, and the photographic techniques as a primary method for its investigation and coordination.

The final period of one or two years should be devoted to some additional general courses in earth sciences, specialization in a given field if desired, and considerable research, field investigation, project, and thesis work. Basic introductory courses might be offered in *geography, taxonomy,* and *phytogeography,* plus the *mathematical, quantitative, and qualitative analyses of terrain studies.* Additional courses, projects, and research should be provided in the specialized or general use of aerial photographs, including a considerable proportion of photo-field correlation.

It might be said in summary, and since this section is one involving opinions, that to the author, the above type of training appears inevitable. Overspecialization, increasing requirements, decreasing scientific manpower, and an increasing awareness that terrain studies *cannot be compartmentalized,* all lead toward this result. It is to be hoped that aerial-photographic interpretation will, in itself, provide much of the stimulus.

8 FINAL INTERPRETATION

8-1. General. This section, which has been dignified by the name of chapter solely in the interests of logical presentation, describes and demonstrates final interpretation.

8-2. Convergence of Evidence. In Sec. 1-16, the sequence of interpretation was described. It was said that the *pattern* displayed by each of the elements discussed in Chaps. 2 to 6—landform, rock type, surface-drainage pattern, erosion features, gray tones, culture, vegetation, fourth-order features, nontopographic microdetails, etc.—was evaluated individually. Finally, the indicative weight of each element was compared with that of all the others, and a conclusion was formed upon the basis of convergent evidence.

This is a fairly brief and simple way of describing a specifically indescribable process, for of course it is not all that simple.

In the first place, interpretation is done in terms of *areas,* and the pattern exhibited by a single element may be confined to one or all of these depending upon the nature of the terrain and the preference of the interpreter. If a fairly large area, including a number of component areas, is being interpreted, it is usual to make a preliminary examination and to catologue the over-all pattern in the brain (subconsciously?) and then to dissect the area into its other, smaller component patterns for each element.

Once this dissection has been accomplished, it is usual to draw the best conclusion that one can regarding the indicative significance of each element, and then to add them up mentally. If most or all of the elements can be logically, academically, and truthfully inferred to indicate a certain set of conclusions, then it is usually safe to set these conclusions down. If all but one—or possibly two—elements indicate one thing and the one or two elements indicate the opposite, the interpreter must have recourse to his experience, intuition, and knowledge (Secs. 1-12, 7-24, and 7-25). If there is more contradiction than this, the interpreter had best be quite careful and schedule a selective field check.

This entire process is the arrival at a conclusion based upon *convergence* of evidence. *Divergence* of evidence and *dispersion* of evidence do not allow effective interpretation. They merely allow planning of field check.

The whole process may be compared to the legal doctrine of circumstantial evidence.

Figure 8-1 indicates the process of interpretation in a schematic manner.

8-3. Application of Interpretative Theory—Generalist and Specialist. The author is a firm believer in the status of aerial-photographic interpretation, not only as a technique, but also as a natural coordinative science (Secs. 7-23 to 7-26).

Because of this, he is also a believer in the doctrine that an aerial photograph should be interpreted first from the standpoint of the generalist, in accordance with interpretative theory as we know it, and then in accordance with the particular speciality of the interpreter.

This method of approach has two advantages. It guards against conclusions that are seen through a certain colored filter of knowledge, and it perpetuates and extends the field of interpretive knowledge and experience. There are other reasons, such as those implied by the above-cited sections of Chap. 7 as well as Sec. 24-21.

8-4. Demonstration of Final Interpretation. Figure 8-2 shows a small part of an area in the Far East. Although space will not permit a complete, detailed interpretation of this area, a complete preliminary interpretation will be developed. Most of the steps that comprise this interpretation are taken by the brain with lightninglike rapidity. Consequently, it is difficult to include anything more than the major facets of analysis.

The first thing that the experienced interpreter

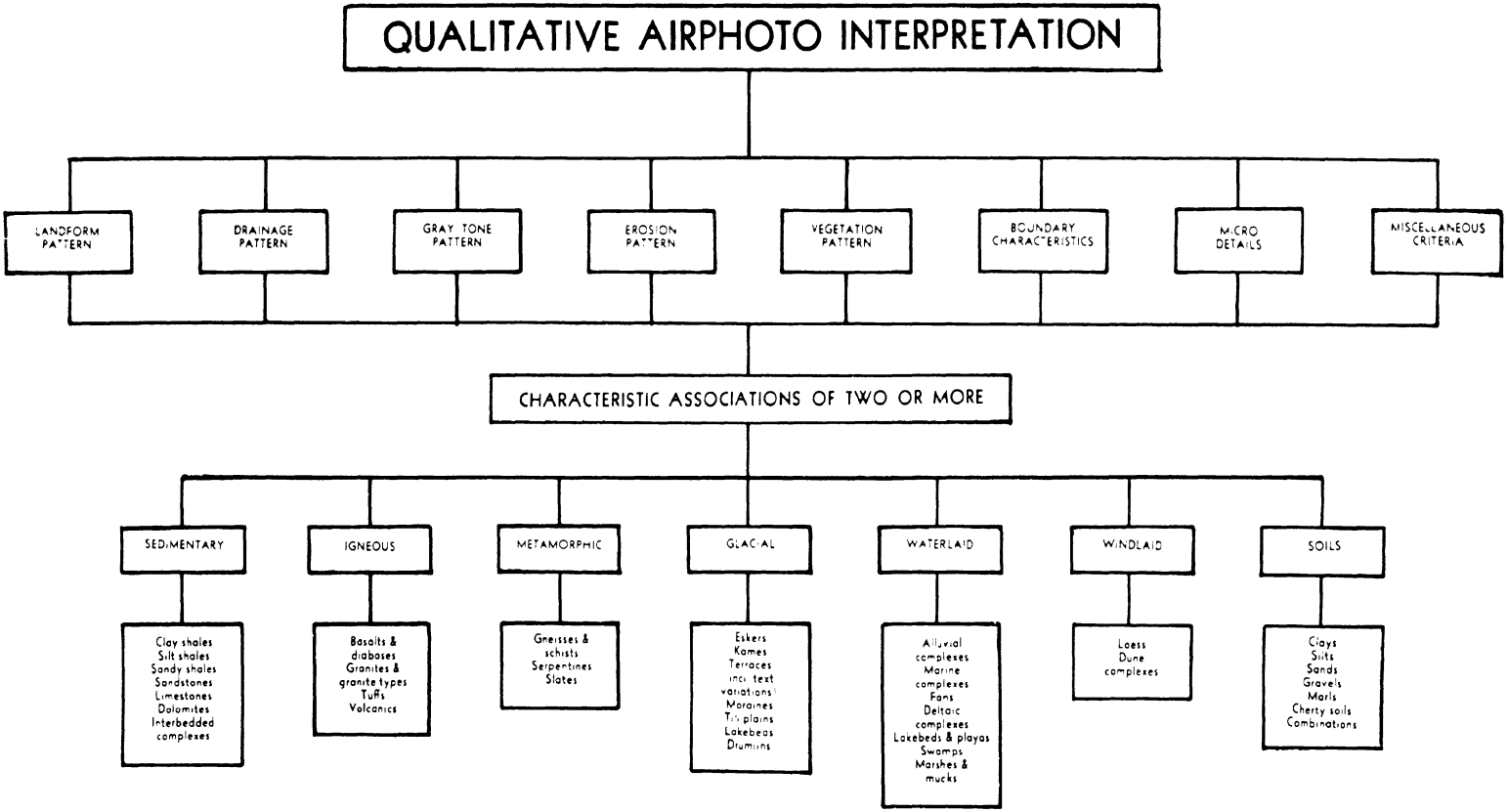
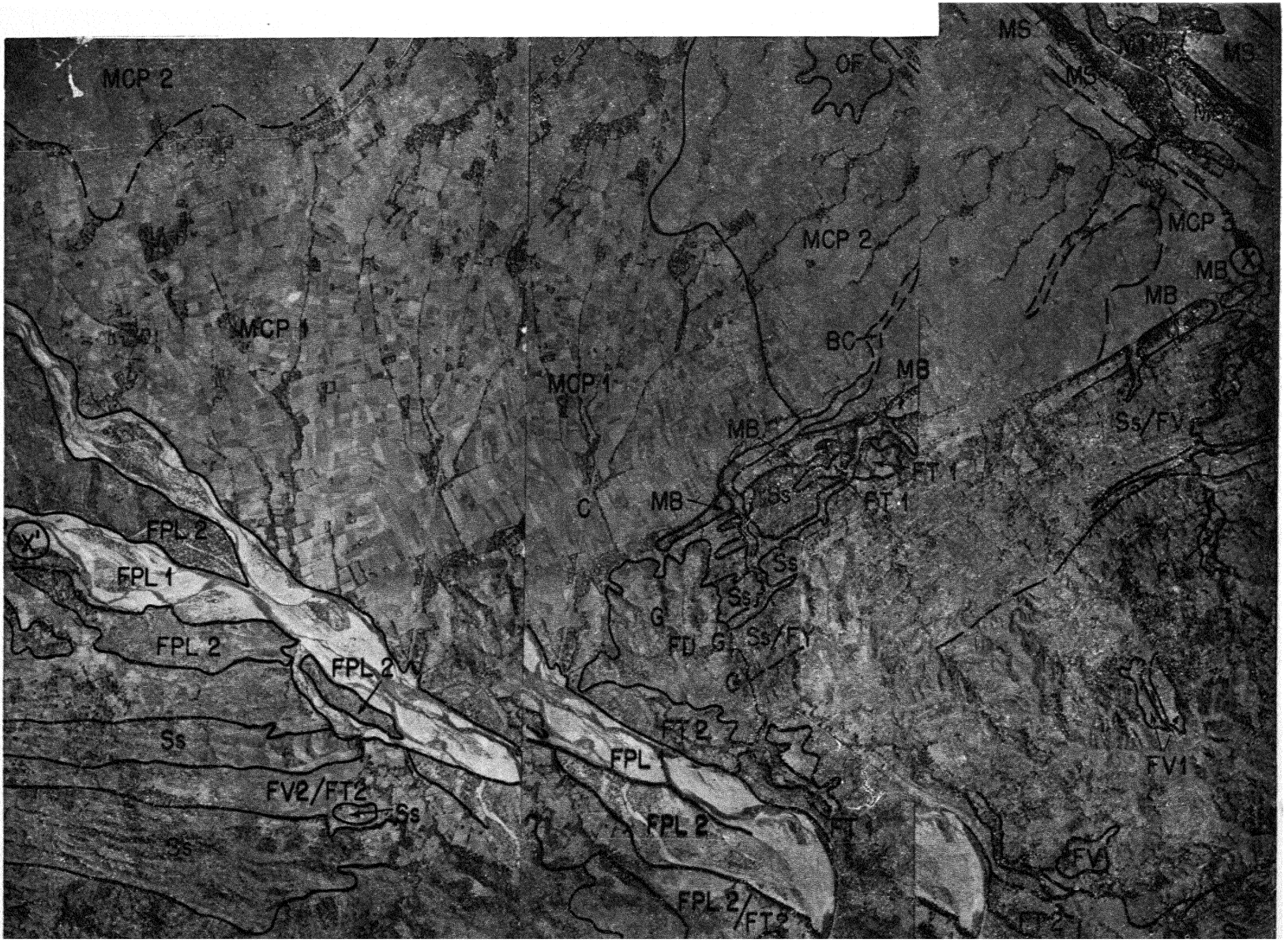


Fig. 8-1. A schematic representation of the process of final interpretation.

Fig. 8-2 (*facing page*). The interpretation of this stereotriplet is given in Sec. 8-4.


MCP 2
MCP 1
X'
FPL 2
FPL 1
FPL 2
FPL 2
Ss
FV2/FT2
Ss
Ss
OF
MCP 2
BC 1
MB
MCP 1
MB
C
MB
Ss
FT 1
FT 1
Ss
Ss
G
FU G
Ss/FV
G
FT2
FPL
FPL 2
FT 1
FPL 2/FT2
MS
MS
MS
MCP 3
MB
X
MB
Ss/FV
FV1
FV
FT2

notices about the area shown in this photograph is its over-all subdued tone. Only light to medium grays appear. This may be a function of a variety of the factors discused in Chap. 5, but the interpreter is inclined to relate it to two factors primarily—processing and natural colors. He is inclined to consider processing as a major cause because of the relatively dark tones associated with the unvegetated river bars. Such dark tones—overall—are a rarity unless anomalous conditions obtain. However, being a pedologist, the interpreter also ascribes some of the dark tones to the natural lateritic reddish weathering colors. He also attributes certain of the tones to moisture content. In substance, his first survey of tones indicates that relatively slight differences in tonal value will have more significance than they might have in other areas that he has studied.

Next the interpreter begins to examine landform through the stereoscope. It is easy to outline the two major levels of bar meander activity [*FPL*1, recent, and *FPL*2, subrecent (Chap. 9)]. From their pattern of light (relatively) tone, the numerous bars, and his knowledge of their geomorphic formation, it is possible to predict with confidence that they are composed of sands and gravels having the lithological character of the materials within the stream's watershed. It is also possible to predict, since the stream is obviously overloaded, that a relatively recent rejuvenation has occurred.

The next thing that the interpreter notes is the marked change in pattern and topography that occurs across the photographs in the general direction *X-X'*. In order to establish the nature of the terrain on either side, he continues with his analysis of landform. The area toward the top of the triplet is exceptionally flat and has few topographic features. Therefore it is almost indubitably water-deposited, and in view of its relation to the sea (just off the photos) and low, featureless character, it is probably a recently emergent coastal plain. This conclusion is reinforced by the discovery of marine beach ridges and tidal marsh (*MB, MS, MTM*) (Chaps. 11 and 15) and the previous indication of rejuvenation. This conclusion is temporarily laid aside as tentative while examination of the terrain further inland is made.

The first prominent unit landform that he notices is that indicated by *FD*. He comes rapidly to the conclusion that this is a fossil delta (Chap. 10) indicating a previously lower elevation with respect to the sea and supporting the conclusion of rejuvenation suggested by the bar meander plain. The flat surface, modified arcuate shape, sharp break of the foreset beds with the fossil bottomset beds (now part of a probable emergent coastal plain, *MCP*), the mouths of the distributaries, and the remnant of the upstream alluvium (now a fluvial terrace, *FT*1) are all apparent. The courses of the former distributaries have been filled in by sheet wash, back-weathering, sedimentation, and cultivation. Gullies (*G*), however, have begun to eat backward, starting from the distributaries and eating through the recent fill of the old channels. Because of this, it is difficult to decide whether the gully characteristics truly indicate the textural nature of the deltaic materials. They do not indicate either very granular or very fine materials. Rather, they indicate sands and silts with some clay, the general dominant sizes increasing upstream, as might be expected. It also appears that the deltaic materials are deposited over lower bedrock ridges on either side. These modify the lithological continuity, structure, and composition of the delta. Surface drainage indicates relative perviousness, but because of youth, the possibility of functional drainage, and small, elevated area, this is of little significance. Cultivation indicates surficial imperviousness, but this is also insignificant in the Far East. Tone is nonindicative.

The most that can be said about this landform, for the photography being examined, is that landform and gullying indicate a composition of fine to medium sands and silts, overlain by surficial clays, underlain by gravels and coarse sand, and interrupted by ridges of rock.

It will be noticed that the delta extends back into the hinterland (*FT*1), connecting ultimately with broader remnants of old valley fill now existing as a terrace (*FT*1). This level of deposition, a little lower than the dissected hills to the right, is picked up at various points as remnantal plateau-like cappings or extensive plains, more properly labeled *FV*1.

A lower level of fluvial working, divided into a series of complicated sublevels and characterized by evidences of both lateral and vertical activity (considerably subdued by the effect of rice paddying), represents successive past stages of fluvial activity during gradual rejuvenation. Their composition, vertical stratification, and horizontal continuity may be expected to be highly complex.

These fluvial deposits surround and partially cover the lower edges of tilted (metamorphosed?) sedimentary formations to the left and right.

These sediments are interbedded and display some variation, but are predominantly of a sandstone (*Ss*) character in certain areas and shale (*Sh*) in others. The major criteria for these conclusions are landform, orientation, and drainage pattern (Chap. 16). All the sedimentaries are undergoing dissection. Concurrently, the valley fill that originally covered them is being removed and reworked. In some areas, the tilted edges are covered by a variable but generally thin overburden composed of these residual and dissection products (for example, *Ss/FV*), creating a complex area. Such an area would be difficult for construction involving cut.

In some areas progressing through the rock, small fluvial plains (*AR*) are developing. These have breached the beach (*MB*) that once formed the shoreline. This beach is relatively well drained and coarse-textured.

After examining the general area, the interpreter returns to the area tentatively defined as emergent coastal plain and definitely identifies it as such. He also divides it into subareas *MCP*1 to *MCP*3. These three areas are a bit puzzling. To some, they might indicate significantly different surficial soils conditions, say, fine sands and silts in *MCP*1 and *MCP*3 (lighter tones), but a careful interpreter looks further. He notices that the lighter pattern is largely bounded, in detail, by field edges; that it is related to the main irrigation canal (*C*) and other distributaries leading from the major river; that it is responsive to local changes of relief; and that the surficial texture of *MCP*2 is different from that of *MCP*1 and *MCP*2. From this he concludes that the tonal boundaries are due to different crop covers and are related to different current water demands or availability. However, to be safe, he lists this difference as one to be selectively checked in the field.

Finally, the interpreter locates the course of one of several old channels, now largely buried (*BC*), and an area of flatland marsh and bog (*OF*) that is probably brackish because of inseepage through the intervening beach ridges (*MS*) from the nearby tidal marsh (*MTM*).

This may be said to complete his rough preliminary interpretation. It must be evident that he could go further without field check. Areas could be outlined in considerably greater detail and lower level of generalization. Compositional differences would receive more attention. Practical problems, in terms of probability and for whatever field he was interpreting, would be outlined. A selective field check could be planned.

A completely detailed picture could be obtained at the conclusion of any field check that was allowed. Finally, if desired, a planimetric map, controlled mosaic, or topographic map could be used to map the information (Chap. 24).

INTRODUCTORY STATEMENT

This portion of the book expands the basic material of Part I and illustrates the manner in which the various elements of the air-photo pattern *combine in various typical ways to identify different unit landforms and rock types in various parts of the world and under different climatic conditions*. In short, it is a lexicon of landforms and rock types as viewed through the medium of aerial photography.

It includes fairly lengthy discussions of the development of the various *unconsolidated* landforms (and lesser comments on certain rock types) that are associated with each of the geological origins mentioned in Chap. 2; discussions of the "typical" aerial-photographic characteristics associated with each landform and rock type; and numerous illustrations, primarily aerial-photographic, of each landform in various parts of the world.

The discussions of geomorphology are based, in large part, upon the work of the modern and classical specialists. It has been the author's intention to present the important aspects of the subject in a logical order and manner—not for the specialist, but for the person who is unacquainted with the subject. As a result, he discusses the salient points of the particular formational process being discussed, and also the formation of various landforms, before considering their air-photo characteristics.

The author feels that a clear understanding of such material is absolutely essential to a proper interpretative approach. As was said in Chaps. 2 and 7, landform is the dominant element of the aerial-photographic pattern, and a knowledge of petrology and geomorphology forms the basis for its proper evaluation. He does not feel that it is wise to assume that such a knowledge is the possession of the reader, without pointing out its important aspects.

The discussions of air-photo characteristics, together with the illustrations, are intended to provide a *fundamental* knowledge of the aerial perspective as a depicter of many geomorphic landforms. Even though the illustrations are numerous, limitations on space did not allow the inclusion of numerous examples indicative of special aspects. An attempt has been made to include a sufficient number of both *typical* and *atypical* examples to provide a basic framework. This is only a first differential, however, and a full treatment would expand this book to three times its present size.

Finally, the author regrets that space did not permit the inclusion of detailed discussions of the practical characteristics associated with each landform and rock type in so far as they apply to engineering, geology, agriculture, etc., as well as the specific means by which the air-photo pattern can be used to extract them. This, with regret, must be reserved for a possible future effort.

II

A Lexicon of Geomorphology and Landforms as Seen by the Aerial Photograph

9 FLUVIAL LANDFORMS

9-1. General Introduction to Fluvial Action. Fluvial action is the major factor responsible for the detailed three-dimensional shape of the earth's visible surface. Other factors—tectonicism, glaciation, wind action—are important in certain areas. In some of these, they are the dominant factors responsible for the present shape of the terrain. However, there are very few places where fluvial action is not, or has not been, present to such an extent that reflections of its present or past operation are not apparent. Moreover, there are few places where it cannot be expected to prove the dominant landscape former of the future.

The cause for this dominance is a simple one, namely, that fluvial action is water action, and water action is, has been, and will always be, in so far as we can foresee, operative in all portions of our globe.

Water action sounds elemental enough. Everyone is familiar with the fact that water will erode and deposit materials. Yet the very fact that water action is, or has been, always present, that it operates in conjunction with other landforming processes, and that it both erodes and deposits a great variety of materials under an infinity of topographic and environmental conditions makes the clear and systematic discussion of fluvial action, as well as the separation and consideration of its distinctive landforms, one of the most difficult tasks of geomorphology.

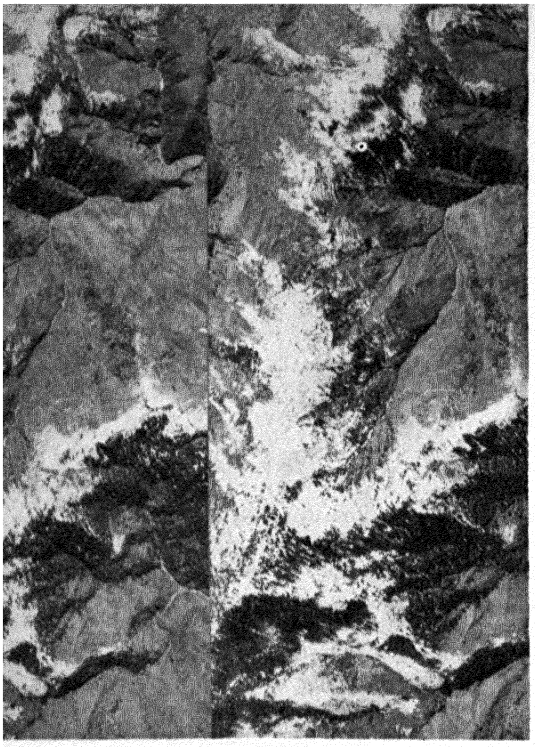
Fortunately, geologists and geomorphologists of the past and present, in cognizance of this fact, have given a large proportion of their time and effort to the study of fluvial action. This has led to a rather good qualitative understanding of its operation.

9-2. Types of Fluvial Action. There are *two major types of fluvial action.* One is *erosive,* tending to create landforms that are predominantly the result of degradational sculpturing. One is *constructive,* tending to create landforms that are predominantly the result of aggradational deposition. More often than not, these two actions work simultaneously, or in alternate regular and irregular sequence. Indeed, some of the major fluvial "constructional" landforms (Sec. 2-28) have dominant characteristics that reflect a combination of the two types of action, rather than constructive action alone. In addition, landforms with aspects predominantly reflecting constructive action may be greatly modified by erosive action.

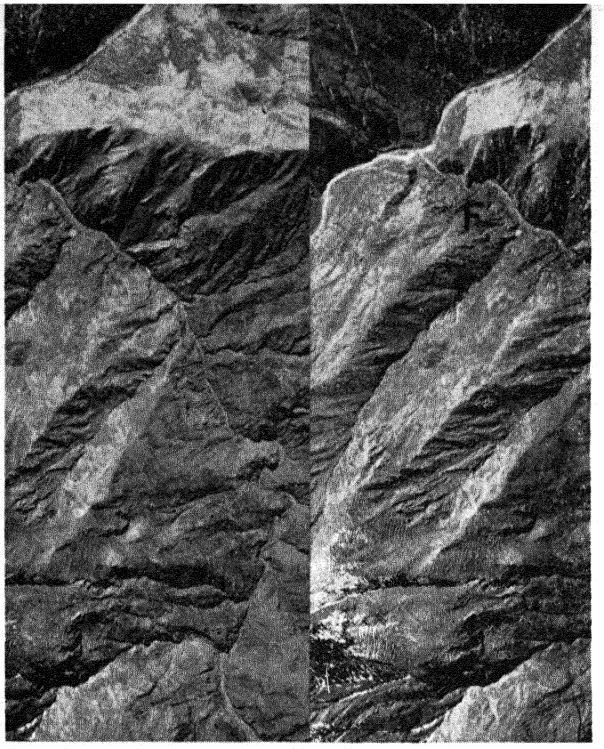
The erosive type of fluvial action is present everywhere and is of exceptional interest to geomorphologists concerned with the classification and evaluation of landscape features. However, the major aspects of this type of action are best developed in the older portions of the earth's surface, e.g., the consolidated and semiconsolidated rocks. Also, they must usually be studied on a broad scale. As a result, erosive fluvial action is not of *dominant* interest to the aerial-photographic interpreter. This is because of his usual emphasis on relatively small areas (1 to 100 square miles); his usual practical, specific, and unrelated interests (soils, drainage, land use, etc.); and his current limited pertinent knowledge (elemental state of information on correlations of erosion and drainage patterns with rock types, soil types, fracture analysis, and climatic factors, Chaps. 3, 16).

Nevertheless, erosive fluvial action should be generally understood by all professional scientists who utilize aerial-photographic interpretation, both because of its fundamental nature and because of the possibility that its macro- or microfeatures, as revealed in the air-photo perspective, will prove of significance to their specialized endeavors.[1] Erosive fluvial action is discussed, therefore, in Sec. 9-3.

[1] As an examination of cut-bank and slipoff-slope details in a meander belt will often prove of aid in reconstructing the tectonic history of an area.



(a)



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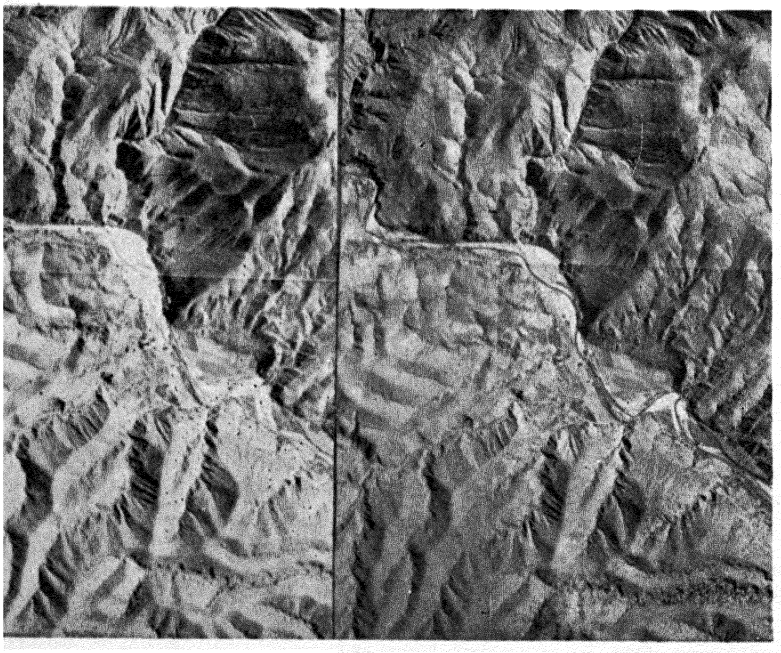


(c)

Fig. 9-1. Three narrow stereopairs illustrating the shape of young stream valleys. In (*a*) and (*b*) are shown V-shaped and narrow U-shaped cross sections (Middle East). The steep gradients and at least one falls (*F*) are shown. The terraced areas are used for cultivation and are partially covered with snow. In (*c*) are shown young valleys (Arizona) in consolidated and semiconsolidated materials (above river) and a geomorphologically older river (forming a meander plain) traversing the area occupied by younger streams. This emphasizes the point that the development of a stream valley is a function of things other than the geomorphic age of a region. A given stream may have different ages along different stretches. (*Photographic Survey Corporation, U.S. Forest Service.*)

The constructive type of fluvial action is of considerably more interest to the interpreter. This is due to the variable and unconsolidated nature of the constructive fluvial landforms (and the practical problems created thereby); the universality of occurrence of fluvial constructive landforms (as compared with that of glacial, aeolian, marine, etc., forms); and the relative lack of emphasis that has been given to the detailed nature and occurrence of the individual forms (on geological maps, for instance, which would lead one to think that the earth's surface is covered with nothing but bare rock).

The constructive type of fluvial action and its resultant landforms are the major topics of consideration in Chaps. 9 and 10, beginning with Sec. 9-4.

9-3. Erosive Fluvial Action. Erosive fluvial action begins with the fall of rain or the appearance of ground-water effluent on the earth's surface. As explained in Sec. 4-3, such rain or ground-water elements coalesce first into rills, then into runlets, next into gully flows, and finally into streams having definite channels.

Each of the initial elements of fluvial action—rills, runlets, gully flows, and the *young* streams as well—are essentially erosive in action; e.g., they remove the preexisting material from the locus of flow and its immediate surroundings (Sec. 4-1). The initial gradients of flow are steep and irregular, and the major tendency of flow is the removal of relatively large quantities of material. Some of this removal takes place in a lateral direction because of sidecutting, undermining, and bank collapse. However, its dominant direction is downward. This is the result of gravity (drawing everything toward the earth's center); youth of the flow channels (bringing the flowing waters into continual contact with fresh, usually impervious rock or other materials); initial steep gradients (concentrating the force or flow in a downward direction); and the available relief.

During the period of dominant downward erosion, relatively deep and narrow valleys are carved in the country rock or material. At any point during this stage, the stream occupies most or all of the valley floor (Fig. 9-1). Moreover, it is characterized by numerous irregularities of gradient (rapids, falls, various bottom slopes), valley shapes (trenchlike, V-shaped in varying widths), and depths.

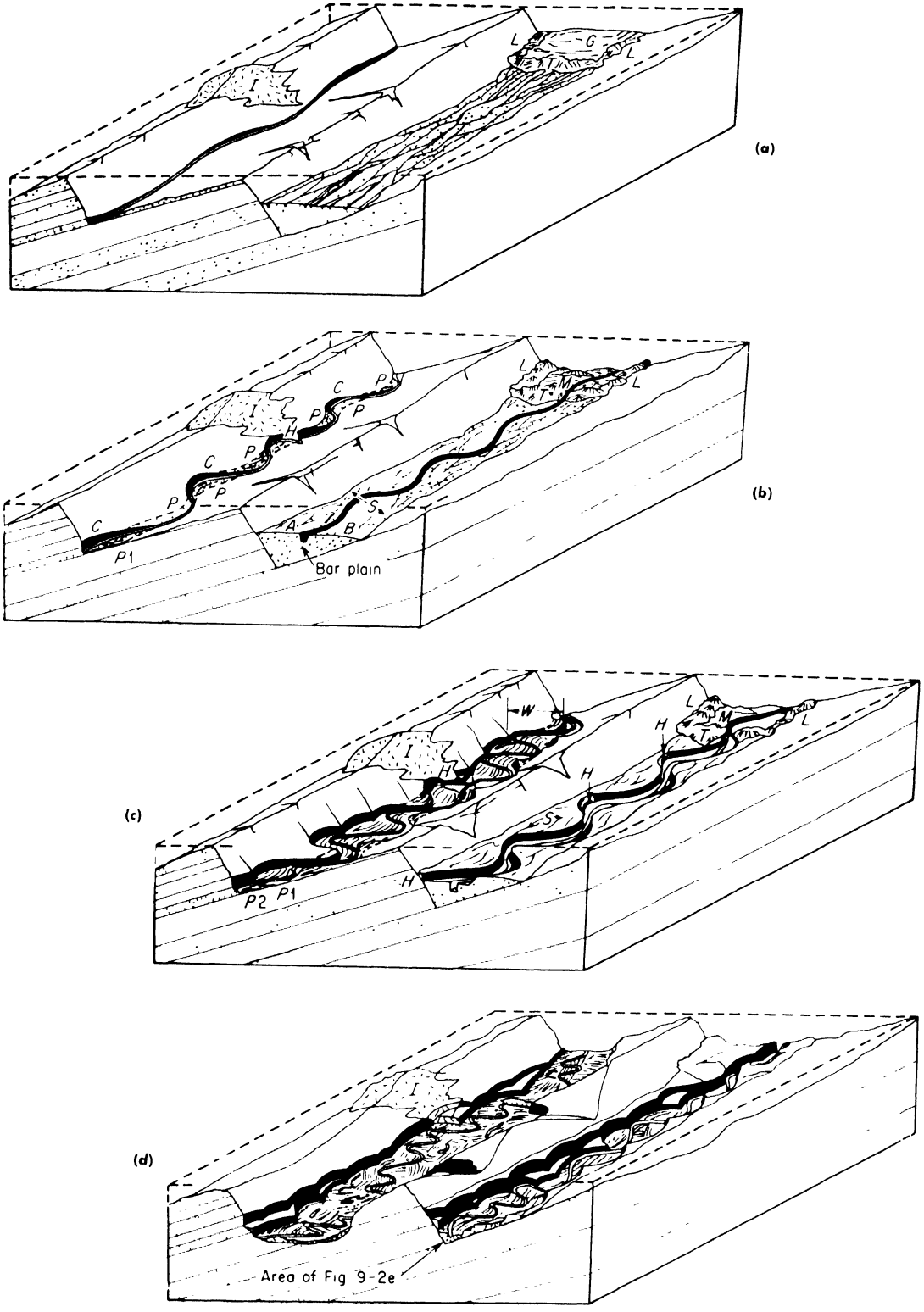
At any given point along a stream, as time passes, the process of downward erosion becomes increasingly less dominant. This is caused by two simultaneous effects: (1) decrease in the erosive power of the flowing water and (2) decrease in the distance above base level.

As time passes, the initial steep and irregular gradients are reduced and smoothed (at a given point, remember, and assuming no tectonic changes in elevation). This is partially due to the fact that the process of erosion is proportional to gradient, the highest rate of erosion being associated with high gradient, i.e., high velocity, i.e., high transporting corrasive and "plucking" power. The higher gradients, for an equal quantity of flow and resistance of formations, are lowered at a greater rate than lower gradients. At the same time, the gradient is smoothed. This is partially due to the reasons given in the preceding sentence and also to the fact that more resistant formations protect their upstream sections from erosion by encouraging slack-water deposition or at most backwater scour. The smoothing and lowering of over-all stream gradients is also partially due to their approach to *base level*, i.e., the imaginary plane, existing all over the earth, somewhere between high and low sea level. This base level provides a downward limit to fluvial erosion that is reached only at the point of a stream's entry into the sea.[2] Though difficult to explain concisely, it should be intuitively acceptable that the closer any point along a stream becomes (by erosion) to its unattainable base level, the lower is the gradient between it and any successive downstream point and the lower is the erosive power at its location.

As the gradients are decreased and smoothed, the velocities of flow are reduced and made more uniform as are, in turn, the carrying power and transported loads. Eventually a semibalanced or *graded* condition is reached at which the stream tends to acquire and maintain a gradient that is just sufficient to move the sediment that it receives. This leads to a stream profile having as its *ideal* shape a hyperbolic curve.

At this point in a river's development it may be considered in the first stage of maturity and ready for the development of its first major fluvial constructive landforms. *It must, however, be remembered that erosive action still goes on, even though fluvial constructive action becomes dominant.*

[2] The concept of base level assumes that all land occupied by flowing streams lies *above* sea level. In the case of Death Valley, the Dead Sea, etc., local (within their drainage basins) base levels are much lower than no mal Therefore should a major stream system be induced to contribute its entire flow to one of these areas, and should the flow be removable through an integral porous subsurface into the center of the earth, then the stream system would undergo rejuvenation and eventually empty the oceans through its channel and into the valley.



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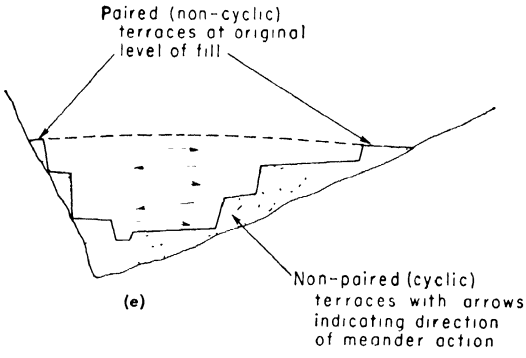


Fig. 9-2. This series of diagrams indicates the manner in which floodplains and terraces are developed by fluvial action. In (*a*) two parallel valleys, carved in tilted sediments, are shown. An intrusion of highly resistant igneous rock *I*, probably coincident with a major joint, is also shown. One of the valleys has been occupied by a glacier, whose terminus *G* is now static. The faces of the glacier are occupied by terminal and lateral moraines *T* and *L* (Chap. 12). Periodic meltwaters from the glacier have filled the right-hand valley with granular alluvium to considerable depth. This was originally deposited as a valley train (Chap. 13), and its present surface is that of a bar plain (Sec. 9-7). The left-hand valley, unoccupied by a glacier, has proceeded through a period of normal downdip erosion with its dominance of downcutting (Fig. 9-1) to the point where it is graded to base level. Not having been interrupted by glacial filling, it is beginning to engage in lateral activity and, in fact, has developed incipient meanders characterized by small cut banks and slipoff slopes. In (*b*) the glacier has disappeared, leaving ground moraine *M* behind. The valley fill is beginning to be dissected by a stream. Because the valley fill is far above base level (downstream), downcutting is rapid and dominant. As a result, valley cutting is deep; its floor is occupied by another bar plain caused by overloading, and meandering, while present because of uniformity and relative softness of materials, hemispheric reflection, etc., is minor in nature. As a result of downcutting, two matched terrace levels *A* and *B* representing the old valley floor are created. These have on their surface the old channel scars *S*, remnants of the old braided channels. These are the same as those described in Secs. 9-8 and 9-10. In the meantime, the nonfilled valley has been subjected to continuing lateral action and has developed more pronounced meanders, together with steeper cut banks *C* and slipoff slopes creating point bars *P* that are characterized by meander scrolls. At *H*, the igneous rock forms a hardpoint, deflecting the stream and causing a localized change (Chap. 3, Fig. 3-3). The point bars have only a thin veneer of alluvium (as at *P1*) over the laterally corraded rock. In (*c*) both valleys have progressed to a considerable degree. In the filled valley, as base level (apparently temporarily higher than that of the left valley) is approached, meandering has become more pronounced, exposing rock hardpoints *H* at several places. Channel scars *S* are still apparent at both of the terrace levels, indicating the overloaded condition of the stream, and although base level is being approached, downcutting is still in progress. In the nonfilled valley, successive meandering has progressed to the meander belt stage *W*, transecting old point bars, leaving old meander scrolls and abandoned channels, cutting into the valley walls, and leaving several thin, point-bar, terrace-veneer levels (*P1*, *P2*). The rock-defended point has been responsible for the formation of a persistent terrace. In (*d*) the filled valley has been cut to near base level, leaving a series of rock-defended terraces. Meandering has become active, and a meander belt has almost been formed. In the nonfilled valley, the meander belt has begun to migrate back and forth across the valley floor, engaging in broad planation and depositing a natural level and backswamps, in short, a composite floodplain (Sec. 9-7). In (*e*) the difference is shown between the topmost paired (or noncyclic) terraces, representing the previous valley fill, and the nonpaired (or cyclic) terraces, due to normal erosion and meander action.

9-4. Fluvial Constructive Action. After fluvial action has proceeded through its dominantly erosive stage to the point where the stream is mature, i.e., graded, the process of fluvial constructive action begins to assume some importance and depositional-erosive or depositional landforms are created.

The beginning of the process is signaled by the start of widespread meandering action. Meandering action is caused by (1) hardpoints, (2) tributary effects, (3) earth rotation, and (4) transfer of dominant river action from the vertical to the horizontal plane. All streams have along their banks points and areas where erodibility is less than that at other points and areas. These "hardpoints" may be caused by harder rocks, boulders, very porous gravel deposits, or very tough clay deposits. The flowing waters, impinging upon these deposits, are reflected laterally, creating irregularities in what would otherwise be a straight, or structurally controlled, downward course.

The rush of waters entering a stream from a side tributary has a similar deflecting effect upon flow.

Hemispheric deflection, caused by the earth's rotation, is alleged to have an effect upon the veering of a stream from its "normal" course.

Finally, the attainment of grade and the resultant minimization of downcutting force the stream waters in general, *and the floodwaters in particular*, to engage in lateral migration.

When streams are young and downcutting action is dominant, the effect of the first three factors is largely *negated*, though exceptions occur. How-



Fig. 9-3. An oblique aerial view of a superbly developed meander floodplain. All the important and typical features of combined lateral erosion and deposition are shown. These include meanders (*A*); oxbow lakes (*B*) representing the location of former channels; meander scrolls formed by lateral accretion (*C*); a point bar which will soon be cut off (*D*); slipoff slopes where lateral deposition is occurring (*E*); and cut banks where lateral erosion is active (*F*). This floodplain has progressed to the stage of a migrating meander belt. The vegetation pattern on the surface of this plain is quite striking. It is usually indicative of the marked changes that occur in soil, organic, and drainage conditions. The drainage pattern on the point bars is of the constructive type (Chap. 3). (*Arctic North America. U.S. Army.*)



Fig. 9-4. This oblique shows a natural levee in the early stage of formation. The river is virtually flowing across *the lakes* in a channel confined by its own natural levees. Note that the levees slope *away* from the channel. *(Northern Canada.)*



Fig. 9-5. A high aerial oblique of a composite plain that shows considerable evidence of both lateral deposition and erosion and vertical accretion. Evidence of over-the-bank floods are the natural levees *C*, emphasized by land-use patterns, the backswamp area *D*, and the general lack of features associated with lateral activity (except near the river). Along the river, abandoned channels *A*, point-bar and high-velocity flow bars *B*, together with their associated meanders, slipoff slopes, and cut banks indicate the effectiveness of bank-full floods. It seems apparent that the regimen of this stream has altered within recent geological times, the previous existing dominance of overbank floods being succeeded by bank-full floods that are destroying the covered plain. (*Far East. U.S. Army.*)

ever, when the streams are graded, the first three factors still are present and are *supplemented* by the change in river erosive action from valley deepening to valley widening. It is at this stage that lateral migration of the stream (meandering), widening of the valley floor (planation), sculpturing of the valley sides (cut-bank erosion), and deposition on the widened valley floor (floodplain accretion) begin to assume real importance as landscape modifiers.[3]

The actual process of meandering as a river proceeds from its first incipient meanders to well-developed meanders to meander belt to migrating meander belt to the creation of terraces is rather complex and is most simply described by means of general stage diagrams (Figs. 9-2 and 9-3).

The foregoing remarks indicate that even for floodplains and terraces, *fluvial constructive action is complex; it involves a simultaneous degradational and depositional process, or sequence of the process;* some *large* amount of depositional action is associated with it; the resultant landscape modification is much different from that created by fluvial erosive action, tending toward a low flat order of relief rather than a high rugged order.

[3] Thwaites (201) presents a number of comments summarizing those things that are known about fluvial transportation and deposition.

From these statements the basic criteria can be established for fluvial constructive landforms. The landforms must be:

1. Composed of materials transported by *flowing, surface, stream waters* without the modifying action of any large-scale extraneous factors or features (tectonicism, winds, glaciers, waves, large bodies of relatively still water, etc.)
2. *Largely composed* of materials derived from normal erosion and *deposited* by normal runoff waters related to the climatic regimen that existed when the landform was created
3. Distinguished by a landform that is the product of *depositional action alone* or *combined depositional* and *degradational action* or *sequences of these actions*
4. Distinguished by a landform whose surface tends to be smooth, flat, or accordant, reflecting both water deposition and over-all reduction of relief

9-5. The Fluvial Constructive Landforms. The fluvial constructive landforms may be classified according to whether the dominant characteristics of their form are the result of a close, or nearly equal, combination of fluvial-erosive-depositional action or depositional action alone. The classification may be made as follows:



Fig. 9-6. Stereopair showing a portion of a meander floodplain in the meander-belt stage. The meander scrolls on the point bars *PB*, a truncated point bar (fairly rare at this early stage), is at *TPB*. An oxbow lake O is filled largely with mineral material toward the river and is farmed. The remainder still holds water. The oxbow is fairly young, as indicated by the organic marsh deposits *M* that are just beginning to encroach (Chap. 15). Part of the reason for the oxbow filling is the small stream delta *D*, remnants of which are still visible. The cut banks are characterized by land slippages *Ls* (Chap. 18). The remnants of a former floodplain appear at 1. The river valley is eroded in a glacial plain. The nature of the individual point-bar ridges has special significance to an experienced interpreter. (*Canada. Photographic Survey Corporation.*)

A. Landforms whose dominant topographic characteristics result from a close combination of fluvial erosive and constructive action
  1. Floodplains
    a. Associated with streams of predominantly single channel flow
      (1) Meander plains [4]
      (2) Covered plains [4]
      (3) Composite plains [4]
    b. Associated with streams of predominantly multiple channel flow
      (1) Bar meander plains [4]
      (2) Bar plains [4]
  2. Terraces

B. Landforms whose dominant topographic characteristics result primarily from fluvial constructive action
  1. Fans
  2. Bajadas
  3. Bolsons and filled valleys
  4. Fluvial piedmont plains
  5. Fan deltas
  6. Fluviodeltaic plains

[4] These terms were proposed by Melton (126).

In addition to these true, exclusively fluvial, constructive landforms, there are certain landforms with characteristics that are greatly affected by fluvial action but are also affected by processes associated with another origin. These include:

A. Colluvial and colluviofluvial forms
  1. Talus or screes
  2. Colluvial cones
  3. Colluviofluvial cones
  4. Rock glaciers (often considered a glacial form, Sec. 12-8)

B. Fluviomarine forms
  1. Deltas
    a. Arcuate and modified arcuate
    b. Bird's-foot
    c. Estuarine and bayhead
  2. Fluviodeltaic plains
  3. Fluviomarine flats and marshes (tidal flats and marshes)

C. Glaciofluvial forms
  1. Outwash forms
  2. Terraces
  3. Eskers and crevasse fillings
  5. Kame-type and other ice-contact deposits

D. Glacio-fluvio-lacustrine and marine forms
  1. Deltas and deltaic fronts
  2. Subaqueous beds.

E. Fluvially sculptured and veneered rock forms
  1. Rock pediments
  2. Rock fans
  3. Veneered rock terraces.

Of the true fluvial landforms, those resulting from combined erosive and depositional action (floodplains and terraces) are treated in this chapter. Those resulting from a predominance of depositional action (fans, bajadas, etc.) are treated in Chap. 10. The glaciofluvial forms comprise the subject matter of Chap. 13, and the fluviolacustrine-marine forms are discussed in Chap. 11.[5]

9-6. Formation of Floodplains Associated with Streams of Single-channel Flow. In Sec. 9-4 it was said that once a stream attains a graded condition it engages largely in lateral migration (meandering), lateral erosion (planation and cut-bank erosion), lateral deposition (bar and scroll formation), and vertical deposition (covering), creating distinctive landforms called floodplains.

The type of floodplain that is formed depends to a large extent on the dominant types of floods which the stream experiences, for it is during the periods of greatest flow that the great erosive and depositional changes occur. Neglecting the minor effects of vertical erosion, a stream in flood may erode laterally or deposit vertically and/or laterally.[6]

If the graded stream is subjected, with most frequency, to "bank-full" floods, it will engage in lateral erosion and lateral deposition, creating a *meander floodplain*. If a change in stream characteristics causes "over-the-bank" floods to occur with predominant frequency, vertical deposition will create a *covered floodplain*. Combinations of the two types of floods will result in the formation of *composite plains*.

All these plains, as associated with streams of single-channel flow, are flat plains of comparatively low topographic situation, existing at the level of, slightly above, or slightly below an adjacent parent stream and characterized by distinctive remnants of erosion and deposition.

The visible differences between meander and covered floodplains are found in the nature and distribution of the erosion and deposition remnants. Meander floodplains are characterized by well-developed, often intricate patterns composed of closely spaced, often overlapping series of channel scars, meander scrolls (bar deposits), oxbow lakes, etc., and a surface at or very slightly higher than the present channel. The present channel may be single in nature, or it may be braided. The braided variation, called a *bar meander floodplain*, is treated in Sec. 9-7. Figure 9-3 shows a well-developed meander plain in oblique view. Meander floodplains display many variations. However, they may usually be expected to be largely composed of coarse-textured materials and seldom subject to over-the-bank floods.

Once a meander plain has been constructed, a change in the flood characteristics of the stream may produce a *covered floodplain*. Such a plain is constructed by an effective frequency of "over-the-bank" floods. When such a flood occurs, there is a fairly sudden decrease of stream velocity in the vicinity of the natural banks and some medium (silty) to coarse (sandy) sediments are deposited. These streamside deposits are called "natural levees" and sometimes exist at elevations which are 10 to 15 feet above the surrounding plains (Fig. 9-4). The finer sediments (silty clays and clays) are carried far over the plains, being

[5] Except tidal flats and marshes, which are discussed in Chap. 15.

[6] The following discussion is partially based upon a paper by Melton (126).

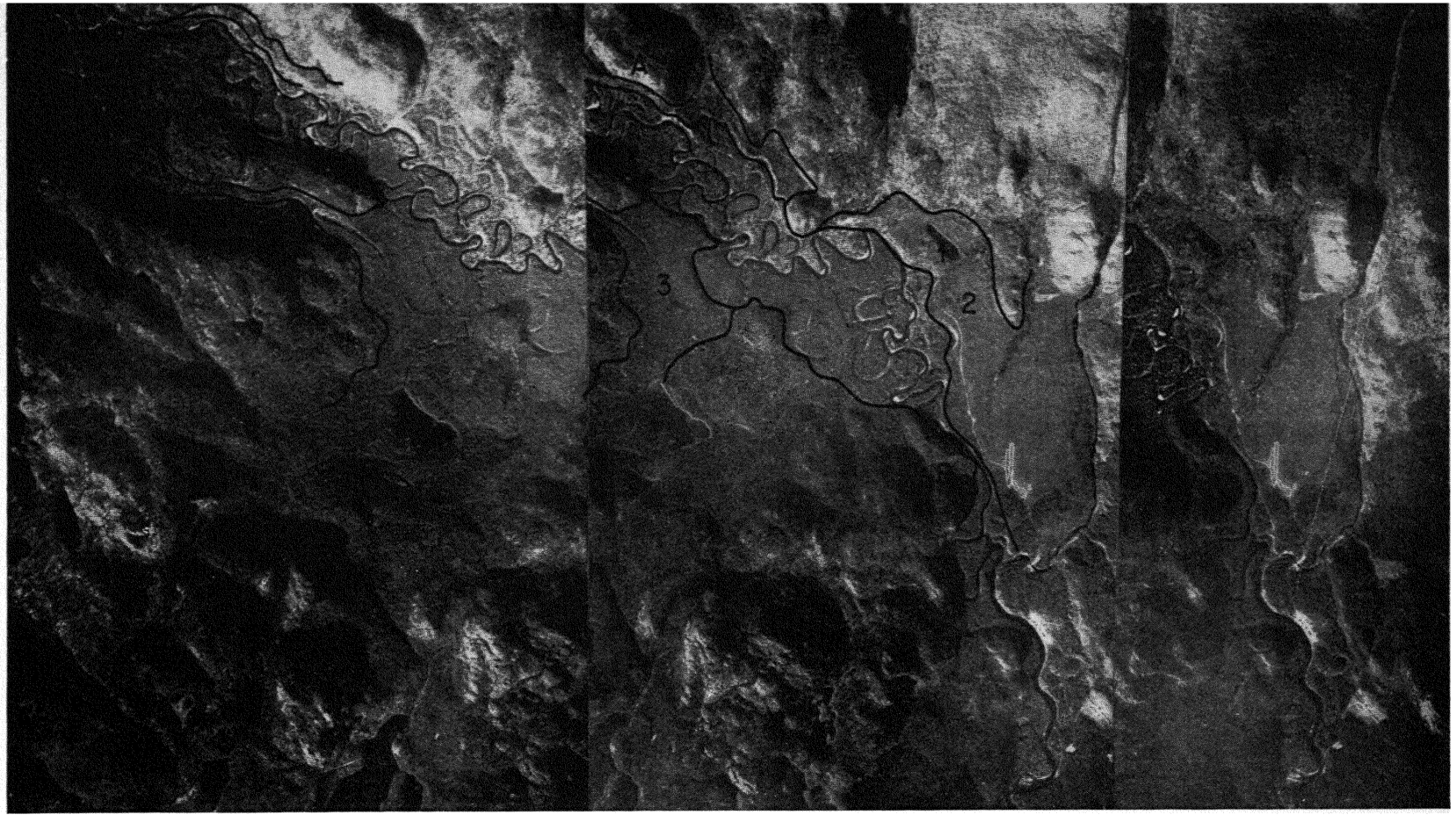


Fig. 9-7. A stereotriplet showing a meander floodplain a little beyond the meander belt stage. The belt is beginning to migrate. This stage, and indeed meander floodplains in general, are fairly rare in this geomorphically youthful country. It is probable that the development shown is the result of an approach to local base level. Normally, such attainment would result in a very narrow plain, as at *A* and *B*, because of the rock strength (granitic gneisses, Chap. 16). However, in this particular stretch the valley has been filled with glaciofluvial outwash (Chap. 13), which is much less resistant to erosion, and the plain has been carved into its surface. All the features of lateral erosion and deposition can be seen or inferred (despite vegetative cover) on the meander plain. This is quite a contrast to the almost featureless surface of the preexisting valley fill. Only a few indications of flow are apparent (1, 2, 3) where a kettle, faint channel scars, and the remnant of an old outwash distributary persist. The outwash, of course, is granular, as indicated by its lack of erosion, relatively light tone, landform, and certain drainage details. (*Quebec. Photographic Survey Corporation*).



Fig. 9-8. This large-scale stereoview of meander floodplain details shows the truncated areas of forested meander scrolls at various levels and representing various ages: the constructional meander-scroll drainageways *D* (Chap. 4); a recently abandoned channel *C* filled with sediment; typical point-bar organic-mineral marshes *OM* and bogs *B* (Chap. 15); very recent sand-gravel bars *SB*; and a well-developed, soon to be cut, point bar *PB*. *AD* indicates sand-dune developments. The circles indicate points of survey control. (*Alberta. Photographic Survey Corporation.*)

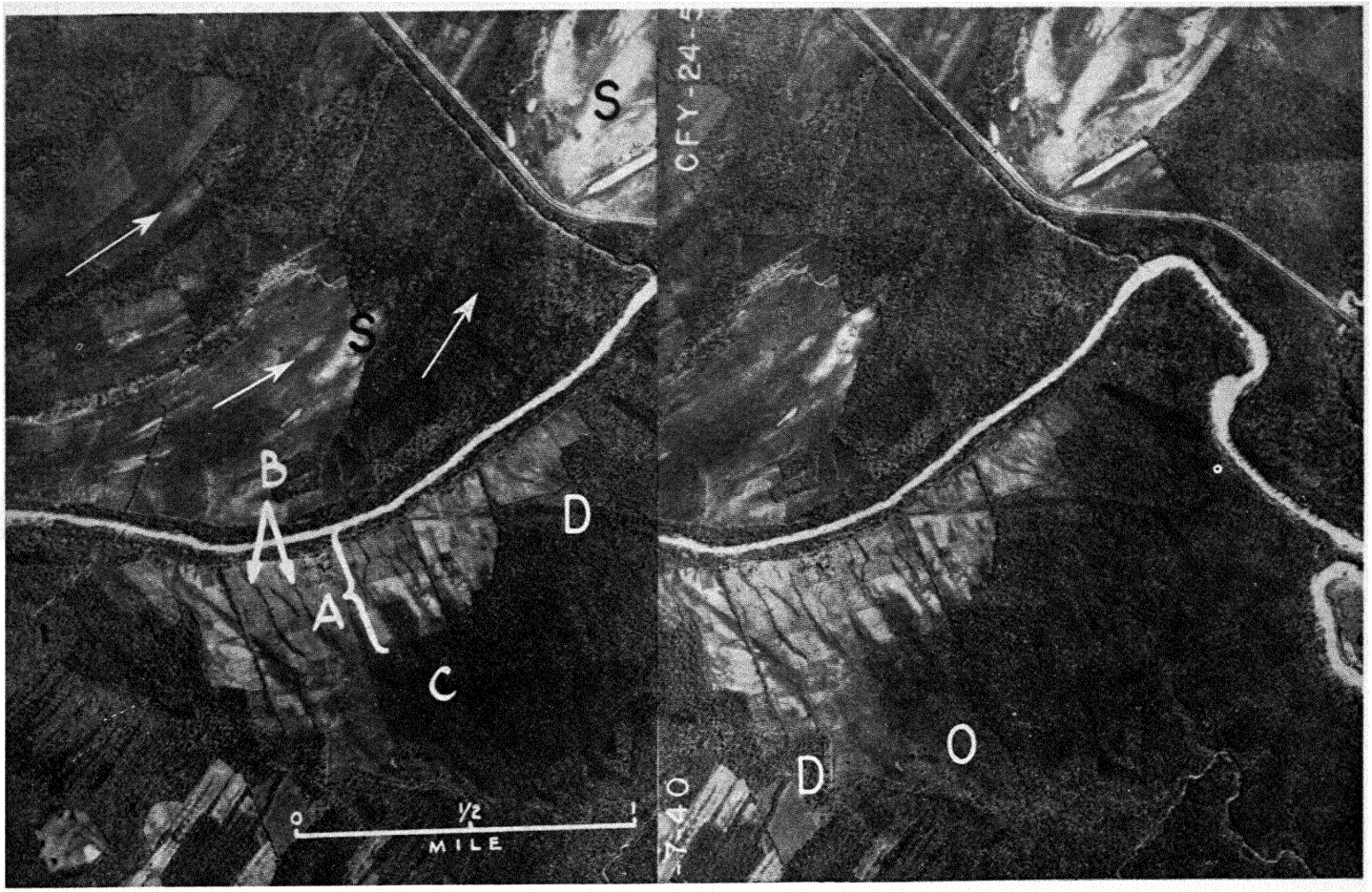


Fig. 9-9. This stereopair is an excellent depiction of many covered floodplain features. The natural levee *A* with its inward drainageways *B* leading toward a low backswamp area *C* are all shown. A former channel *D* with its accompanying levee drainage is visible. This portion of the floodplain is composite rather than truly covered, since these remnantal channels, as well as a tiny oxbow *O*, are still evident. Also, a recent high-water stage breached the natural levee off the picture to the left and flowed rapidly across the covered portion of the plain, leaving flow scars (arrows) and granular to semigranular deposits (light tones *S*). (*Texas. USDA, Commodity Stabilization Service.*)

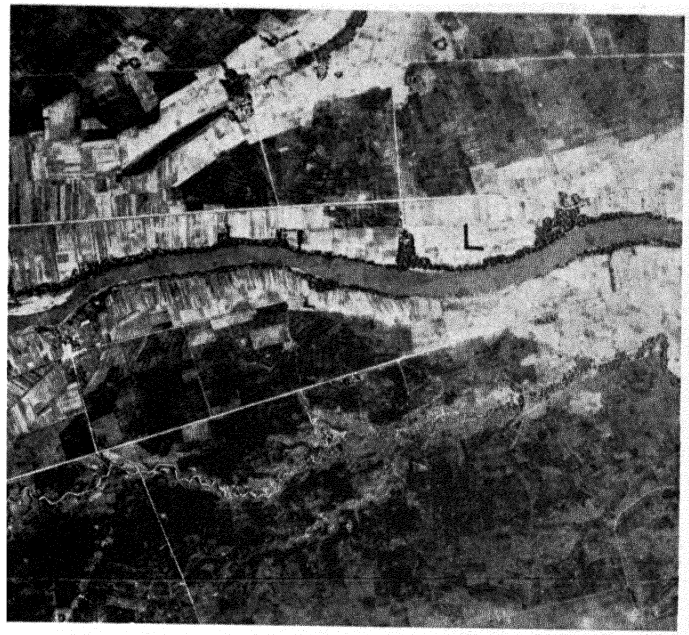


Fig. 9-10. A single photograph of a covered floodplain that shows a remarkable correlation between cultivation pattern, tonal pattern, natural levees, and backwater areas. The light bands adjoining the present and old channels are relatively high, coarse, and well drained. The darker areas are low and have a high water table. A Yazoo-type river appears in the bottom of the picture. (*Philippines. U.S. Army.*)

dropped only when the velocity of flow becomes very low, to form temporary lakes and, ultimately, backswamp and slack-water deposits.

Since these sediments are spread over a previously existing floodplain, and since bank-full floods may still induce meandering, the remnants of oxbow lakes, meander scrolls, channel scars, abandoned channels, old sand bars, etc., may exist in the midst of the alluvial cover. It should be remembered that this plain is largely a surface of vertical deposition. Consequently, the alluvium (except for possibly granular natural levees) may be expected to be fine-grained in texture and of considerable thickness.

Many streams experience both bank-full and over-the-bank floods with reasonable frequency. In such cases, features of both the meander and covered floodplain may be present, but natural levees will usually be absent. The landforms are designated as composite plains. In many cases, while a true composite plain may exist, one type of deposition may be more effective than the other, in which case the composite plain may be predominantly a covered plain or predominantly a meander plain (Fig. 9-5). A decision regarding the type of composite plain is important since the physical texture varies as the type of plain varies. Since a meander plain is largely composed of laterally deposited coarse materials and a covered plain is an area of vertically deposited fine materials, combinations of the two may be expected to be rather complex. As a rough guide, the frequency and visible development of meander scars, oxbows, etc., can be noted. As the frequency and development decrease, the amount of fine-grained materials present usually increases. In a true covered plain, practically all the meander evidences would be absent except those immediately adjacent to the river.

9-7. Formation of Floodplains Associated with Streams of Multiple-channel Flow. If during the flood stage, the stream is not overloaded, a simple meander plain, similar to that considered in Sec. 9-6, will be formed. If during flood, overloading does occur, a "bar meander plain" may be formed. Such a plain is characterized by a level surface existing between valley walls, scarred with evidences of past irregular and bar deposition and adjacent to a slightly lower stream channel which is *partially braided*, the greatest amount of braiding usually occurring at the bends. This bar meander plain is formed when the flooded channel engages in meandering and bar deposit. When floodwaters subside, quantities of sediment are dropped, partially choking the channel. The choking is most noticeable at the bends where erosion appears to progress faster than transportation.

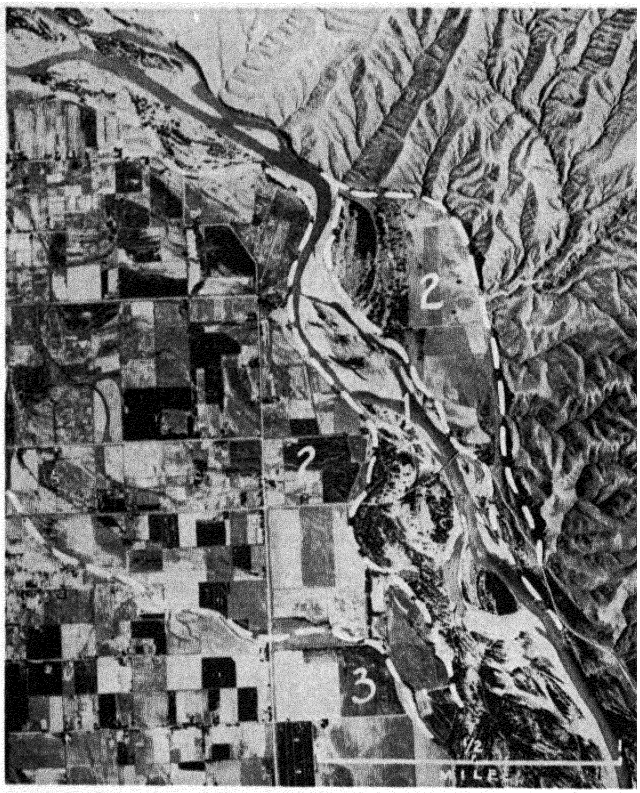


Fig. 9-11. This figure shows a bar meander plain developed at two major levels (1 and 2). Notice the angularity of both the active and fossil meanders. Note also the braiding at the bends. These are both features of bar meander plains. Level 1 is composed of sands and gravels. Level 2 includes about 1 foot of loam over sand and gravel. Level 3 includes silty clays to clays varying in depth from 2 to 12 feet. It represents an old partially covered plain of fluvial activity. (*Montana. U.S. Department of Agriculture.*)

During low water, braided channels are formed in these deposits. The low-water channel in other portions of the river may consist of a single, often straight, channel. The alluvium of such a plain may be expected to be largely sands and gravels from the surface down to the floor of the plain. The present partially braided channel may be filled during flood, but the adjacent meander plain will be inundated only rarely.

If the level plain continues but the meander scars and braid scars fade out, the existence of a covered plain must be considered.

Another type of floodplain associated with braided flow is the "bar plain." If conditions are such that great floods of water periodically discharge under conditions of overloading through relatively narrow valleys, this type of plain may result. Under such conditions, the entire valley floor is periodically completely occupied by raging floodwaters that literally obliterate any preexisting features of the valley floor. The floodwaters may carry large volumes of sediment, and when they subside, considerable quantities are dropped on the valley floor. Through these deposits, braided flow is developed until the next flood. These bar plains are usually composed of relatively coarse materials such as silts, sands, and gravels and are subject to periodic inundation of a violent nature.

In some locations a portion of the level plain, usually at a higher elevation, does not display any significant evidence of meandering such as channel scars, oxbows, etc. Such marks, even though they may be apparent on the bar-meander portion of the plain, seem to fade out. Level surfaces lacking these scars must be suspected as covered plains created during earlier, higher flood stages or by colluvial wash. This emphasizes an important point: *a braided stream channel does not necessarily imply that the surface deposits of the surrounding plain are coarse.* A braided stream is the result of overloading and may be created at any time or place, if such overloading is caused. Therefore a braided stream implies the presence of coarse materials only in its own channel, together with those portions of the surrounding plain which display evidences of past meandering. Where these



Fig. 9-12. The pattern displayed by a large bar meander plain in this semiarid region is well shown here. Relief is very low. The various active low-water channels *C*, spill-over channels and bars *B*, some of which are being used for seasonal agriculture (dark tones), and the abrupt bends of the main channels are well shown. (*Middle East. Photographic Survey Corporation.*)

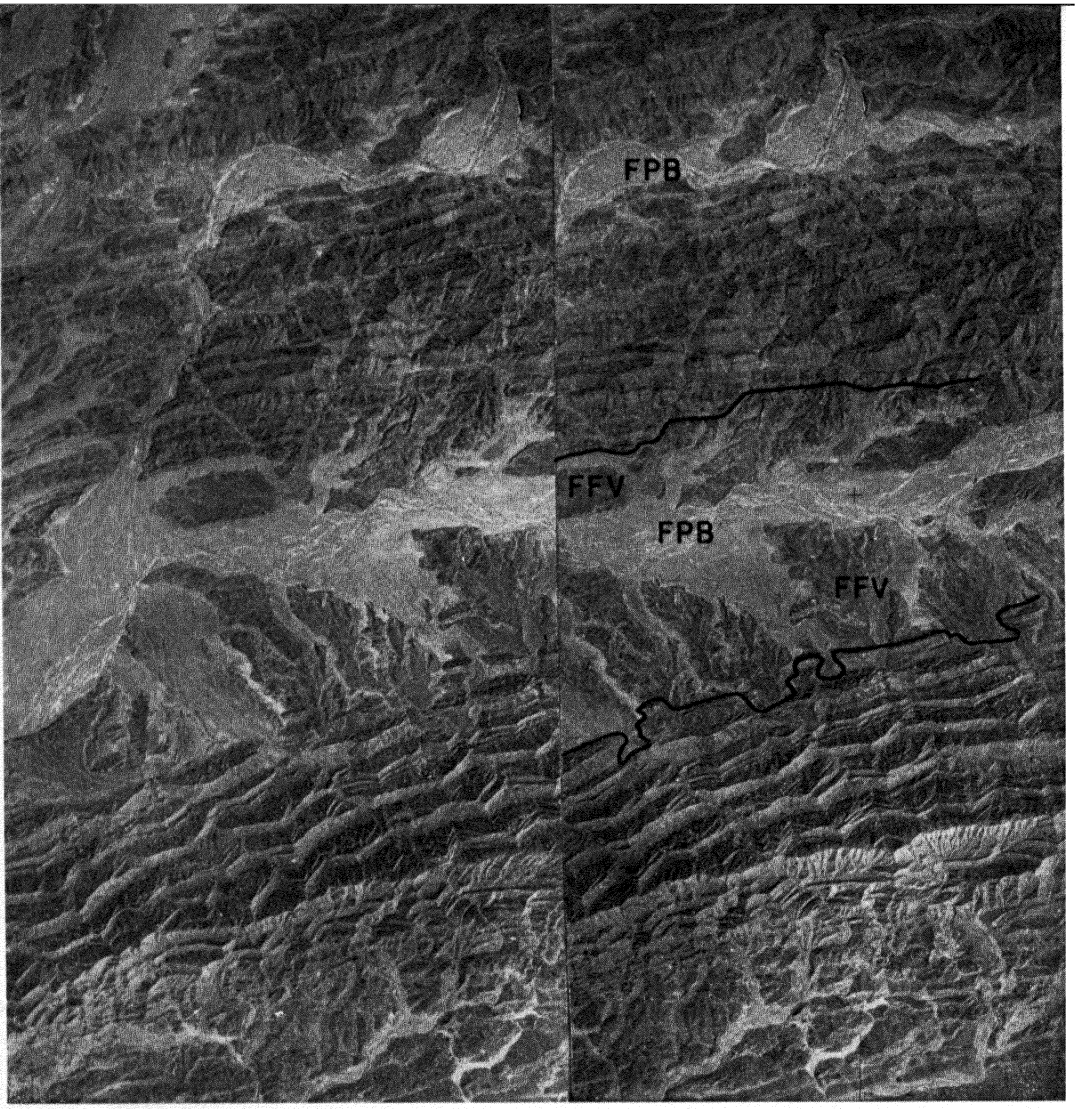


Fig. 9-13. This stereopair shows bar plains *FPB* developed in former valley fill (the remnants of which are easily discernible), which in turn is developed in steeply tilted, fine-grained sedimentaries. The boundary with the filled valley is approximately shown by line. Note the intricately braided channel of the bar plain. Its dark color is due to the fact that it is eroding relatively fine grained materials, having a dark color initially. (*Middle East. Photographic Survey Corporation.*)

evidences fade out, a covered plain may exist. Although such plains may be underlain by coarse materials at depth, their surficial characteristics must be separately interpreted.

9-8. Formation of Terraces. The formation of fluvial terraces is illustrated diagrammatically by Fig. 9-2. As shown by these diagrams, it must be remembered that fluvial terraces are the eroded remnants of old stream bottoms and, consequently, have variable textural characteristics.

The formation of glaciofluvial glacial terraces is similar. However, the meltwaters and stream load are usually much greater in volume, the materials coarser, aggradation and the formation of bar plains the common case. As a result, fluvioglacial terraces are surficially characterized by braiding scars rather than the features of meander or covered plains and are usually quite thick (Chap. 13).

9-9. Aerial-photographic Characteristics of Floodplains Associated with Streams of Single-channel Flow. The dominant characteristics of all floodplains are their relative elevation and topography.

In general, floodplains *are* the lowland within

any local area. The waters of the master stream, together with local deposits of very recent river sediment, usually occur at only slightly lower elevations. Occasionally, because of recent geological uplift, increase in load, or other interruptions of the normal fluvial cycle, the parent stream may again be engaged in substantial downward cutting. If such is the case, there may be one or a series of abrupt drop(s) between the general surface of the floodplain and the master stream. The latter will be carving a new floodplain, and the surface of the upper level and any succeeding levels should *strictly* be considered as fluvial terraces. Normally, however, they are not so considered until the height of the dropoff and the extent of the new floodplain become relatively large. So far as aerial-photographic interpretation is concerned, it is of little significance which they are termed.

A generally flat surface, combined with relatively low elevation, is the universal characteristic of floodplains regardless of whether they are meander plains, covered plains, bar plains, etc. The word "flat" should not imply either a table-top surface or a level surface. The processes of formation dictate that both surface irregularities and slopes shall exist. However, the differences in elevation resulting from these irregularities are of minor nature compared to the broad extent of the plains.

The surface irregularities are associated with those remnants of erosion and deposition such as oxbow lakes, abandoned channels, channel scars, and point-bar sloughs (all depressed); point-bar meander scrolls and natural levees (relatively elevated); and low terraces representing successive short-term levels of river cutting (steplike). Most of these features may be called fourth-order types (Fig. 9-6 and Sec. 6-7). Their identification is



Fig. 9-14. This stereopair shows the fluvial plain (in a young stage of meandering, but modified by occasional vertical deposition) of a small river. The incised plain and low present channel are well shown (these have been incised because of rebound of the region following retreat of the glacier, as well as recent heavy flooding). A high stage of fluvial terracing *FT* also appears. This is being removed, as is attested by its remnantal nature, indications of lower levels, and old channel scars *C*. (*Ontario. Photographic Survey Corporation.*)

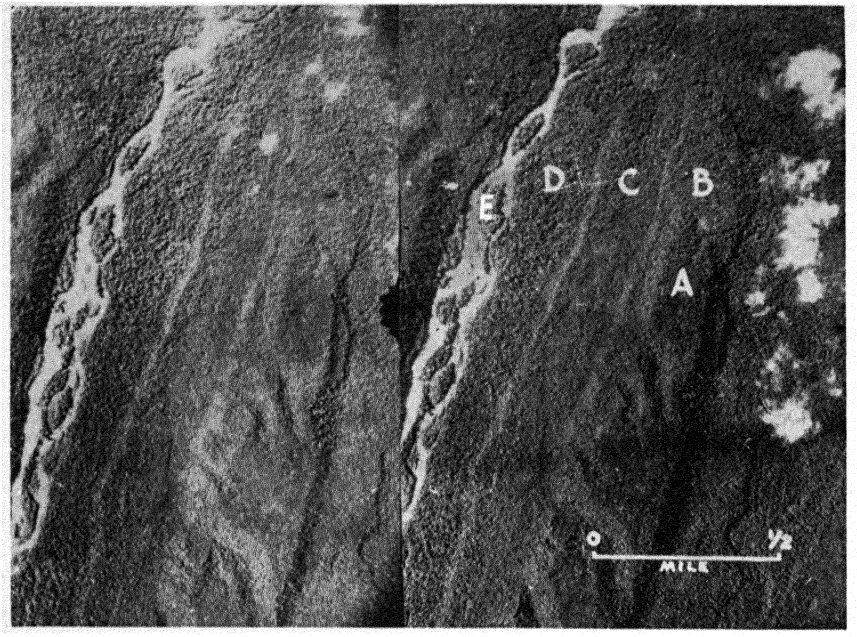


Fig. 9-15. This stereopair shows a remnantal terrace development having five levels *A–E*. The uppermost two levels have been subjected to extraordinarily deep gullying. The reason is somewhat obscure, and it is not even clear whether erosion began at the lower level and ate upward, or vice versa. This erosion indicates a certain amount of cementation, or finer grain sizes than might be otherwise suspected. This stereopair was included to show that landform and erosion pattern is not hidden by dense tropical forest cover. The river has formed a small bar meander plain. (*New Guinea. U.S. Army.*)

important confirmation of floodplain deposition as well as an indication of differences in the texture and stratification of such deposition.

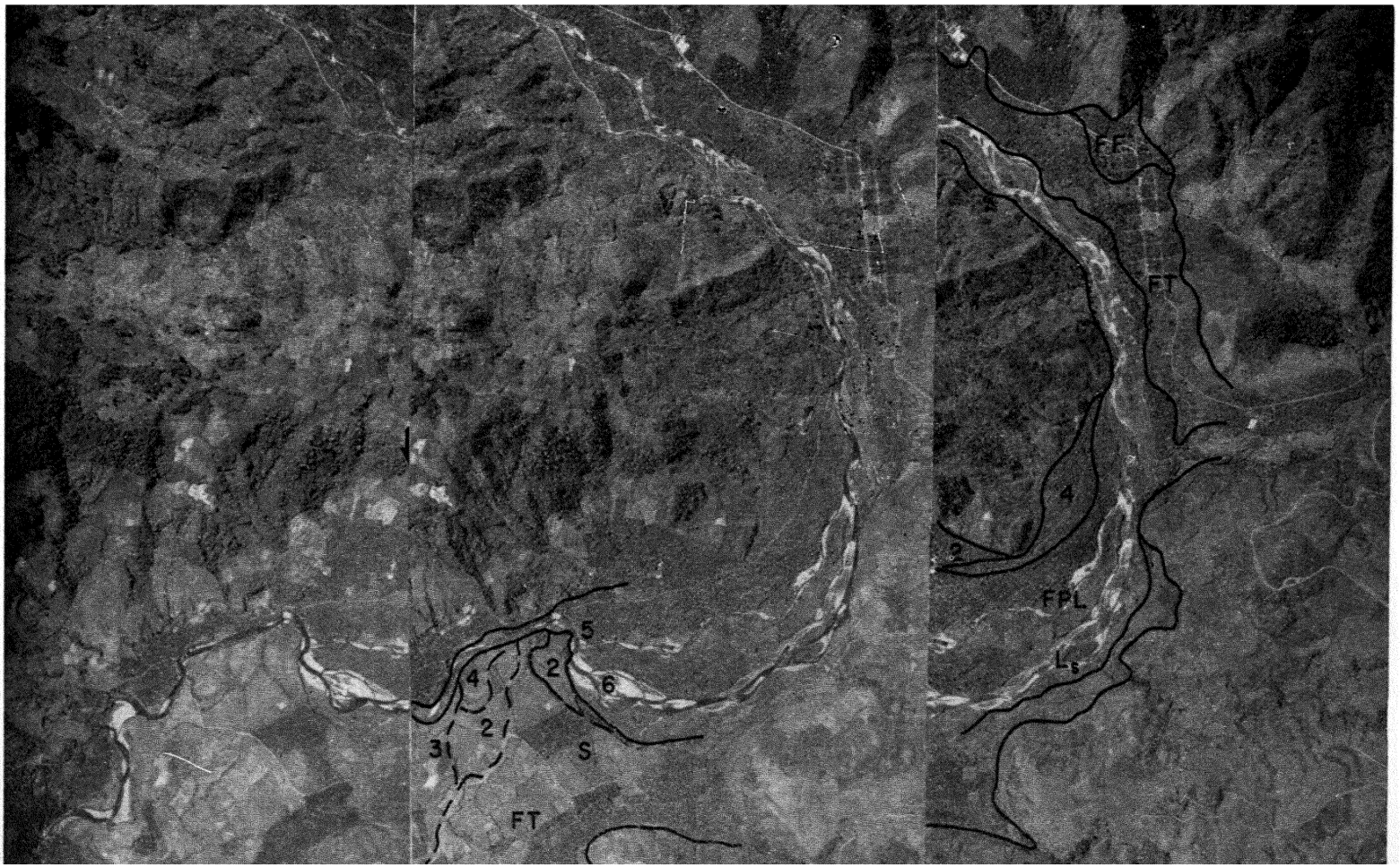
Surface-drainage features associated with single-channel-type floodplains are variable. The master stream is always present, near or far away (the floodplain of the Mississippi has a width of 125 miles at one point). Generally, it may be expected to have few or no rapids unless it is undergoing rejuvenation or encountering fresh competent rocks. Riffles, particularly on meander plains, may be present in the areas of bar deposition. Except for the master stream and its tributaries (which cut *across* the floodplain), integrated drainage is lacking because of low position and periodic flooding or deposition. Of course certain constructional drainage patterns (Sec. 3-5) may exist in connection with fourth-order features, e.g, meander scrolls, oxbows, abandoned channels, and old braided flow scars. These do not represent integrated drainage.

Often drainage patterns develop on large natural levees. However, if present, such patterns show that flow waters are proceeding *inward*, away from the master stream, rather than in a normal direction.

The tone characteristics of floodplains may range from almost uniform to exceptionally variable, depending on both the area within the floodplain that is being examined and the type of floodplain development. Alternating light and dark streaks, indicative of slipoff-slope action, are common even on plains that may be properly classified as "covered." Dark tones, coincident with the depressed muck-filled or poorly drained sloughs, abandoned channels, etc., are also common. Light- to dark-gray uniform tones in slack-water areas, complicated braid patterns, and lighter natural levee tones are other variations that may be expected when examining the aerial photographs of floodplains associated with streams of single-channel flow. The exact nature of tone patterns

Fig. 9-16. This stereotriplet shows a well-developed fluvial terrace *FT* in the tropics. The usual flat-topped and scarped landform, developed on at least four general levels (*FT* to *5*) is well shown. Channel scars are largely absent, except at *S*, probably because they have been obscured by processes of tropical weathering. These processes have apparently not gone far enough to allow the creation of erodible surficial layers (Chap. 4) and the consequent development of a drainage and erosion pattern, although a stream has been established in the vicinity of *D*. Elsewhere, drainage and erosion are almost completely absent, and even the highland streams disappear when they reach the terrace. Exceptions occur where the terrace is very narrow. The over-all uniform dark-gray tone of this photograph is typical of photography taken in tropical areas. It is partially caused by the predominance of reddish weathering colors.

A fluvial fan *FF* (Chap. 10) occurs along the valley wall. A bar meander plain *FPL* has been developed in the valley, the most active level being 6. Cut-bank erosion has caused land slippage at L_s (Chap. 18). (*Central America.*)



has no norm and must be related to the history of the floodplain as well as the climatic environment in which it has developed.

The vegetative and cultural characteristics of single-channel floodplains are also variable. Except in remote or relatively inaccessible areas, floodplains are intensively used for agriculture of all types and natural (wooded) vegetation is lacking. Where high water tables or adverse drainage conditions inhibit agriculture (backswamps, abandoned channels), natural swampy or marshy vegetation may be present.

Figures 9-6 to 9-10 illustrate floodplains associated with streams of single-channel flow.

9-10. Aerial-photographic Characteristics of Floodplains Associated with Streams of Multiple-channel Flow. The remarks included within the first five paragraphs of Sec. 9-9 may be considered applicable to floodplains associated with streams of multiple-channel flow. Of course, surface irregularities and surface-drainage features related to natural levees will be absent; those associated with meander scrolls will be less frequent or

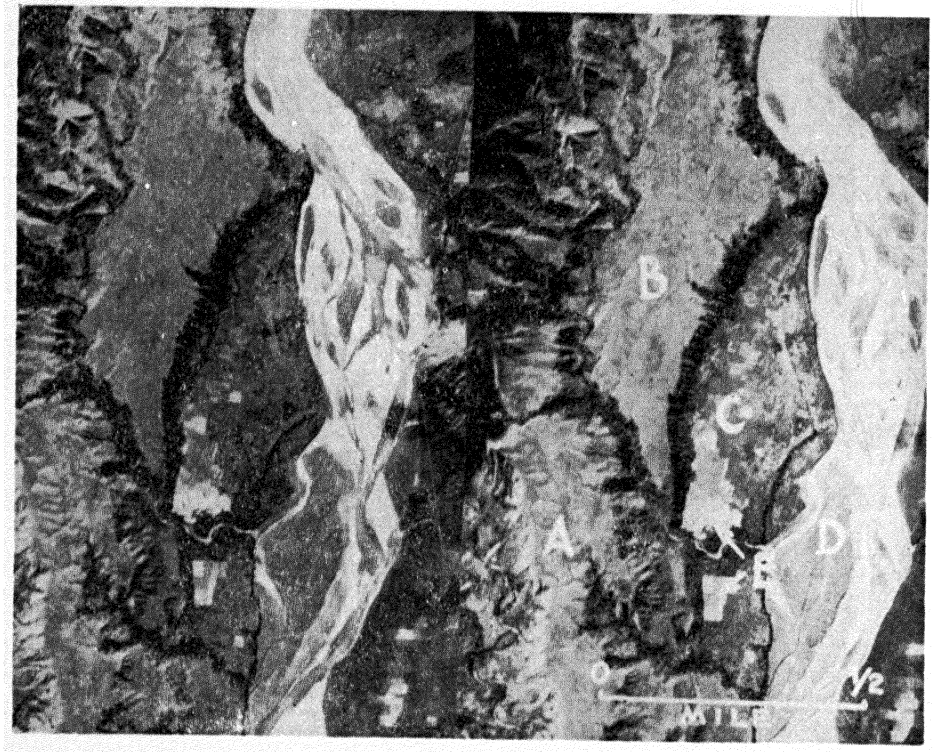


Fig. 9-17. This stereopair was chosen from the author's collection to illustrate a common appearance of terraces in the tropics. Five distinct levels of terracing are apparent. The oldest and highest (*A*) is characterized by intensive erosional development along its scarp, as well as the beginnings of a drainage network over its surface. It has already virtually been separated from its valley wall by the headward erosion of a stream running along the rock contact. The sides of the scarp along this terrace are not as steep as might be adjudged normal for granular deposits. The second level (*B*) has steeper sides and little side erosion, although some gullies appear to be starting. Some long shallow gullying is apparent on its surface. This presents a rather anomalous pattern since the channels have great length with few tributaries. A rock-contact stream is also beginning to separate this level from the wall of the valley. The lower levels, including the bar meander plain (*D*), are devoid of erosion scars and drainage. The *B* level offers better materials for construction by virtue of being somewhat more granular and less deeply surficially weathered. It is probable that its surface will resemble that of the *A* level in time, but its sides are much steeper. The lower levels are composed of the best material of all.

Note the common uniform medium- to dark-gray tone, except in the river plain and at *E* where granularity and lack or change of vegetative cover have altered the pattern. This uniformity of cover reflects both the widespread grass cover and the weathered color of the soils. (*Philippines. U.S. Army.*)

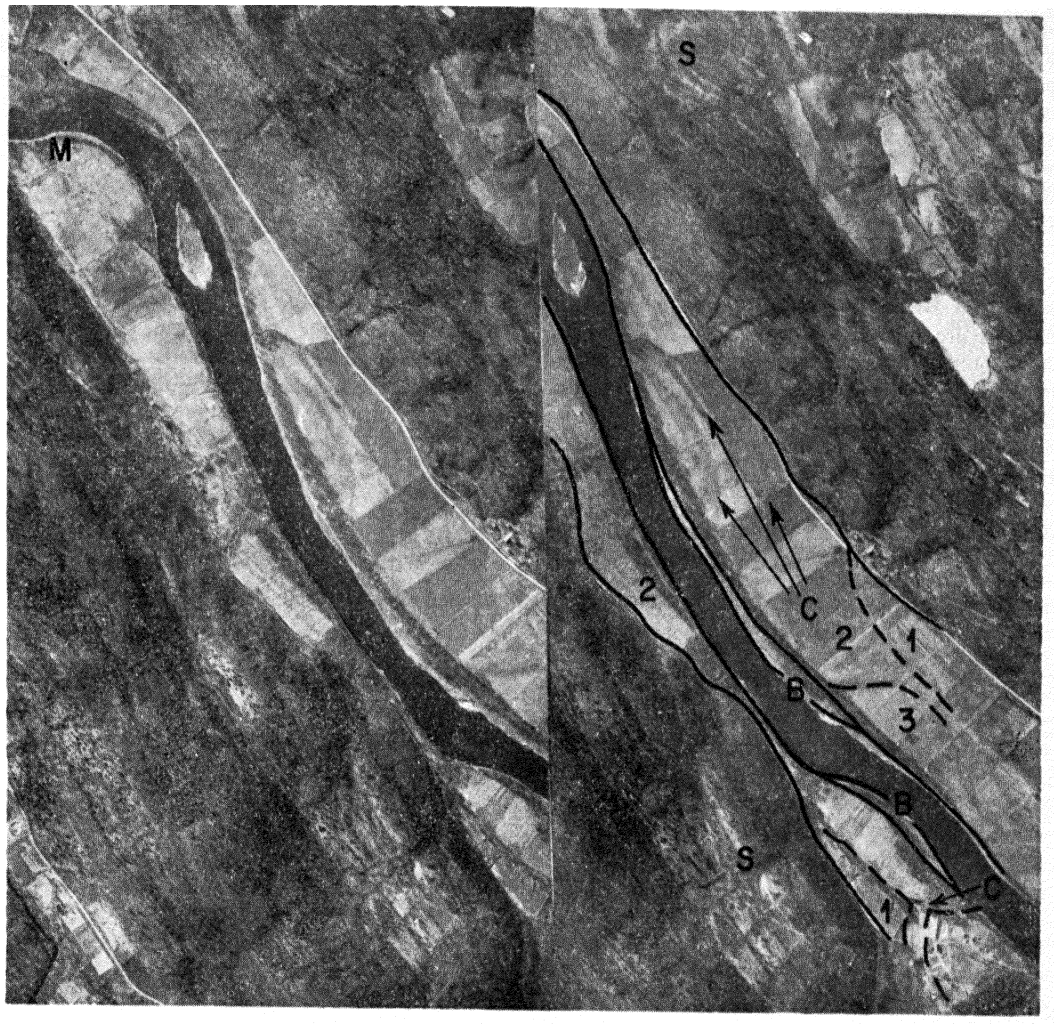


Fig. 9-18. A glaciofluvial terrace in a humid climate. The typical flat-topped, steep-sided, multilevel (1–3) landform is distinguishable even though somewhat subdued (one reason why this pair was chosen rather than a more striking example). Old channel scars are apparent at C. Recent bars occur at B. It will be noticed that the river, even though there is a wide valley, shows only an incipient meander. This, combined with the fairly deep filling, lack of fossil features indicating past lateral activity, and any features indicative of vertical accretion, allows one to make the confident prediction that the valley has been occupied by outwash, now in the early stages of dissection. Evidences of sedimentary bedding appear at S. (*New Jersey. Aero Service Corporation.*)

entirely lacking; and those caused by braided flow will be more frequent or dominant.

The elements of tone and vegetation or land use provide additional major differences between floodplains of single- and those of multiple-channel flow.

The soil tones on the subaerial higher portions of both bar meander plains and bar plains are predominantly light gray to white.[7] Abrupt changes from light to dark occur at the boundaries between these areas and those areas occupied by braid scars, old channels, and oxbows that are lower and more poorly drained.

Vegetation is almost entirely absent on bar plains because of periodic torrential flooding. Sub-

[7] Except where natural soil tones are dark.

stantial growths of brush and trees may occur on the higher and/or older portions of bar meander plains. Some cultivation may also be developed on these higher areas, but in general, floodplains associated with streams of multiple-channel flow are not considered ideal, or even safe, for agricultural or other cultural pursuits. Figures 9-11 to 9-13 illustrate these flooded plains.

9-11. Aerial-photographic Characteristics Associated with Fluvial Terraces. Inasmuch as fluvial terraces are merely the eroded remnants of old stream bottoms, i.e., floodplains, their aerial-photographic characteristics are almost identical with those of floodplains. Their surfaces have the topography, surface drainage, tones, etc., of the type of floodplain that was developed before they were eroded. There are, however, two important differences: landform and erosion pattern.

The landform is different because of its remnantal character. Since it is a remnant of an old floodplain, it stands above the stream that eroded it and the floodplain developed by that stream at a lower elevation. Consequently, it has the typical flat-topped and scarped-terrace landform. The steepness and sharpness of the scarp are dependent upon the textural composition and stratification of the terrace deposit. They must be interpreted. It might be well to emphasize that, because terraces are remnantal stream bottoms, they need not always be granular in nature, although granularity in part or *in toto* is the commonest case.

Because terraces are relatively elevated, their scarp sides are susceptible to gully erosion. The degree of erosion and the nature of its pattern are dependent upon the nature of the materials forming the terrace and may be interpreted in accordance with the discussions of Chap. 4. Figures 9-14 to 9-18 illustrate the aerial photographic appearance of terraces.

10 FLUVIAL LANDFORMS (Continued)

10-1. Formation of Fluviomarine and Lacustrine Landforms—Deltas and Deltaic Plains. The origin of deltas and deltaic plains is complex. Their existence, composition, and other major characteristics are directly affected by stream action, and in fact they are an extension of stream-bed deposition. However, they have one important difference, that of deposition beneath the surface of the water. This factor is sufficiently important to remove them from the category of solely fluvial forms.

Because they are an extension of stream-bed deposition, and therefore related to the subject matter of Chap. 9, the deltaic forms are considered prior to fluvial fans, which are true fluvial landforms.

When a loaded stream empties into a comparatively large body of water, such as a lake or ocean, its velocity is reduced and its load begins to settle. If the currents and tides of the water body are strong enough, or if the load is small, most of the potential deposition will be carried away from the area around the mouth of the stream. If, however, the currents and waves are weak, or the load is large, deposition will occur at the mouth of the stream, and delta formation will begin.

Ideally, delta formation begins with the deposition of beds that are close to shore and, in all probability, relatively coarse grained (early foreset beds, Fig. 10-1). These beds are deposited under water and have steeper slopes than the underlying floor. Their actual inclinations depend upon many variables, including the coarseness of the material, the profile of the subaqueous floor, the stream regimen, and the nature of current and wave action. It is possible, for example, to have gently inclined beds of coarse material, if current, wave, and river action are such that it can be distributed over broad areas. The fine portions of the load that can be carried by the river and water currents for great distances are very broadly distributed (bottomset beds, Fig. 10-1). They are, in practically every respect, lacustrine or marine sediments (Chap. 11).

Of course, the river maintains its channel across the initial beds (which have the effect of increasing its length and decreasing its gradient, load-carrying capacity, etc.). In the process of doing so, it aggrades subaqueously in the vicinity of its channel. This subaqueous aggradation tends to extend upstream, ultimately becoming subaerial and merging with the true fluvial deposits. These

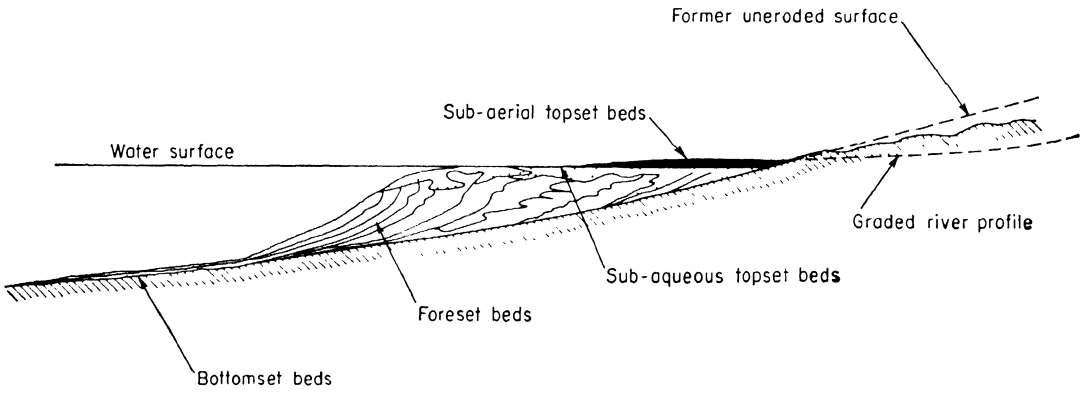


Fig. 10-1. Schematic cross section of a deltaic deposit showing the general relationship between the various types of deltaic beds.

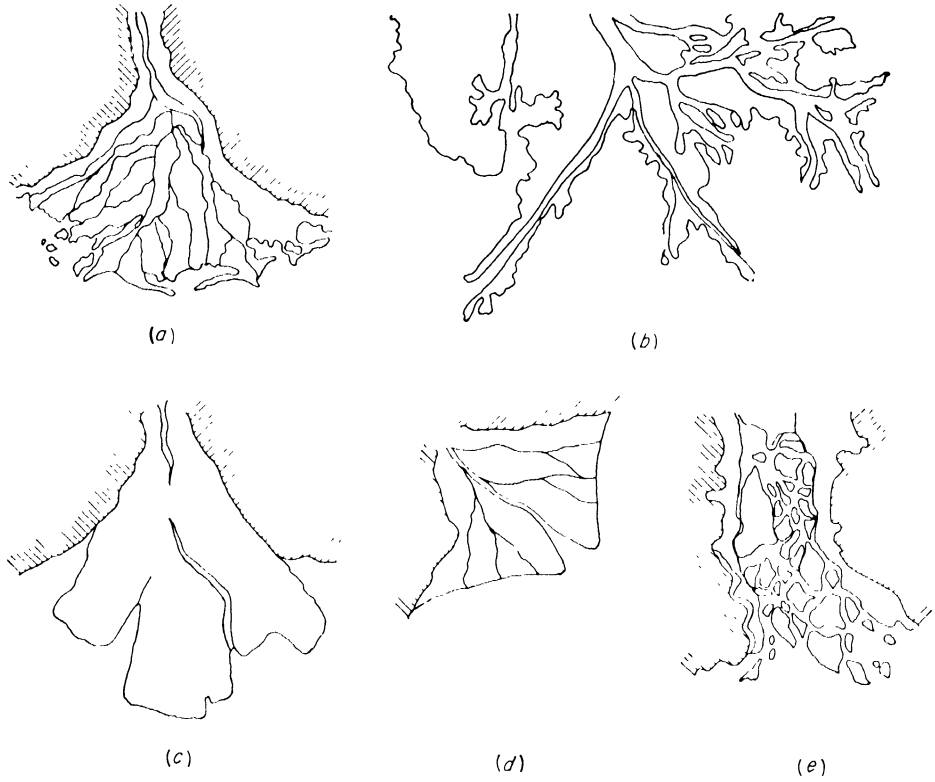


Fig. 10-2. Various general types of delta shapes, including the classical arcuate (a), bird's-foot (b), modified (usually glacial) arcuate (c), the pointed arcuate (d), and one type of estuarine (e).

upper beds, shown in Fig. 10-1, are called the topset beds and *are the sediments which comprise the visible portion of the delta landform.* They are usually gently inclined, both because of their mode of deposition and their dominant sizes in relation to the transporting power of shallow water waves and currents. For similar reasons, they may display cross-bedding. Materials carried beyond the area of topset deposition either fall on the foreset slope, becoming late foreset beds (Fig. 10-1), or if fine enough, are carried by water currents to some distance beyond the delta, settling out as they go and forming fine-grained bottomset beds.

This process continues to progress outward, ultimately building over previous bottomset beds and forming a cross-section structure that may resemble that of Fig. 10-1.[1]

The processes as described, like most fluvial processes, are difficult to discuss in other than a general way. Many things—a frustrating list of variables involving loads, tides, currents, waves, age, and tectonicism—may combine to complicate the picture. As a result, all but the most elemental deltas may be expected to be landforms having great local structural complexity. This complexity increases as deltas get larger until the large deltas, like those of the Nile, Mississippi, Indus, are so complicated as to defy description and structural prediction in any but the most general ways.

There are three main types of delta shapes, the "arcuate" shape, the "bird's-foot" shape, and the "estuarine" shape (Fig. 10-2). Of course, there is considerable variation in each of these. The arcuate shape is most common, the delta of the Nile being a classical example. The bird's-foot shape is

[1] It might be mentioned that the foreset and bottomset beds, while a part of the deltaic form, may be considered as predeltaic lacustrine and marine sediments from the standpoint of their contribution to the visible landform. This latter is provided solely by the topset beds; i.e., a delta is really a fluvial deposit resting upon fluviomarine and fluviolacustrine sediments.

typified by the St. Clair and Mississippi deltas. It is a fairly rare type, occurring only in conjunction with a few rivers. The estuarine shape is extremely variable and occurs quite commonly. The delta of the MacKenzie River is an example.

The visible landform possessed by a delta is primarily dependent upon the character of the water body, the amount of stream load, and the type of stream load. The character of the water body includes the type, strength, and direction of waves and currents, together with the submarine slope. These factors have an effect upon the elevation of the delta above water level and create the minor features which distinguish the delta shore line. The amount of load affects the size and growth of the delta, and in combination with the type of load, has an effect upon visible shape. The type of load, if tides and currents are satisfactory, is primarily responsible for shape.

If a stream, heavily loaded with coarse materials, enters a calm water body, its velocity may be immediately reduced to such an extent that its coarse load will be dropped in the channel which it has maintained through any subaqueous beds. This deposition will tend to dam the flow, causing it to divide around the dam, seeking another, less impeded path. This process, multiplied many times, will create a series of braided distributaries, branching outward in radial pattern from the original stream mouth. An additional stimulus to the creation of braided streams is the loss of stream volume because of the permeability of the subaerial beds. In response to variations of load and to volume, the distributaries will shift extensively, always pushing radially outward and extending the shape equally in all directions. In other words, an "arcuate delta" will be formed. The arcuate shape, therefore, possesses subaerial topset beds which are *comparatively* granular, being composed largely of silts and sands with some gravels. In time, as variations in load decrease, the flow will tend to concentrate in one or two distributaries which will shift only in response to exceptional stream floods.

If the river is carrying a large load of fine-grained sediments, a different sequence occurs. The velocity of the parent stream is reduced as it enters the calm water. However, because the load is fine, deposition occurs more gradually along the bed and sides of the channel which has been created in the subaqueous beds. In time, natural levees, similar to those occurring on cov-



Fig. 10-3. This well-known photograph of a fluvial fan is practically a classic. The landform, drainage pattern, trench-shaped dry washes, and relation to the uplands are well shown. (*California. Spence Airphotos.*)

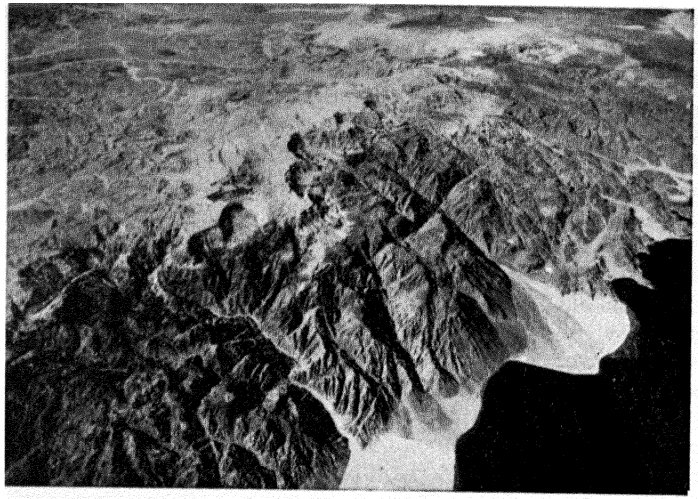


Fig. 10-4. Superbly developed fan deltas in the Middle East. The landform, steep slope, braided drainage, and sedimentation stains are evident. In the background, it can be seen that horizontal sedimentaries (or effusives?) are being dissected. These enclose a shallow filled valley. When headward erosion reaches this fill, the delta fans will be rapidly enlarged, becoming coalescent, a bajada, and ultimately a fluvial piedmont grading into a coastal plain (submerged).

ered alluvial floodplains, will be constructed. As they are built above water level they become the typical "bird's-foot projections." Usually, because of the channel depth and the cohesiveness of the bankside deposits, the channels are quite stable. Occasionally, a bank-full flood will exploit a weakness in the existing natural levees and will break through, carving a new channel, new levees, and a new projection. Once several projections have formed, the area between them is filled with fine-grained materials deposited during the "overbank" stages of the stream. During the overbank flooding, the coarsest materials in suspension are deposited on the natural levees. The entire process is very similar to that which creates covered floodplains.

Several rivers may create separate deltas relatively close to each other along the same coast line. As these deltas expand laterally, they ultimately coalesce, and a "fluviodeltaic plain" is formed. Such plains are usually extremely broad, flat, and complex, and their analysis may be difficult.

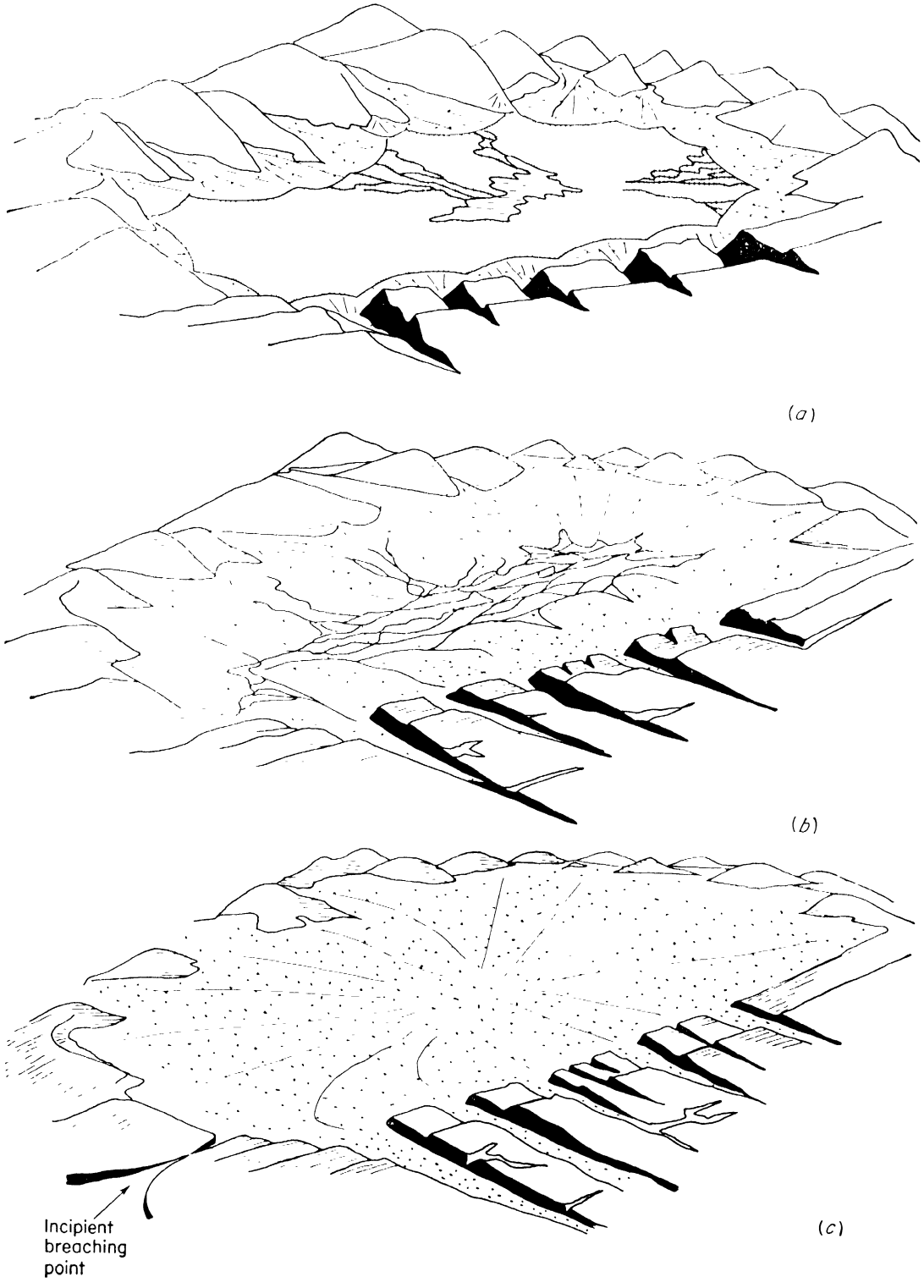
If the mouth of a stream has been submerged, creating an estuary, deposition will occur between the bordering highlands and an "estuarine delta" will be formed. Such deltas are exceedingly variable in shape and characteristics. The deposits may consist of submerged to semisubmerged bars and islands, tidal marshes, or, in later stages, deltaic fill existing above water level.

10-2. Formation of Colluviofluvial and Colluvial Landforms—Talus Deposits, Colluviofluvial Cones, Rock Glaciers. In Secs. 8-1 to 9-8 the topographic features created by normal fluvial erosional and depositional activity were discussed. These ranged from the young, steep valleys (erosional) to mature valleys occupied by graded streams, meander belts, floodplains, etc., to old valleys having terrace remnants to deltaic features.

At any point along a stream path—and at any stage in such a range of ages—additional landforms of a colluviofluvial or semifluvial nature may occur. These include the colluvial deposits, the colluviofluvial cones and rock glaciers, and the fluvial fans. The colluvial and colluviofluvial forms are discussed briefly in this section as a matter of convenience.

Colluvial (from Latin *colluvies,* a mixture) is the origin name applied to heterogeneous accumulations of rock detritus resulting from the transporting action of gravity. It may be applied to a variety of landforms which are known by the general name of "talus deposits." Each of these landforms is created because the downhill, gravity-inspired movement of rock detritus is halted by a reduction of slope and velocity. Many of the landforms (debris-avalanche slides, talus aprons, rock falls, screes, etc.) have an irregular and variable nature conditioned by the topography of their surroundings. Blocks, boulders, chunks, and

Fig. 10-5 (*see facing page*). Schematic diagrams showing a theoretical filled valley (*a*) at the stage when bajadas surround a playa; (*b*) when the bajadas have met at the center, creating an ephemeral (because of the insoaking) braided stream; and (*c*) in the final stage of centripetal development, just prior to breaching and dissection.


(a)
(b)
(c)
Incipient
breaching
point

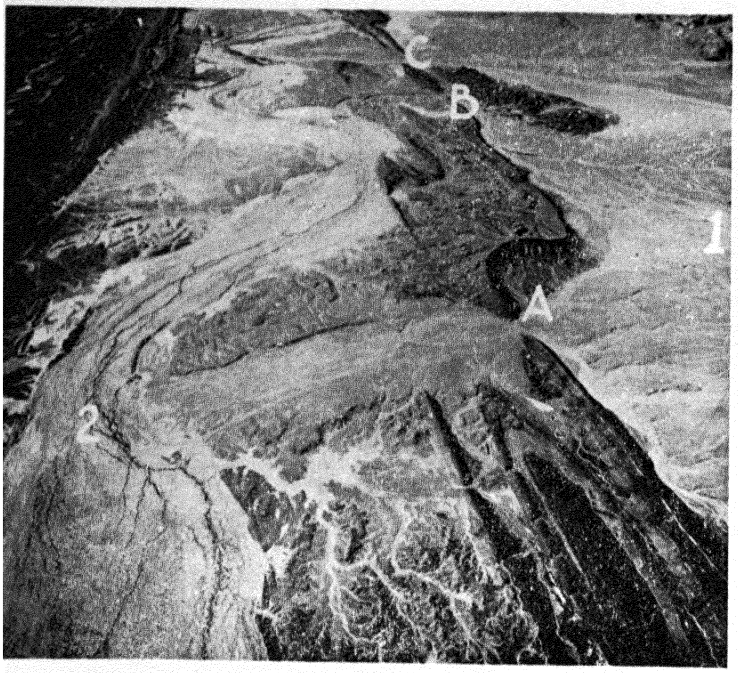


Fig. 10-6. This fine photograph shows a filled valley (1) in the process of dissection. Breaching occurred at *A*, *B*, and *C*, and dissection is proceeding from these points. The contributed fill from above is filling the lower valley (2), where braided intermittent stream flow apparently transports it with some effectiveness. (*North Africa. U.S. Army.*)

grains of bedrock are detached by weathering processes. Because of existing steep or vertical slopes, these detached fragments fall or roll downward, accumulating as talus where the slope changes and velocity is reduced. If the fragments fall in a random manner, all along the crest of an outcrop, miscellaneous talus piles (screes) and slopes are formed. If they move with a mass-rush avalanche, deposits are created. If, however, their fall is channelized into lines, a talus cone is formed (Fig. 10-13).

The talus cone is composed predominantly of coarse fragments. The segregation of sizes is very uncertain. On some cones, a ring of the largest sizes is found around the outer edge of the deposit. These larger fragments rolled there by virtue of their greater momentum, often with the aid of snow deposits on the upper slopes. On other cones larger fragments lodge near the top, while smaller ones spread out to the base. The cones may be quite large, extending upward more than 1,000 feet where conditions are suitable. In addition, they are often exceptionally steep, with angles of 25 to 35° being common. Steeper angles have been observed. In general, the steeper the angle, the coarser the deposit.

Colluviofluvial cones (commonly called "alluvial cones") are talus cones which have also been subjected to the effects of surface water flow, carrying material in suspension and/or as bed load. The water is able to carry particles of a given size a greater distance than they would fall by gravity alone. This combined gravity-water action forms a deposit with gentler slopes than those of the talus cone, together with a more complex mixture of fragmental and particle sizes.

"Rock glaciers" or "rock streams" have not been studied to an extent necessary to arrive at a widely accepted theory. Their formation is mentioned in Sec. 12-8 and they are illustrated in Fig. 12-2. Landslides, mud flows, etc., are discussed and illustrated in Chaps. 4 and 18.

10-3. Formation of Fluvial Fans, Bajadas, and Fan Deltas. "Fluvial fans" are formed almost completely by the action of heavily loaded running water. When a loaded stream, flowing down steep slopes, debouches from a valleyside onto a relatively flat area, the abrupt change of slope causes a reduction in velocity and partial deposition of the stream load in the path of the stream. The water, which still retains considerable energy, branches outward around this temporary dam. This process continues in the branches until a series of braided streams is formed, usually quite close to the original stream mouth. As the branches

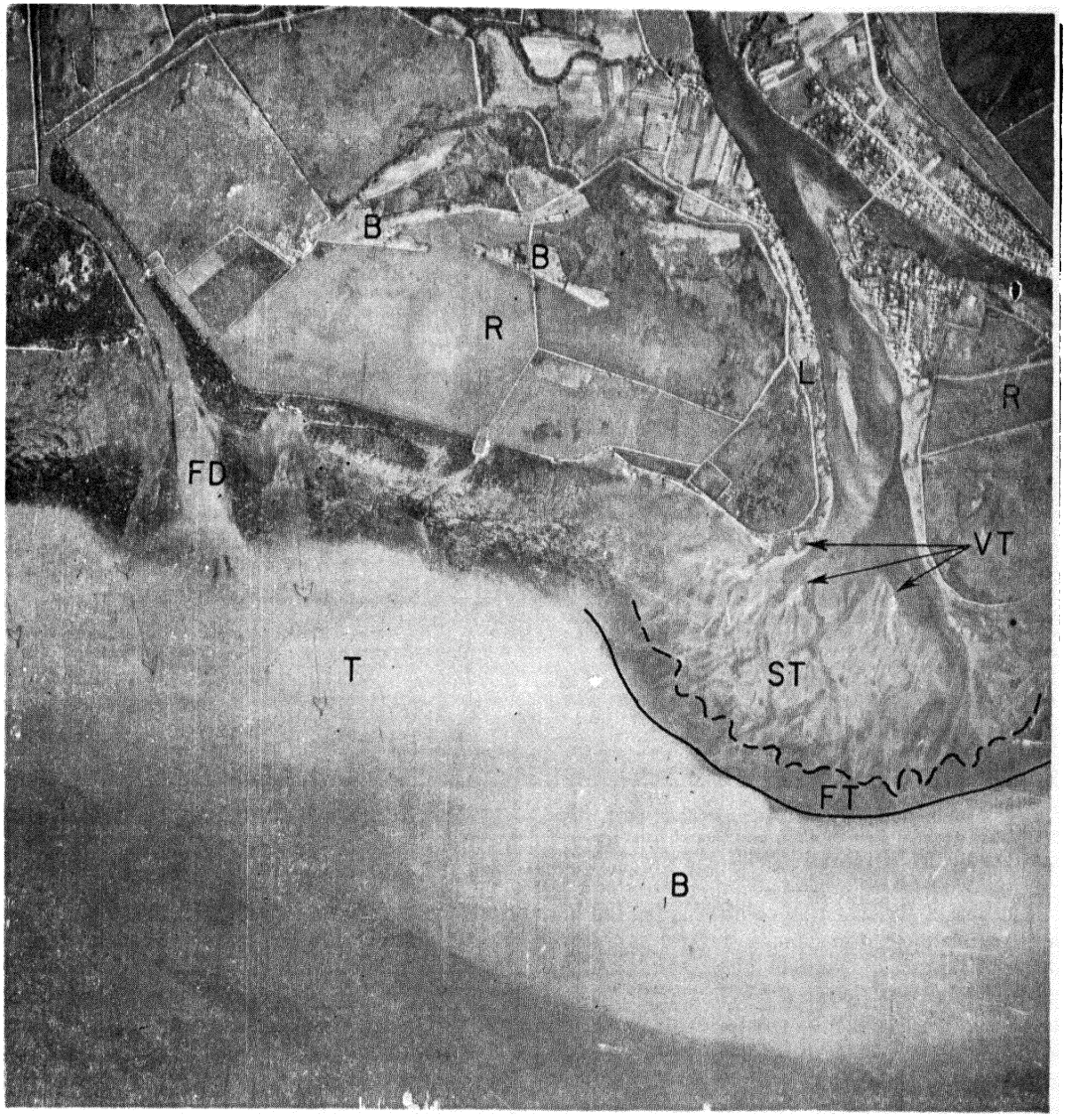


Fig. 10-7. This shows an incipient delta (or at least an extension of a delta). The only subaerial topset beds are indicated by *VT*. Submerged topset beds *ST* extend much farther, and finally merge into the steeper foreset beds *FT*. The finest materials are deposited in the bottomset zone *B*. Another extension or incipient delta occurs at *FD*. Without wider coverage it is difficult to estimate the predominant textures and ultimate shape of the delta. There is much indication, in the form of possible old bars *B*, reclaimed land *R*, and possible old natural levees *L* that this deposition is the outer part of a larger delta, now modified by human activity. Fish traps are shown by *T*. (*Far East.*)

become smaller, they often soak into deposits which were previously laid down and disappear. The result of this process is a gently sloping (1 to 5°) fan-shaped deposit with its head at the mouth of a highland stream and its border feathering out into the surrounding flatter areas.

The materials of the fan are usually roughly sorted by water action into pockets and lenses which extend vertically and horizontally for short distances. The coarser sizes tend to be most thickly distributed near the head of the fan while the finer ones tend to occur near the outer edges.

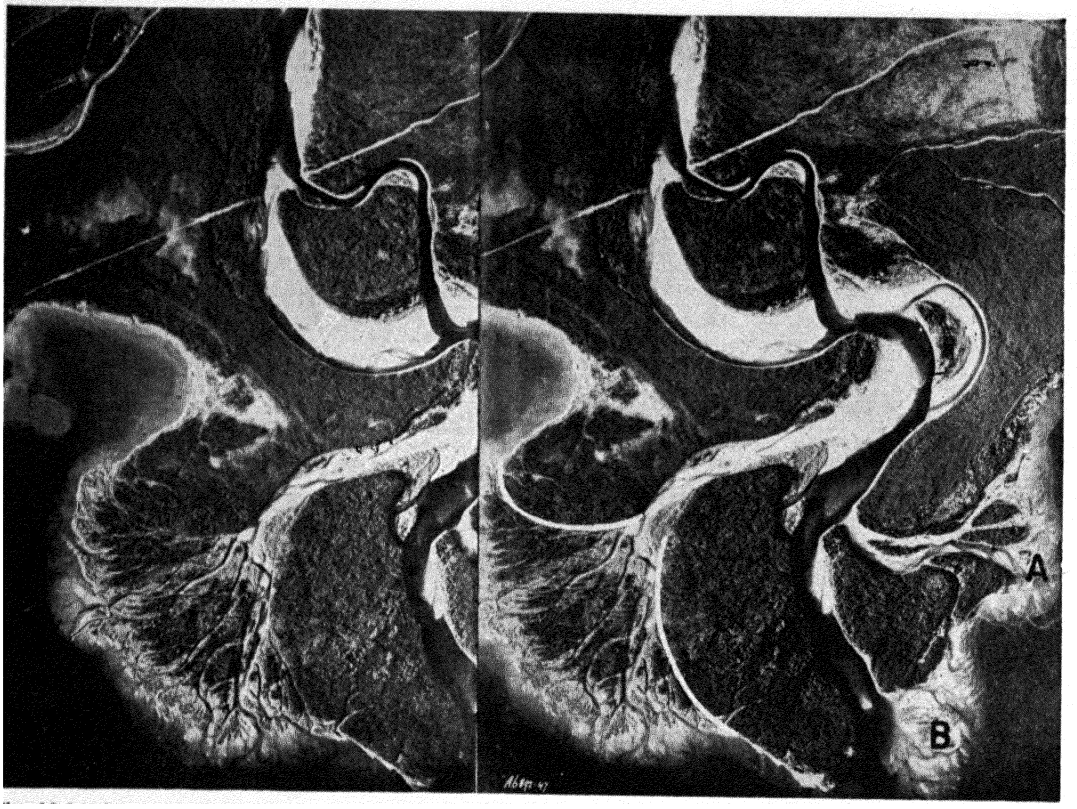


Fig. 10-8. A stereopair showing a young arcuate delta. The shape, braided distributaries, and foreset beds are well shown. This delta is composed of coarse materials. Other, incipient deltas appear at *A* and *B*. Selected and annotated by the author while with the Cornell group (43). (*Labrador. RCAF.*)

The size of the materials composing the fan has a close relationship to climate. In arid and semiarid climates, where physical weathering and intermittent torrential flooding are predominant, the texture is predominantly coarse. Sand sizes and small gravel up to 1 inch in size usually make up the bulk of the deposits. However, the extreme coarseness of some of the materials is a very striking feature of most fans. Boulders of 1, 2, and 3 feet in diameter are usually thickly distributed over the surface and downward through the deposit. Larger boulders, up to 8 and 10 feet, are common, and in California, boulders larger than two-story houses are found several miles from the mountains, resting on, or partially buried in, smaller fan deposits. In humid areas, because of more pronounced chemical weathering and a perennial flow of water, silts and clays may be found in significant proportions.

The size of fans in arid areas depends largely upon their age. Small ones are widely distributed. However, it is also common to find fans which have deposited materials to depths in excess of 1,000 feet at their head end and which spread out in horizontal directions for 5 or 10 miles. Such fans are normally gashed with radiating dry channels from 25 to 100 feet wide and 5 to 25 feet deep. In some cases, because of superfloods or dissective processes, huge "washes" may gash the surface. These broad, steep-sided channels may be several hundred feet wide and up to 250 feet deep (Fig. 10-3). Some fans, because of dissection, may consist of several distinct levels, each with characteristic fan features.

In humid regions fans are generally quite small, ranging up to several hundred feet at their widest point. In addition, their surface is generally fairly smooth.

When two or more fans are built by nearby streams, they may ultimately spread in sideward directions until they merge. Such fans are called "coalescent fans." They are normally separated by

broad, ill-defined, shallow depressions which have not yet been filled with alluvium.

If a series of fans are built outward along a mountain front, the process of outward spreading will ultimately merge the entire series to form a fluvial piedmont apron, or "bajada." The component fans of such an apron will usually be separated by the broad depressions characteristic of coalescent fans. Occasionally, however, because of long-continuing deposition, these depressions may be obliterated (Fig. 10-5). Bajadas are also often in the process of dissection and are scarred with large "washes."

When a stream issues into a lake, its load is deposited under water as predeltaic deposits (Sec. 10-1). Occasionally, however, deposition occurs so rapidly that the materials are built upward into an alluvial fan resting upon the predeltaic deposits. Such a landform has all the aspects of a fan, except that its outward edges are in contact with a permanent body of water. It may be called a "fan delta," for convenience. Where marine beaches have been formed around its outer margins, and if it is large enough, it may be called a "filled-valley coastal plain." This, in a way, is a misnomer.

10-4. Formation of Filled Valleys and Bolsons. True filled valleys refer to those natural basins and valleys of arid or semiarid regions which have been filled with erosion products derived from the surrounding mountains. The products were moved downward from the mountains by typically arid-type, torrential stream floods and deposited in the basins and valleys as fans, bajadas, playas, floodplains, and lake-bed deposits. In time, because of the upbuilding and coalescence of these various depositional landforms, the valley floor was covered and raised by accumulations of fluvial materials. While the valleys were being filled, the highlands were being reduced. Ultimately, the two levels approached each other, and erosion and deposition became temporarily insignificant. This latter stage of almost complete filling characterizes the true filled valley and implies a definite set of identifying criteria.

For the purposes of this book, the term "filled valley" implies a much broader range of conditions than those described above. It includes, in addition to the final stages of valley filling, many of the intermediate stages. Valleys existing in partially filled stages are composed of various individual landforms such as fans, bajadas, etc., and their characteristics are variable, depending upon the number, type and arrangement of the component landforms. Unlike the true filled valley, they are not distinguished by any accurate list of identifying criteria except those of a general nature, such as being situated in an arid basin and being filled by fluvial deposition.

Normally, a valley which is being filled by alluvial deposition consists of a basin surrounded by mountains from which a series of alluvial fans (or a bajada) spreads outward over the surface of the basin. These fans (or the bajada) usually occur

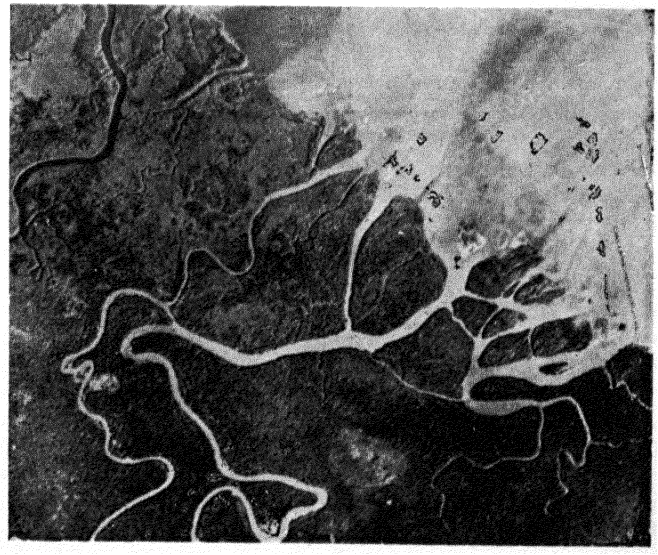


Fig. 10-9. A deltaic front displaying a highly irregular complex of islands, indentations, distributary outlets, and tidal inlets. Some sand bars are also visible. Note the underwater stain caused by the bottomset sediments. (*East Inches. U.S. Army.*)



Fig. 10-10. An excellent and rare view of a deltaic plain, showing the numerous distributaries over a wide front, the feathering off into a quiet lagoon, and the barrier beach created on the gentle slope by breaking waves. This beach allows the feathering off, and where the beach is broken (top of picture), so is the feathered edge. Note the intensive cultivation (right) and dark tones on the deltaic plain. (*China. U.S. Army.*)

along the entire border of the valley and drain toward a central playa or playas. This type of partially filled valley is shown schematically in Fig. 10-5*a*.

In a further stage of this normal process, the fans or bajada encroaching upon the valley floor from two sides meet in the center, leaving an irregular depression along the line of contact. The water, which passes beyond the borders of the fans and bajadas during intermittent flooding, accumulates in, and flows along, this depression, creating an intermittent braided stream. This situation is shown in Fig. 10-5*b*.

Eventually a valley may be filled by alluvial deposition to such a point that the highest mountain areas are only slightly above the level of the valley surface. Stream slopes are low. At this point water erosion and deposition are insignificant, and a true filled valley exists (Fig. 10-5*c*).

This latter stage may be called a "bolson," defined by von Engeln (212) as an intermontane desert area where the "drainage is centripetal, with gentle gradients toward the low point of an extensive mountain-girt alluvium floored basin."

Of course, the structure of the valley may be such that filling is accomplished by fans which proceed outward mainly from one side and contact the other side of the valley at their outward boundaries. In such a case, an intermittent braided stream may flow along a rock contact. Or the fans may surround and bury an islandlike ridge of rock in the central portion of the valley.

Ultimately, the true filled valley must be destroyed. There are several ways by which this can be accomplished. One common process is the filling of a valley to such a point that water flow over its surface can drain through some low divide in the surrounding mountains. The flow of water immediately attains an increased gradient and velocity as it flows through the divide, and the gap is deepened and widened. As this occurs, the filled valley behind the gap is rapidly dissected, its materials being transported through the divide to lower regions (Fig. 10-6).

The valley can also be dissected by a newly created stream or river which flows with sufficient velocity and volume through the fill material and initiates rapid dissection.

Still another method of destruction depends upon wind action. The wind may attack the surface of a true filled valley, picking up and transporting its silts and clays beyond the confines of the basin; grinding its sands into fines by wind abrasion, thus subjecting them to transportation; and grinding away at previously buried rock masses as they are uncovered. Eventually, a rock floor thinly covered with very hard gravels may be expected to develop.

A lake bed (Chap. 11) can be considered as a special form of filled valley. It, too, can be dissected because of the advent of a stream with sufficient eroding capacity.

10-5. Formation of Fluvial Piedmont Plains. A piedmont plain is merely an extension, vertically and horizontally in a direction away from the mountain front, of a bajada(s). It may be considered the equivalent of a filled valley, except that it does not occur in a valley, but at the foot of a mountain front(s).

The formation of a fluvial piedmont plain occurs when, because of uplift and accelerated erosion, heavily loaded streams debouch upon lower land along a mountain front. At the point of exit they rapidly construct fluvial fans, coalescent fans, and bajadas (Sec. 10-3). Having no confining valley walls, deposition continues in a direction away from the mountains, and eventually may cover thousands of square miles, with unconsolidated stream deposits over whose surface braided streams wend their sluggish way. At this stage, they resemble the southeastern fluvial piedmont plain of Turkestan as described by Davis (46*a*):

> . . . every grain of sand and silt that the Tejen and Murg-ab bring from the mountains of their upper courses must be deposited on the plains, where their lower courses wither away. The plains are dead-level to the eye; yet the muddy rivers detect a slope. . . . The habit that these rivers have of flowing on the plains, instead of in valleys eroded somewhat below the plains, is highly suggestive. Such a habit is easily explained as a necessary consequence of the formation of the plains by rivers; it would be difficult to explain it if the plains had been laid down in a sea or lake basin and then laid bare by uplift.

These rivers may be expected to deposit sediments that *generally* grade from coarsest near the mountains to finest at the outer edges of deposition. Coincident with this general tendency is a counter tendency for coarse materials to be carried along the rivers to points that would otherwise seem uncommonly far. Added to this is the normal disorganized fluvial sorting typical of heavily loaded streams. The end result of these conflicting tendencies is a general vertical coarse to fine stratification from bottom to top, and a similar horizontal variation from mountains to edges, that shows considerable erraticism from point to point.

Ultimately, deposition on a fluvial piedmont plain slows down because of completed erosion, end of uplift, etc. The rivers and streams gradually change their regimen from one of horizontal ag-

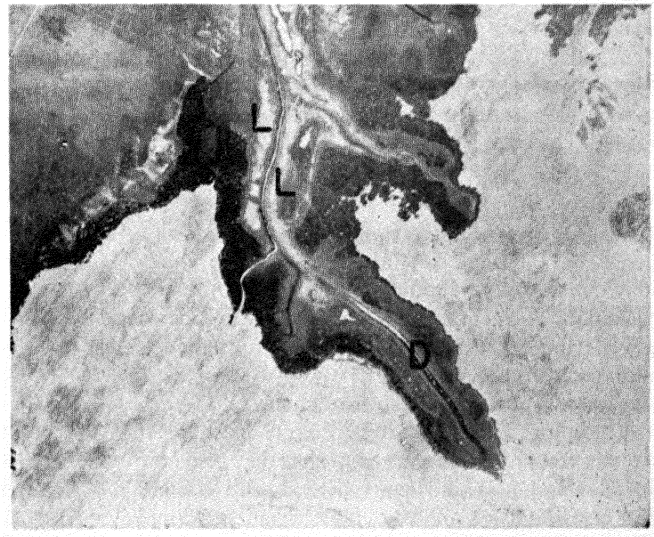


Fig. 10-11. A comparative rarity, the small bird's-foot delta. The typical elongated tongues enclosing the stable (nonmeandering) distributaries *D*, with their higher, better-drained natural levees *L*, are well shown. It can be seen that, when the space between two distributaries is filled in, the bird's-foot delta is essentially the same with respect to the top zones. (*Mediterranean. U.S. Army.*)

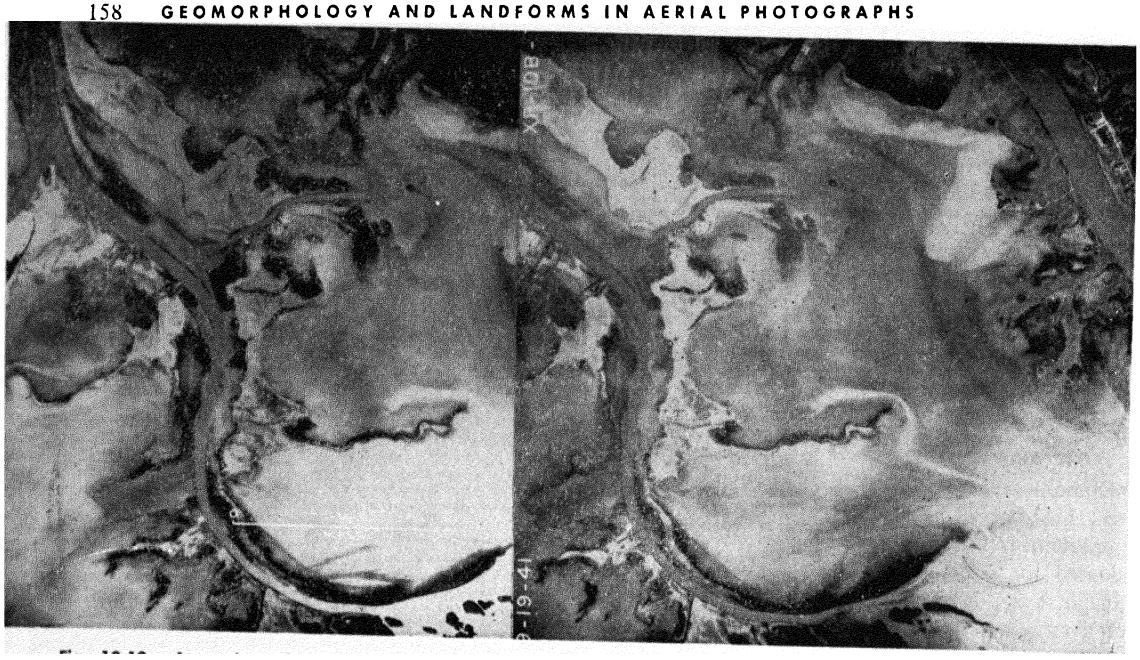


Fig. 10-12. A portion of a large bird's-foot delta. The stable, elongated channels, contained by their own natural levees, are well known. Both low- and high-water channels can be discerned. The light-gray areas will some day be backswamp, and ultimately subaerial backplains. At the moment deposition is occurring under water. This delta is composed of fine-grained materials. (*Michigan. USDA, Soil Conversation Service.*)

gradation (Sec. 9-7) to one of lateral planation and vertical downcutting (Sec. 9-4). At this point fluvial action is complex, eroding one landform (the piedmont plain) while creating another (the floodplain) through combined fluvial erosive and constructive action. Ultimately, like a filled valley (Sec. 10-4), the piedmont begins to undergo destructive erosion that will finally destroy it. This destructive process is under way on the great fluvial piedmont plains east of the Rocky Mountains in the United States and south of the Himalayas in India.

10-6. Formation of Fluvially Sculptured and Veneered Rock Forms. In arid regions, there are forms sculptured in rock that resemble fans, coalescent fans, and bajadas. These forms, presumably, are fluvially sculptured by processes of lateral planation and are thinly veneered with coarse gravels and boulders. Their theory of formation is disputed. Von Engeln (212) and Cotton (44, 45) discuss their probable formation.

The important thing about pediments, in so far as interpretation is concerned, is that they resemble bajadas and fans and are veneered with gravels, but are composed almost completely of rock, and thus are susceptible to misinterpretation.

10-7. Aerial-photographic Characteristics of Deltas and Deltaic Plains. The aerial-photographic characteristics of these landforms are, of course, variable, just as their shapes are variable. And, as discussed in Sec. 10-2, shapes are important as indicators of textural nature. They are also important because, contrary to the opinion of some people, deltas, as visible landforms, are not always bounded by water. In many areas, and particularly glacial areas, the water has disappeared, leaving the delta as a fossil landform of considerable practical importance.

Generally, the delta landform, whether a fossil or not, can be recognized by its protuberance from the existing or old shore lines (except for estuarine deltas). This protuberance has the arcuate (Fig. 10-2), the modified arcuate, or the bird's-foot shapes. Its boundaries with adjacent materials are either indiscernible or distinct. Upstream, the deltaic materials merge with those of fluvial origin, and the boundary is one of arbitrary choice. It is often drawn at the point where the main stream channel divides into its first major distributaries.

Downstream, the delta, if bounded by water, has a variable boundary. It may be abrupt but ex-

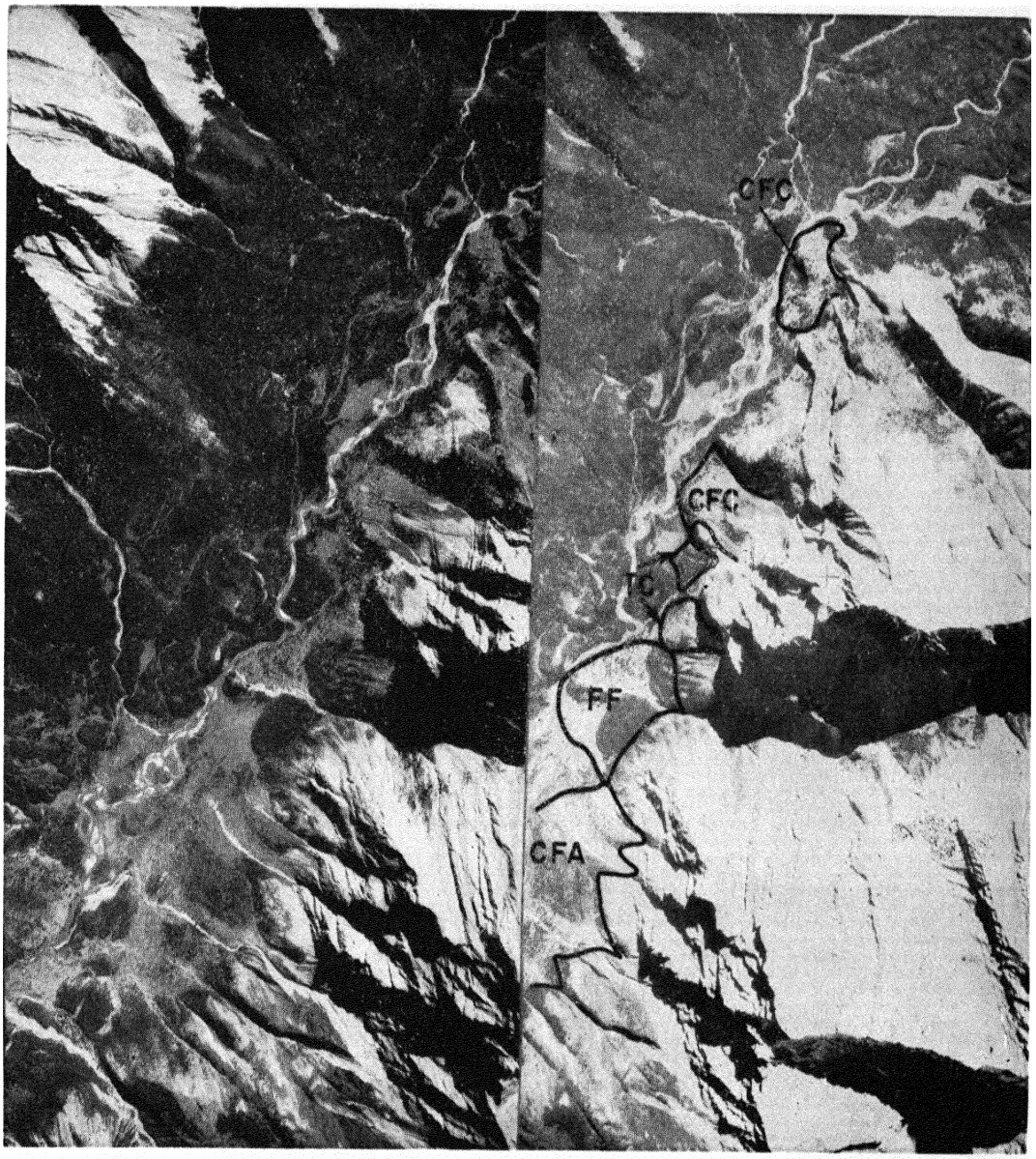


Fig. 10-13. A stereopair showing a large fluvial fan *FF*; two talus cones *TC*; two colluviofluvial cones *CFC*; and a colluviofluvial apron *CFA* formed of coalescent talus accumulations. Note the differences in slope and, therefore, in major agent of transportation. (*British Columbia. British Columbia Government, Air Division.*)

tremely irregular: indentations corresponding with the mouths of distributaries (young, arcuate deltas in calm water bodies); bordered by islands and tidal inlets (Secs. 15-6, 15-10) (deltas in water bodies having gentle offshore slopes and ineffectual current and wave action); irregular but gradually feathered off, usually with offshore bars (deltaic plains on flat coasts); highly irregular to smooth vegetative boundaries (mangrove) that mask the true mineral boundary; with finger-shaped pro-

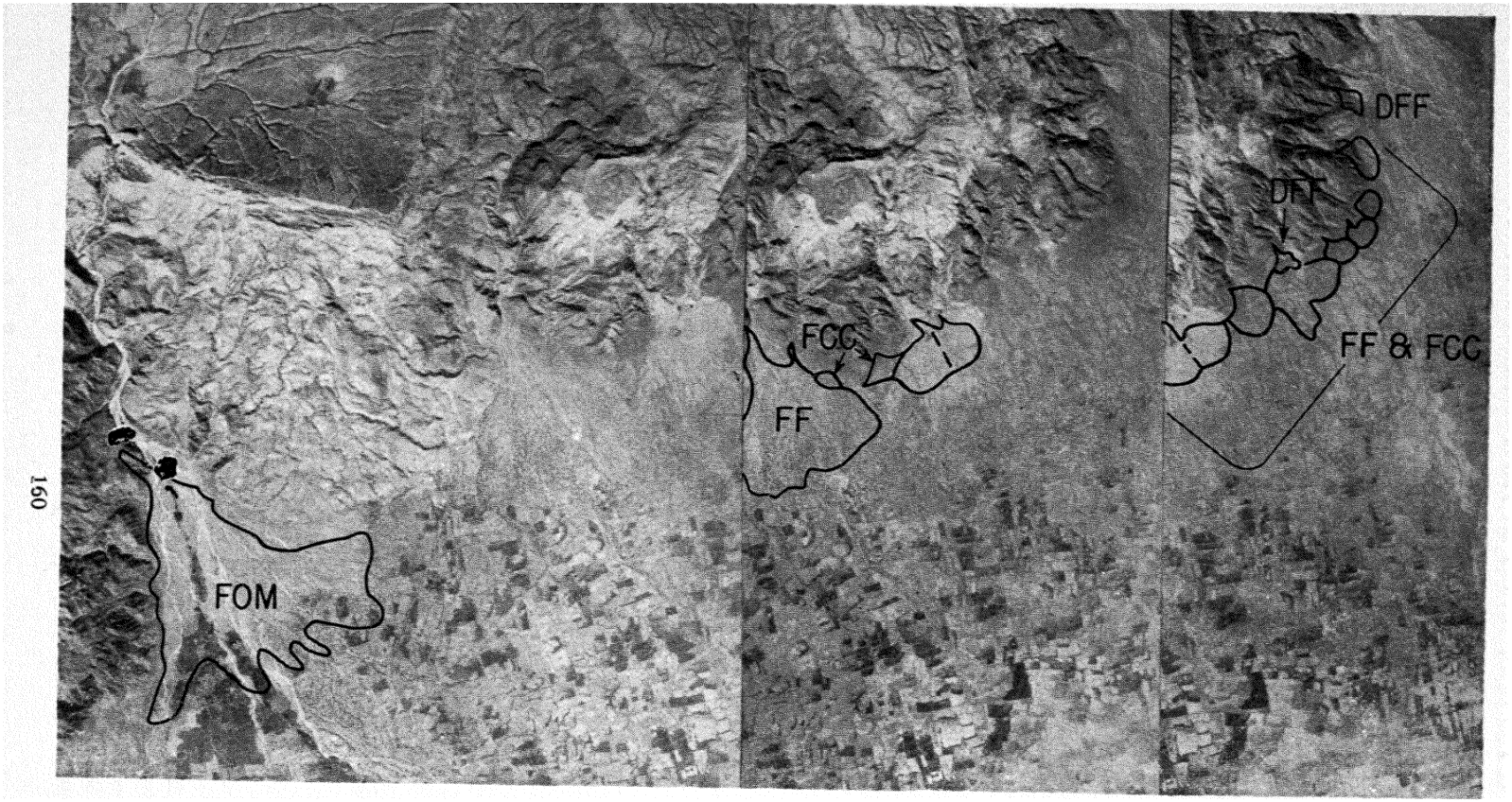


Fig. 10-14. A series of fluvial fans, including a single large one *FF* to the left, and a series of smaller, partially coalescent ones, some of the steeper and smaller of which might be more properly called fluviocolluvial cones. The remnants of some old, higher fans or fill are indicated by *DFF*. On the left, a fanlike fluvial outwash fan mantle *FOM* appears. This is a common feature in arid areas and resembles a fan, except that it is gentler and is formed by a river having perennial, or nearly perennial, flow. (*Middle East. Photographic Survey Corporation.*)

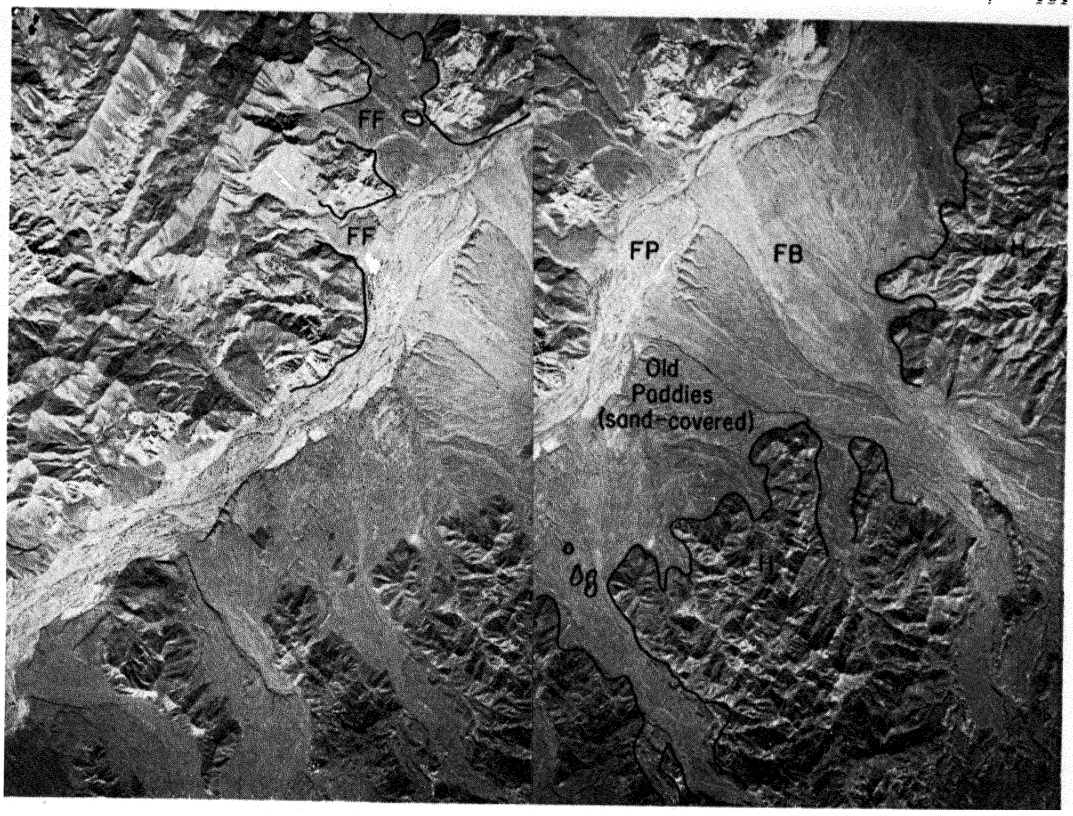


Fig. 10-15. Portion of a filled valley showing the mountain-girt valley *H* floored with fluvium in the form of a bolson *FB* undergoing dissection, truncated fans *FF*, and a bar meander plain *FP*. (*Africa*.)

jections and variable "in-between" conditions (bird's-foot deltas); or smoothly abrupt, with numerous beaches, hooks, spits, etc. (deltas built into water bodies having very effective wave and current action).

Downstream, if the delta is a fossil type, it may be expected to have an abrupt to generally smooth boundary. The point of abruptness indicates the foot of the foreset beds, while the smoothness reflects the disappearance of flow and other water action, together with the softening effects of weathering.

Topographically, all deltas are very much alike, in that they have exceptionally flat surfaces, interrupted only by irregularities associated with the distributaries. These irregularities are insignificant in comparison with the extent of the delta.

Surface-drainage patterns are almost completely constructional (Sec. 3-5), as well as highly variable. Small arcuate deltas are characterized by braided, outbranching distributaries. Larger ones have nonbraided, often tortuous outbranching channels. Bird's-foot deltas, if well developed, have a few main channels tending to branch into fingers toward the water boundaries. Fossil deltas, particularly the coarse-grained types, may have one or two fossil channels. Quite frequently, they have no channels at all. Estuarine and bay-head deltas commonly have a complicated system of channels (usually meandering to tortuous), islands, and abandoned distributaries. Deltaic plains often have several roughly parallel main channels. Any active delta may be further characterized by tidal inlets, numerous lakes, lagoons, and old channels and a general lack of integrated drainage. Deltas upon which vertical accretion is significant may have natural levee-type drainage (Sec. 9-9).

Erosion is present only on fossil deltas, where it serves as a means of identifying the nature of the deltaic materials.

Gray tones, vegetation, and land-use patterns of deltas are so variable that they do not deserve

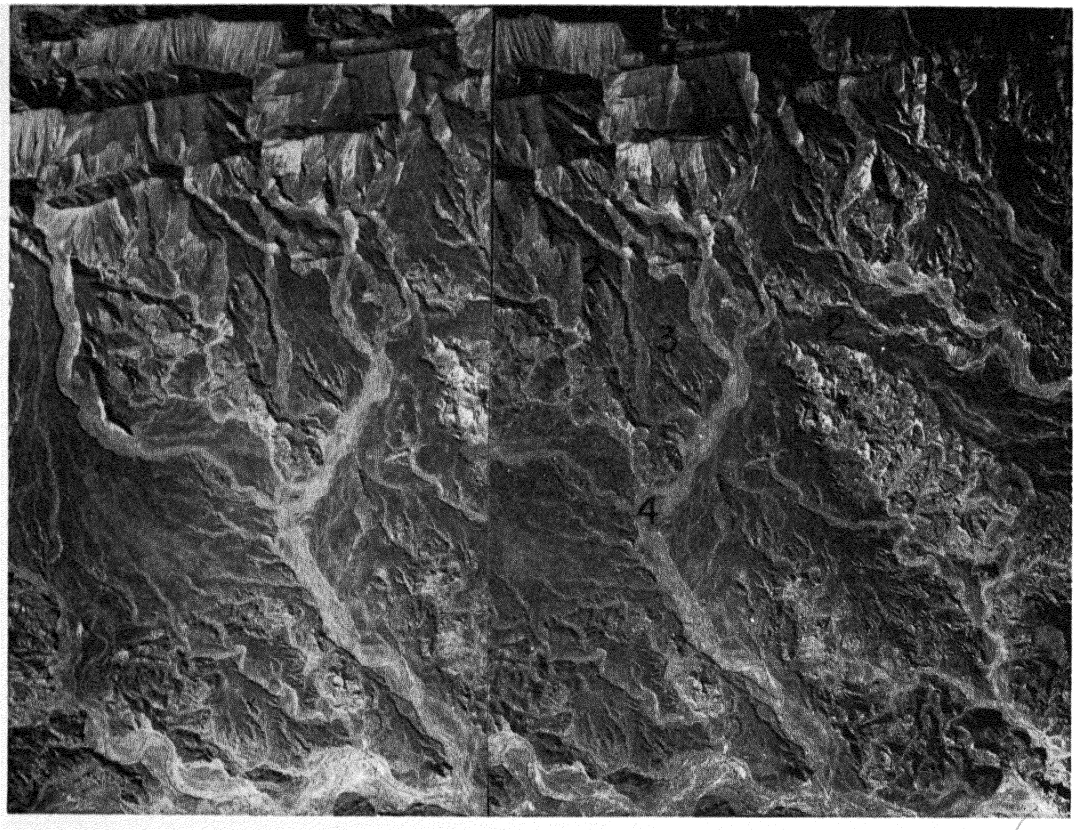


Fig. 10-16. This stereopair includes a major portion of filled valley that is undergoing dissection. Steeply tilted (60 to 70°) sedimentaries form the walls. At least three levels (1 to 4) of fluvial planation are apparent. The highest (1) never reached the top level of the rock walls shown here; breaching occurred at lower points to the left and right. The fluvial fill is dark-toned in color. Gullies indicate several types of material, the dominant being composed of semiconsolidated, or at least cemented, silts, fine sands, and sand sizes. (*Middle East. Photographic Survey Corporation.*)

much consideration. Vegetation and land use are inclined to be sparse, or lacking, on braided arcuate deltas and best developed on bird's-foot types or deltaic plains. Light, gray smudgelike stains in the water beyond the delta boundaries are characteristic. These smudges contain the material that ultimately forms the bottomset beds. Their shapes vary and should be inspected for clues as to the nature of current and wave actions in the delta environment. Figures 10-7 to 10-12 illustrate the aerial-photographic appearance of deltaic deposits; also see Fig. 8-2.

10-8. Aerial-photographic Characteristics of Talus Deposits, Colluviofluvial Cones, and Rock Glaciers. The specific air-photo characteristics of talus deposits depend upon the type of deposit. In general, their major identifying characteristics are topography (steeply sloping, 20 to 40°, to irregular piles); location (invariably at the foot of rock cliffs and steep slopes); association (with various erosion scars above); lack of surface drainage; erosion vegetation and land use; and uniform, generally light-gray tones. Illustrations appear in Figs. 10-13 and 10-14.

Colluviofluvial cones have characteristics similar to those of fluvial fans (Sec. 10-9) except that they are steeper (20° usually), smaller in lateral extent, and relatively unscarred by erosion washes. Figure 10-13 also illustrates this landform.

Rock glaciers can best be described in terms of their even tones, location (in valleys at or toward the bottom of slopes), flowing shape, and lack of surface drainage (see Fig. 12-2).



Fig. 10-17. This stereotriplet illustrates some fine structural details in addition to showing a filled valley whose original fill is being, or has been, removed. (There is stereo nonconformity along the borders of the lines intersecting each photograph.) The steeply tilted, differentially weathered sedimentaries, complete with "flatirons" *F*, are well shown. The geomorphologist and geologist can pose many interesting questions by examining the nature and level of the various deposits such as 4 and 5. The gullies *G* are also rather remarkable. The drainage pattern is developing rapidly. (*New Mexico. U.S. Forest Service.*)



Fig. 10-18. A deposit of continental alluvium (mantle) similar to the deposit shown in Fig. 10-19. The flat surface is typical. Gully and drainage analysis (Chaps. 4, 3) indicate a highly erodible intermediate type of material, probably silts, sandy silts, and silt loams, weathered to imperviousness at the surface. The black patches *B* are burn scars. Note the meander scrolls in the lower right corner. (*Venezuela. Photographic Survey Corporation.*)

10-9. Aerial-photographic Characteristics of Fluvial Fans, Bajadas, and Fan Deltas. Like most fluvial landforms, the outstanding characteristics of fans are their shape and topography. Their shape is that of a fan, obviously, with its narrow end back in the valley or gully from which the fluvial sediment is issuing. Talus cones and alluvial cones have similar, though narrower, shapes. The exact shape of the widening sides of the fan is a function of the shape of the highland walls, and the fan shape does not become noticeable until deposition has progressed beyond the confinements of the walls to assume its typical wide-rounded shape. The boundary of this wide-rounded portion tends to be smooth and round, with either an abrupt break or a smooth feathered edge. Where coalescent fans and bajadas are in process of formation, this outline becomes irregularly and broadly scalloped or semilinear.

Topographically, the fan possesses a "smooth" convex surface that slopes downward from the contributory valley and laterally from its center to its unconfined boundaries (Fig. 10-14). Slopes of fans range between 1 and 12°, with slightly steeper head ends. Where fans coalesce, the individual convexities are separated by broad, shallow, ill-defined depressions. The head ends of adjacent fans occur at different elevations.

Occasionally, fans may be partially or heavily dissected and even have steps.

Another outstanding characteristic of fans—particularly in arid areas—is the radial pattern of braided, dry channels that traverse and dissect the surface of the fan. These channels tend to be most thickly distributed toward the center of the fan, dying out toward the edges because of insoaking. Usually, one or more of these channels are large dry "washes" created by occasional "super-flash-floods." These washes have rectangular cross sections of considerable width (200 to 500 feet) and depth (25 to 200 feet). Where the fans coalesce, the streams tend to follow the interfan depressions. On colluviofluvial and talus cones, drainage lines are often absent.

Erosion details are usually absent on fans, being replaced by the dry channels.

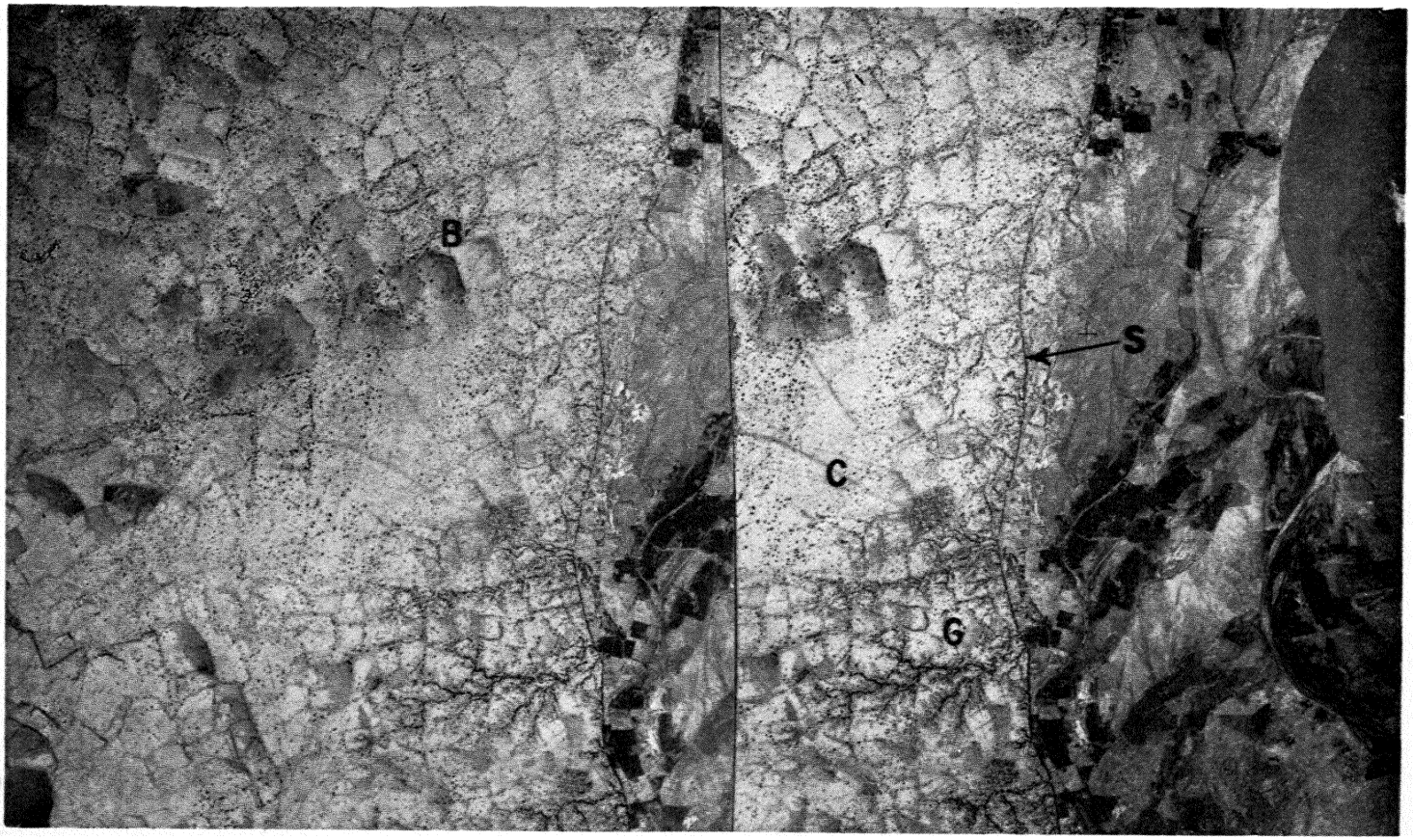


Fig. 10-19. Foot of a vast fluvial piedmont mantle that extends south from a mountain front. The foot has been cut back (*S*) by the river on the left (with its bar meander plain, Chap. 9). Note the almost flat surface of the mantle with its almost indiscernible slope toward the river. Faint braided channels *C* are apparent, proof that water has flowed over the surface. Proof that some water still occasionally flows is given by the bunded fields *B*, some of which have collected water, particularly at their lower ends and corners. Gully erosion is proceeding backward into the mantle from the river. The gullies have intricate plans, abrupt head ends, troughlike cross sections, considerable intricacy, incipient buttresses, low-gradient profiles, and many incipient tributaries. These indicate (Chap. 4) moderately to highly erodible materials (not necessarily impervious because of landform, size of particles, etc.) that have enough cohesion to stand to fair unsupported heights (see river cut bank, for example) without slumping. Some cementation (calcium carbonate) probably is present. Actually, the area is composed of fine sands, silts, and silt loams. (*Middle East. Photographic Survey Corporation.*)

Vegetation is generally lacking because of the torrential nature of the water flow, intermittent flow, and the poor moisture retention of the deposits. Thin lines of sparse vegetation coincide with the drainage lines. Other vegetation may be scattered over the surface.

Tones are light gray to white, either interlaced or uniform. Vegetation peppers the surface with black specks. Around the lower edges of the fan where insoaking water may approach the surface, tones are darker, because of higher moisture content, and vegetative specks are denser.

10-10. Aerial-photographic Characteristics of Filled Valleys and Bolsons. The aerial-photographic characteristics of filled valleys depend, to some extent, on whether destruction has begun and how far it has progressed.

Regardless of the state of destruction, all filled valleys are mountain-girt, and most of them display a fairly distinct break between the mountains and the alluvial fill.

Beyond this, if the valley is "filled" but has not yet witnessed destructive erosion, its outstanding characteristics are its extensive, flat surface and its typical braided, intermittent stream pattern. Gullies are absent, though the occasional dry wash may occur. Tones are of nebulous value, ranging from medium to very light gray with numerous black dots (arid-climate shrubs) tending to follow the stream braidings. Occasionally, white and black patches of alkali may appear.

If the valley is undergoing destruction, the topography is, of course, quite rough, being scarred with numerous dry washes and intricate, fairly deep gullies of the intermediate soil type (Chap. 4). These gullies are obviously progressing in a headward direction. Tones may be variable or uniform. Some braided surface drainage may have established itself in lower areas. Although the topography is rough, the tops of the intergully areas are accordant and flat.

If a valley is in the process of filling, it does not have the above characteristics. Rather, it is composed of various combinations of fans, coalescent fans, bajadas, playas, salinas, bar plains, etc.

Bolsons represent a special stage in valley filling in which the fans and bajadas fill the entire border of the valley, causing all drainage to be centripetal. In very advanced stages of bolson-type filling, the area may be essentially a true filled valley.

Figures 10-15 to 10-17 illustrate aspects of valley filling and dissection.

10-11. Aerial-photographic Characteristics of Fluvial Piedmont Plains. The aerial-photographic characteristics are similar to those of filled valleys and are also variable, depending upon the textural nature of the most recent deposition, the extent of erosion, the textures of the alluvial deposits, the extent of land use, etc.

The major characteristics are extensiveness, flatness (accordance, if dissected), and intricate erosion of the intermediate soil types (Chap. 4) along the outer edges and the valleys of present rivers. Tones tend to be uniform and light gray, modified by the land-use patterns that frequently are found on piedmont areas, particularly near the outer edges. Local effects, e.g., the "buffalo wallows" of the Great Plains alluvium in the United States, may be characteristic features.

Some typical fluvial-piedmont-plain topography appears in Figs. 10-18 and 10-19.

11 MARINE AND LACUSTRINE LANDFORMS

11-1. Scope of Chapter. Because of the similarity in their mode of formation, this chapter is concerned with those landforms that are generally considered to have two different origins, the marine and lacustrine landforms. They are discussed under two separate headings.

MARINE LANDFORMS

11-2. General Discussion of Marine Action. In Sec. 2-16a, it was stated that the marine origin could be assigned to any visible landform or deposit composed of unconsolidated materials that were originally accumulated beneath the surface of a *saline* water body, not in primary association with deltaic or fluvial action, or cast up along the boundaries of such a body by the waves and currents therefrom. The formational chain of origin was shown to be one having considerable possibility for variation and complexity or, contrarily, moderate simplicity.

The formational chain, to become operative, requires three important things: (1) a source of supply and agent of transportation, (2) a body of water adequate to receive deposition, and (3) a proper environment for the marine accumulation of sediments.

The source of supply and agent of transportation should imply that marine sediments may be derived from any existing unconsolidated deposit, or from the weathering of any consolidated deposit, so long as the particle sizes are capable of being transported to the site of marine deposition by any agent of transportation such as water, wind, etc. Source and agent can also imply biotic and chemical processes. In this case, the sources are living organisms, or chemical reactions, that live or occur in the marine waters themselves and that originally are deposited by simple settling out of suspension.

An adequate body of water should imply that there is enough depth to prevent subaerial exposure of the accumulating sediments.

A proper environment should imply the *almost* invariable presence of currents, waves, and tides and their action as agents for the initial sorting, and subsequent re-sorting, of the marine sediments, especially those consisting of mineral particles above the colloid sizes. It should also imply that the water has a high enough degree of salinity to allow both the flourishing of marine organisms and the ultimate creation of special physical characteristics in the emerged marine sediments.

11-3. The Marine Landforms. The marine landforms are complicated by the fact that they fall into two orders of relief, the second and third (Secs. 2-23 to 2-25). Using these as primary subdivisions the landforms may be listed as follows:

1. Landforms of the second order of relief
   a. Emergent coastal plains
   b. Emergent river plains
2. Landforms of the third order of relief
   a. Doabs and interfluves [1]
   b. Cuestas and outliers [1]
   c. Tidal marshes and flats
   d. Beaches
   e. Beach ridges, strand lines, and marine terraces

11-4. Formation of Marine Landforms of the Second Order—Emergent Coastal Plains. A coastal plain is formed when a submerged portion of the sea floor becomes exposed because of a general rise in land mass or a general drop in sea level. Since the sea floor is covered for some distance from shore, with materials deposited under water, its emergent surface may be expected to have a

[1] In conformance with the definiton of Sec. 2-27, there is justification for not classifying these features as unit landforms. Although they are indicative of structure, they provide no information on composition and texture and only a little on uniformity. It is only this latter fact that leads to their inclusion as unit landforms.

generally flat aspect during its initial stages. The flatness is a rather general property, however, since the emergence of the various underwater formations is slow and older deposits are exposed for a longer time than more seaward materials. This difference in time of exposure leads to more advanced erosion in the older deposits and gives them a rougher aspect than succeeding ones.

In addition to slight differences in relief created during emergence, there are minor irregularities which modify the otherwise flat surface of a fully and newly emerged plain. These are associated with channels of highland streams that have maintained their courses across the slowly uplifted deposits; with numerous broad, shallow, ill-defined depressions which exist from the beginning and are commonly occupied by swamps; and with shore features, such as tidal marshes, lagoons, and barrier beaches that usually begin to develop during the early stages of coastal-plain formation.

With the exception of the irregularities described above, recently emerged coastal plains are low and flat and may be described as undissected (Fig. 11-1*a*). This initial aspect is rapidly revised and destroyed by stream erosion. The streams progress headward along the strike of the various formations, and then branch out, creating a dissected landscape having certain characteristic topographic expressions (Sec. 11-6). An advanced stage of dissection is shown in Fig. 11-1*c*. In this figure, it should be noted that the most inward deposits are the most eroded, succeeding formations showing less and less dissection with an almost flat plain existing near the shore. Such a coastal plain can be divided into two broad zones, the dissected, or "upper," coastal plain and the undissected, or "lower," coastal plain.

If erosion proceeds without interruption, a coastal plain will be reduced, over its entire surface, to a level only slightly above the existent sea level. However, this process of uninterrupted erosion after emergence is only occasionally realized. Many coastal plains are subjected to normal erosion for only a comparatively short period, before partial submergences and uplifts complicate the landscape. During partial submergences, underwater deposition will smooth over previously eroded surfaces. Following uplift, these surfaces will be subjected to new erosional activities. If the processes of erosion, resubmergence, deposition, uplift, and new erosion are thought of as recurrent stages of varying duration and extent, the complex conditions that can exist on a coastal plain (especially over the dissected portion) can be easily imagined.

Coastal plains are further complicated by the fact that, being second-order landforms, they include within their boundaries third-order landforms of many types and origins (Sec. 2-26) that do not have expressions related to the normal emergent development of the coastal plain itself.

These various and complex conditions preclude, except for some sea-margin features, the establishment of air-photo characteristics for coastal plains that have other than a very general and often vague nature.

11-5. Formation of Marine Landforms of the Second Order—Emergent River Plains. The general formation of a marine river plain is, in all significant respects, similar to that described for emergent coastal plains. The major difference is that, in terms of present-day physiography, the emergent coastal plain exists on a coast, while the emergent river plain borders a river (or lakes in a river chain). As a result of this current physiographic situation, the river plain is not bounded by tidal marshes and barrier beach–dune complexes. It may, however, have all the other features of the emergent coastal plain—cuestas, doabs, consequent streams (usually entrenched), interior swamps, outliers (rare), and strand lines (probably more common than on coastal plains).

Actually, the difference between a marine river plain and a nearby glacial lacustrine area may be due primarily to some geomorphological accident that caused the former portion of terrain to be submerged beneath saline waters while the other portion was covered with fresh waters. In most other respects the two are similar. The river plain is classified as marine in the interests of accuracy.

Probably one of the most outstanding examples of a marine river plain is that bordering the lower St. Lawrence lowlands. This was created when a glacier that formerly occupied the area retreated, allowing the marine invasion and, finally, rebound and emergence.

11-6. Formation of Marine Landforms of the Third Order—Doabs (Interfluves), Cuestas, and Outliers. When a coastal plain or river plain first progresses through its emergence, it presents, as described in Sec. 11-4, a generally low-lying, flat, and undissected appearance. Irregularities exist in the form of consequent lakes, swamps, and early stream-dissected valleys. Generally, the early stream dissection tends to proceed in a direction parallel

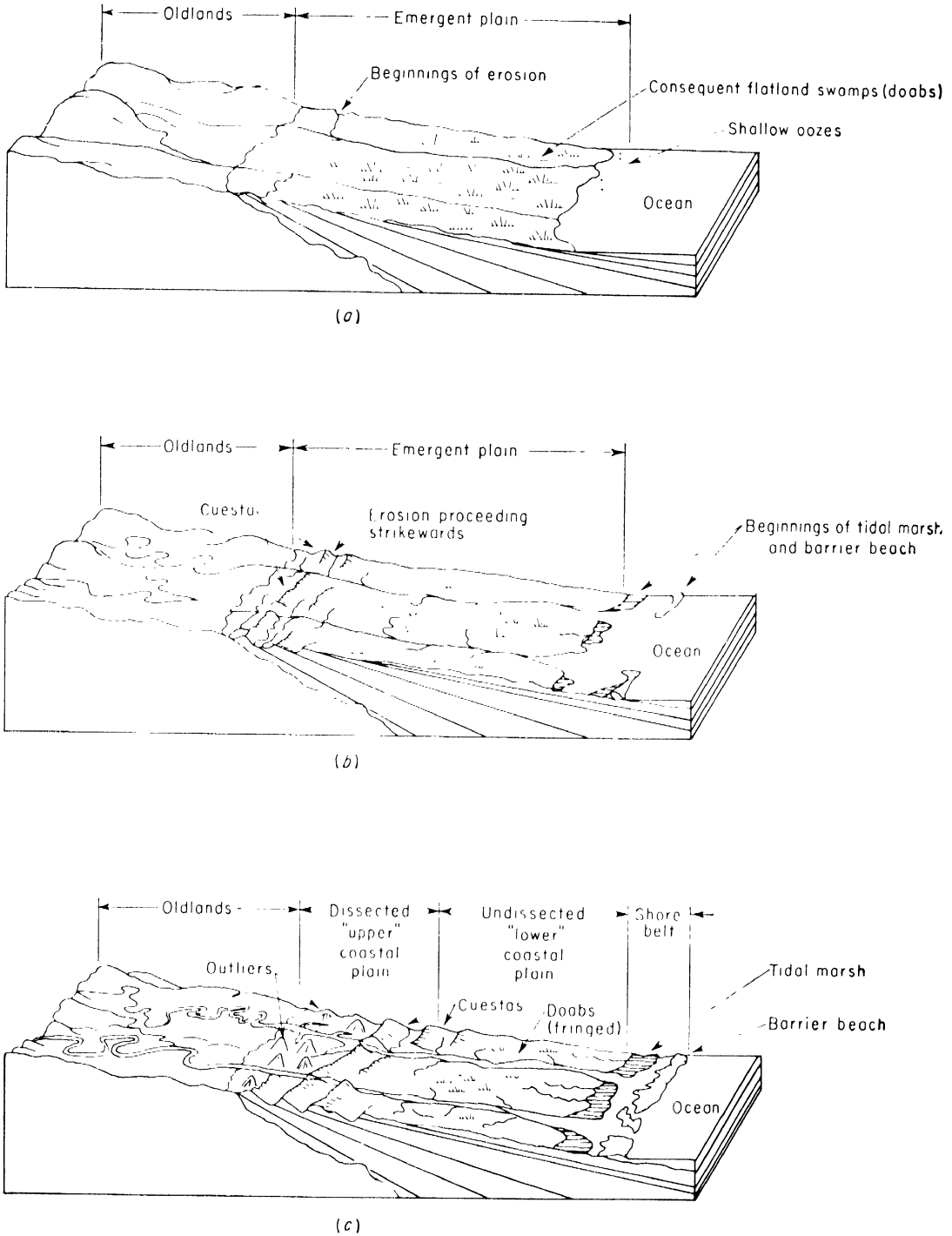


Fig. 11-1. A schematic representation of the process of coastal-plain formation. Stage (a) shows the plain in a late period of emergence but still emerging; (b) illustrates an intermediate stage; and (c), a more advanced stage of erosion yielding a "belted" plain.

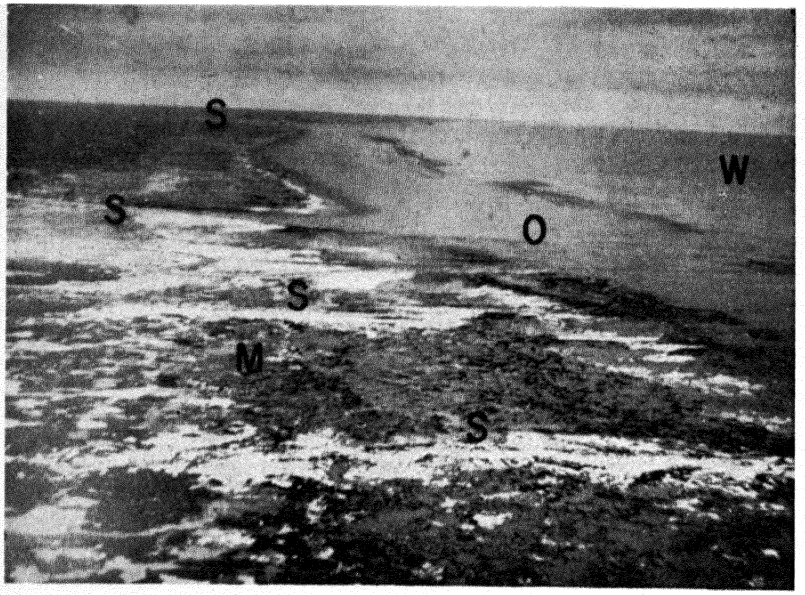


Fig. 11-2. A low oblique of a recently emergent, and emerging, coastal plain. The emergence is due to rebound following the removal of the continental glacial mass. This area changes gradually from water *W*, to ooze *O*, to soft muskeg *M*, to beach ridges and muskeg, to relatively dry land. The parallel downdip streams *S*, accented by snow, are discernible. (*Hudson's Bay. D. R. Lueder.*)

to the dip of the formations. This creates a parallel-drainage pattern, dividing the surface into strips (Fig. 12-2). Ultimately these strips are reduced, by headward gully erosion, to irregular areas whose surfaces are identical with the original emergent surface. These flat-topped, undissected remnantal surfaces are called "doabs" and "interfluves." Eventually, as the processes of dissection continue, they disappear completely, but while they exist, they are an important third-order feature of marine coastal or river plains.

The consequent streams, trending downslope, are soon joined by tributary *subsequent* streams that tend to establish themselves along the more easily eroded coastal-plain formations. Since all coastal-plain formations have general strike directions parallel to the coast, these subsequent streams tend to have paths that are also parallel, extending indefinitely headward in the strike direction. In the process of eroding the weaker formations, the subsequent streams migrate downdip, creating a valley with a relatively gentle updip slope and a steep downdip slope. The downdip slope of one valley and the gentle slope of the next most seaward subsequent stream valley are jointly called a "cuesta" (Fig. 11-1).

Following long erosional dissection, portions of cuestas will become fairly separate detached masses and will tend to exist as small irregular hills having, in many cases, no immediately evident relation to the original escarpment line from which they originated. These cuesta remnants usually have a capping of gravel, consolidated rock, boulders, cemented sands, ironstones, etc., that allows them to resist erosion. Such isolated hills might be called monadnocks, mesas, buttes, or outliers, depending upon one's preference. The author prefers the term "marine outlier" as being most nearly descriptive.

11-7. Formation of Marine Landforms of the Third Order—Tidal Marshes and Flats. The tidal marsh and flat is an outstanding landform that occurs along the present borders of all coastal plains, *or any other landform-rock type,* where favorable conditions exist in connection with tidal action. The major characteristics of tidal flats are related to a combination of marine action, fluvial

action, and in most cases, biotic action. Unlike most landforms, they have a composite origin. In recognition of the dominance of biotic action in all but the youngest, most unstable, and coarsest flats, their formation is discussed in Chap. 15.

11-8. Formation of Marine Landforms of the Third Order—Beaches. Beaches are an outstanding marine (lacustrine, fluvial) landform. Essentially they are formed of unconsolidated sand and gravel sizes mixed with variable amounts of silt (rare), wood, shingle, and shell (the latter two often dominant). These materials are carried by currents and waves to various points along any shore line. After being deposited by their initial transporting agents, they are picked up by scouring waves in the plunge-point zone and cast upon the shore, only to be drawn away again by backwash, undertow, etc. This process goes on incessantly, of course, and is subject to all the variations that can be associated with wave heights, wave frequencies, current direction, duration and velocities, sources of supply, etc. The beaches build up and are eroded (widthwise) and change their slope firmness, composition, and stratification. However, they may be considered, for most practical purposes, as *wave-worked,* relatively thin, stratified deposits of granular materials having gentle slopes (½ to 20 per cent almost exclusively and ½ to 12 per cent most frequently) that border and are washed by the *waves* of water bodies.

In this book, consideration of research on beach gray-tones is presented in Sec. 5-14, and illustrations in Chaps. 5 and 14. Some references on the aerial-photographic interpretation of beaches are cited in Sec. 11-12. See also Fig. 11-9.

11-9. Formation of Marine Landforms of the Third Order—Beach Ridges, Strand Lines, and Marine Terraces. Beach ridges and strand lines are merely beaches (Sec. 11-8) that *once* bordered, and were washed by the waves of, large water bodies, since disappeared or at least removed some distance, leaving the old beaches behind. Quite frequently, these old beaches occur as series of lines, each of which marks a successive shore-line position.

Marine terraces, similar to fluvial terraces (Sec. 9-8), are the eroded remnants of old marine bottoms. Such terraces come into existence because, following partial emergence, the water level remained static long enough to erode a wave-cut cliff in the previously exposed bottom. These terrace fronts are therefore like beach ridges, in that they mark various marine water levels. It is possible, if supply and currents are favorable, for a marine terrace front and a series of beach ridges to be coincident.



Fig. 11-3. A low oblique showing the typical appearance of closely spaced beach ridges. (*Alaska.*)

11-9a. Formation of Glacio-fluvio-marine Plains. It is possible for a melting glacier to deposit its outwash in a body of marine waters, forming a submarine outwash plain. To the best of the author's knowledge, such plains, as visible landforms, are practically nonexistent, though they may be revealed in the lower zones of currently emergent coastal and river plains.

11-10. Aerial-photographic Characteristics of Coastal Plains, Cuestas, Outliers, and Doabs. The various and complex factors that may have come into action during the formation of a coastal plain and the extreme variations in lithology and erosional duration that occur within its boundaries, or are reflected by its third-order features, all combine to complicate a discussion of its aerial-photographic characteristics. The following discussion is general only and applies only to coastal plains developed from unconsolidated to semiconsolidated materials.

Topographic expression is the most important characteristic of coastal plains and their subsidiary landforms. Undissected plains display a fairly level to gently rolling surface only slightly elevated above local water surfaces. This surficial expres-

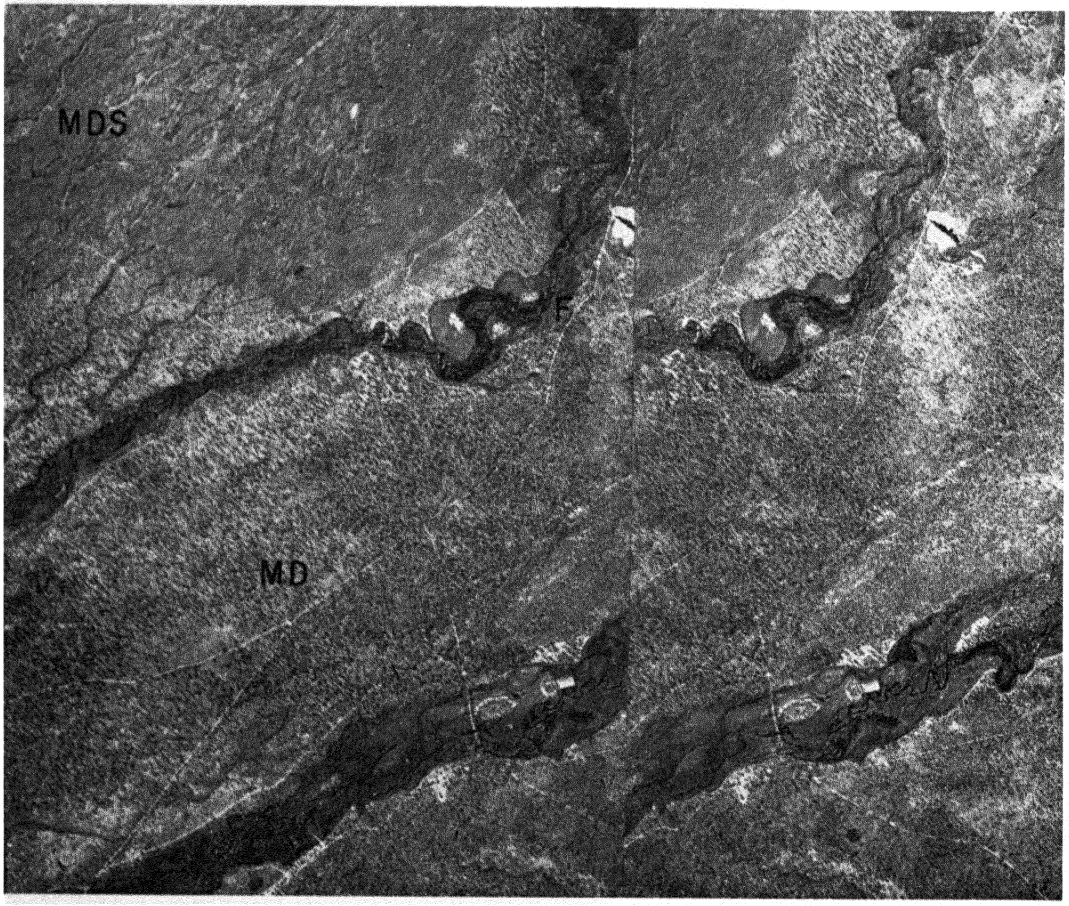


Fig. 11-4. The almost featureless, flat surface of a young emergent coastal-plain region. The areas through which the two streams pass may be considered as unfringed doabs *MD*. Erosion is almost completely absent. The streams show irregularly angular, marshy meandering courses occupying broad shallow valleys. These streams engage primarily in lateral erosion because they are near base level. However, they have not gone through even the early stages of normal lateral fluvial deposition and erosion, except in area *F*. The area labeled *MDS* is almost completely occupied by flatland swamp (Chap. 15). The light tones showing through the vegetative cover reflect the sandy soil texture. The swamp has a subtle tonal and textural difference that is unmistakable to an experienced interpreter. (*New Jersey. Aero Service Corporation.*)

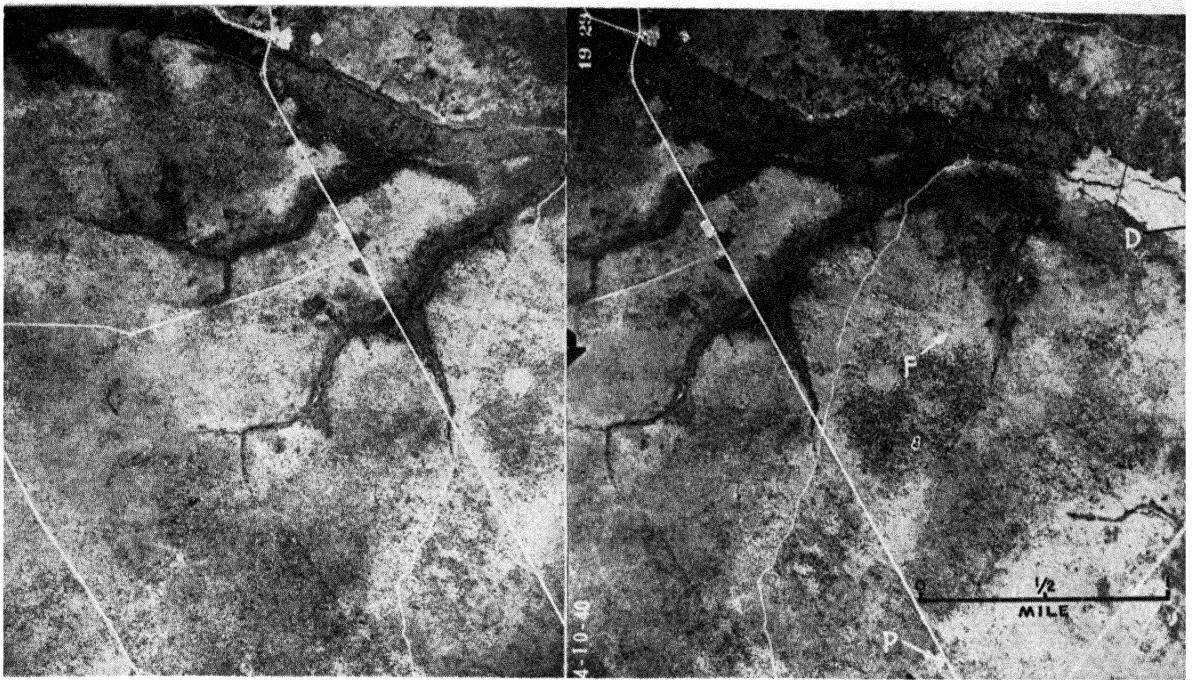


Fig. 11-5. This stereopair shows the edge of a fringed doab with its remarkably flat surface and thin gravelly capping (distinguishable on the air photos). The shallow, broad-bottomed stream valleys, with their appreciable organic accumulations, are also shown. Other minor cultural features are footpaths *F*, a borrow pit *P*, and ditches for artificial drainage *D* of the organic areas. (*New Jersey. Aero Service Corporation.*)

sion encompasses local, and even general, differences of elevation that are practically always less than 50 feet and frequently less than 15 feet. The general surface may be broken by the incised trenches of streams progressing in a headward direction through the unconsolidated materials of the plain. Characteristically, these streams have rectangular cross sections (see following comments on drainage), but other shapes also occur.

Dissected coastal plains show rougher topography with specific features reflecting the types of deposits, their geological history, and their length of exposure to erosion. Two important characteristics of these rough hills are their generally low order of relief and the broad accordance of their remnantal uneroded hilltops. The low order of relief reflects their relatively slight elevation above sea level. The accordant summits reflect the plane-like surface of the original emergent surface. There are reasonably common exceptions to the concept of a single accordant surface. These are the result of "marine-terrace" formation (Sec. 11-9), probably as a result of changing sea levels. The erosion of a series of marine terraces will display a topography characterized by two or more accordant levels.

The topography of cuestas and outliers is related to their geomorphic history (Sec. 11-4) and, though quite variable, will reflect the unequal slopes of the cuesta and the mesa-like form of the outlier. It must be noted that the typical form of the cuesta may be immediately evident but also may be obscured by a jumble of eroded hills composing it, as well as an extent in width that may extend over several photographs. The detached protuberance of an outlier is usually easy to recognize.

The topography of the doabs and interfluves, with their original emergent surface, is quite flat, or gently undulating, and in all respects identical with that of undissected coastal plains.

Undissected coastal plains display few streams. Those major streams that are present often show a parallelism perpendicular to the coast line. Tributaries to these major streams are usually widely spaced, often "stumpy" in appearance, and

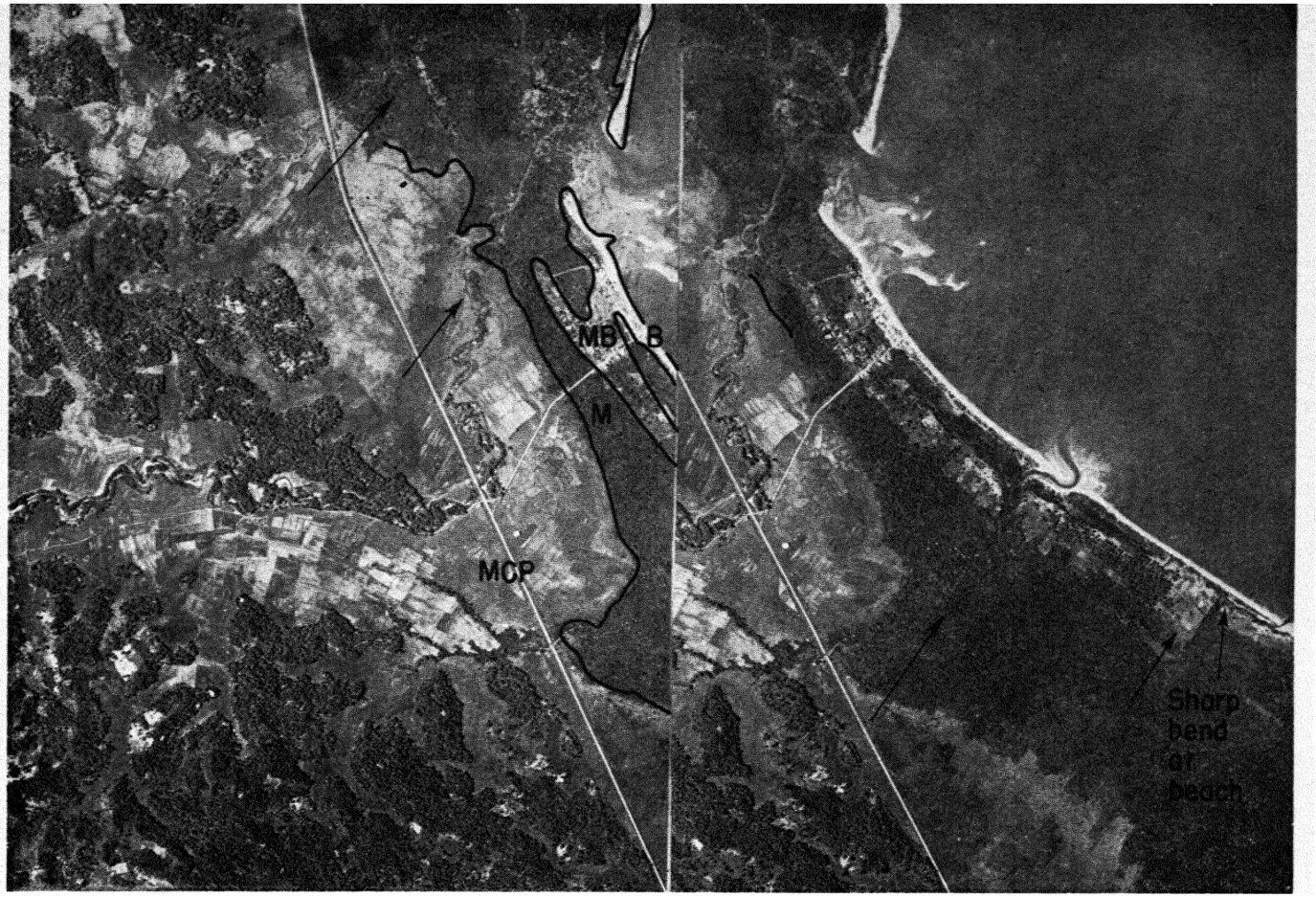


Fig. 11-6. A special type of coastal plain, sometimes called a filled-valley type. This area was subjected to subaerial erosion (the forested hills), then partially submerged and subjected to subaqueous deposition. Emergence then occurred, and is probably still occurring. The beach *B* is backed by marsh *M*, partly tidal and partly fresh, and beach ridges *MB*. The marshes merge imperceptibly into the coastal plain proper. The streams, while they are not yet parallel, show tendencies toward parallelism. The streams are engaging in lateral activity, reflecting proximity to base level. Tones indicate fine-grained sediments (darker grays). The light areas are due to cultivation rather than soil and moisture effects. (*Philippines.*)

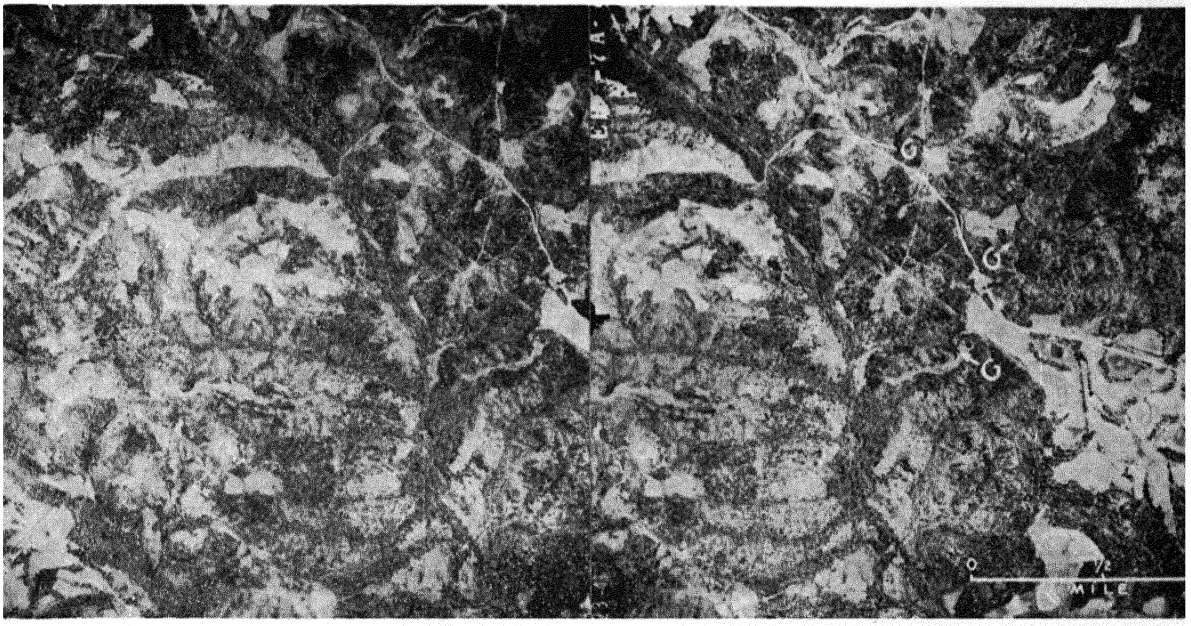


Fig. 11-7. Portion of a severely dissected coastal plain composed of unconsolidated to semiconsolidated erodible material. The *flat* hilltops are accordant. The general order of relief is low. Drainage is *uniform* and well integrated in this formation, although structural control may be seen elsewhere. The generally light tones indicate medium- to coarse-grained materials. The *fresh* gullies G indicate materials having both cohesion and internal friction. These various features indicate the presence of slightly cemented sand-clay to sand-silt mixtures. It should be apparent that this area could not be definitely identified as a coastal plain, nor its physical characteristics determined, without more extensive photographic coverage. Originally selected and annotated by the Cornell group (43). (*Alabama. USDA, Commodity Stabilization Service.*)

have no apparent structural control. The parallelism of streams, often only evident over wide photo coverage, reflects the consequent courses of highland streams that maintained their seaward direction during emergence of the plain. Tributary characteristics indicate the presence of unconsolidated materials that yield readily to sideward valley widening as well as headward lengthening and tend to be responsible for a stumpy tributary shape. The youth of the area is generally responsible for the lack of constructional control.

The major streams, and even the tributaries, often have a rectangular cross section with a wide floor and steep, near-vertical sides.

The wide floors indicate the closeness to base level and the resultant dominance of lateral erosion (Secs. 9-3 and 9-4). The steep sides reflect the presence of interstratified intermediate materials that often predominate in coastal-plain deposits (Secs. 4-19, 4-20). In practically all cases, the larger stream valleys display the superimposed characteristics of meander floodplains (Sec. 9-7).

Dissected areas of coastal plains show exceptionally variable stream patterns with more evidence of control along the major stream paths, particularly along the updip side of the cuesta complex. Often, and particularly in semiconsolidated material, they show interesting drainage patterns indicative of underlying special structures of economical importance (196). Outliers are not usually characterized by active stream drainage.

Doabs, also, have few if any streams developed upon their surface. Instead, they show large expanses of undrained or poorly drained swamps and marsh.

The erosion details of coastal plains are extremely variable, reflecting the great range of materials that may be present. Except on the interior of doabs, gullies are always nearby. On dissected plains, cuestas, and occasionally outliers, they are many in number and well developed. In all cases, their shapes and cross sections are indicative of the materials in which they were developed (Chap. 4). Sheet erosion is often present, along with solifluction features and land slippages.

The tone characteristics of all coastal-plain deposits are exceptionally variable, even within small areas. In accordance with the discussions of Chap.



Fig. 11-8. This stereopair displays several features of the well-known St. Lawrence lowland, a postglacial, emergent, marine river plain. Shown is a series of light-toned strand lines, or beach ridges *MBR*, backed by a marine terrace scarp *MTS*. The strand lines are surrounded by, and the terrace is cut into, the body of the marine sediments. These consist of clays, silts, and very fine sands. Imperviousness of the soil is indicated by origin, landform, tone, the dead furrows, and gully shape. The gullies, particularly, indicate a fine-grained, fairly erodible soil having fair cohesion and critical height. Entrenchment is caused by continuing emergence. These gullies are rather interesting, and careful examination will lead the interpreter to a number of conclusions, speculations, and possibilities. (*Quebec. RCAF.*)

5, these tones reflect the innumerable differences in texture and porosity, level of ground water, springs and seepage, and organic accumulations. Properly interpreted according to judgment, experience, and the material of Chap. 5, tone characteristics are one of the most important criteria for detailed practical mapping of a coastal plain. Often they are the *only* criterion. Chapter 5 includes some illustrations.

Similar to tones and gullies, the vegetative and land-use characteristics associated with coastal plains are extremely variable. Both dissected and undissected areas may be heavily wooded because of unfavorable land-usage conditions of soil, slope, and erosion. In such areas, and in temperate climates, coniferous trees may well predominate, with cedar or cypress favoring the wet spots.

If soil conditions are favorable, the undissected plains and nonswampy doabs may be intensively cultivated, contour-plowed, etc. However, these geographic aspects of marine forms are of little use in identification. In fact, most coastal plains need not be identified because they have already been located in numerous geological, geographical, and physiographical publications. Rather, the coastal plains offer a real challenge to the terrain specialist engaged in practical soil mapping, offering him real opportunities for the application of

air-photo theory, selective field work, observation, and research. Figures 11-4 to 11-8 illustrate some of the photographic characteristics of coastal plains and marine river plains.

11-11. Aerial-photographic Characteristics of Tidal Marshes and Flats. The aerial-photographic characteristics of tidal marshes and flats are discussed in Sec. 15-10.

11-12. Aerial-photographic Characteristics of Beaches. The aerial-photographic characteristics of coastal dunes are discussed and illustrated in Chap. 14. The photographic characteristics of beaches are shown in some of these illustrations. Figure 11-9 illustrates four types. Additional consideration and illustrations appear in connection with Sec. 5-14. For rather detailed information on the aerial-photographic characteristics of beaches, see the three volumes by the Cornell group (13). For information relating the photographic and physical characteristics of beaches, see a series of works by the author (108). Additional information may be found in various military publications.

11-13. Aerial-photographic Characteristics of Beach-ridge and Strand Lines and Marine Terraces. The major identifying characteristics of beach-ridge and strand lines are their shape and topography. They are long, narrow (25 to 500 feet), smoothly curving to straight, low (5 to 50 feet) ridges, having generally smooth surfaces. If they occur in noticeably hilly terrain, they tend to follow contours (unless upwarped by subsequent earth rebound). If in groups, they are more or less parallel, and if associated with a still present, but removed water body, they tend to parallel its present shore line.

Beach-ridge and strand lines have no surface drainage or erosion pattern of significance, although each ridge is usually separated from its neighbors by an intervening trough of wet, marshy, or swampy ground in which an organic-mineral complex forms (Secs. 15-3 and 15-6).

Granular composition gives the beach ridges a light tone. This, combined with intervening dark swales, yields a striped pattern when the ridges are seen as a group on the air photos.

It is common, in populated areas, to find that the beach ridges have been used for roads, railroads, or trail locations. The author knows of several instances in the Hudson's Bay region, where beach ridges may be used to traverse hundreds of miles of tidal marsh and muskeg, with relatively minor breaks. In this area, the ridges have also been used as air strips. The Hudson's Bay region possesses some of the most magnificent beach-ridge-organic sequences in the world, and terrain such as that illustrated in Fig. 11-10 covers thousands of square miles. Figures 11-11 and 11-12 provide additional examples.

LACUSTRINE LANDFORMS

11-14. General Discussion of Lacustrine Action. In Sec. 2-16a, it was stated that the lacustrine origin could be assigned to any visible landform or deposit composed of unconsolidated materials that was originally accumulated beneath the surface of a fresh-water body, not in primary association with deltaic or vertical floodplain deposition, or cast up along the boundaries of such a body by the waves and currents therefrom. It was shown that the formational, or direct, chain of origin was relatively simple.

In order for this direct chain to become operative, certain conditions must obtain (1) a source of supply for deposition, (2) a body of fresh water adequate to receive deposition, and (3) a geological and climatic environment conducive to the effective transportation of materials between source and depositional locale.

These factors are discussed in Sec. 11-2.

11-15. The Lacustrine Landforms. When the proper conditions are present, lacustrine deposits will be accumulated. Subsequently, if the fresh-water bodies are dissipated, these deposits will become visible, forming true landforms. The lacustrine landforms consist solely of lake beds and their associated strand or beach lines. However, the lake beds may be divided into two classes, depending largely upon the climatic-geological environment in which they were produced:

1. Lake beds
   - *a.* Deposited as a result of, and *in conjunction with*, glacial deposition or glaciation (glacial lake beds)
   - *b.* Deposited as a result of climatic changes and/or arid erosion and deposition in topographic basins beyond any contact with glaciation or glacial deposits (alluvial lake beds and playas)
2. Strand beach lines



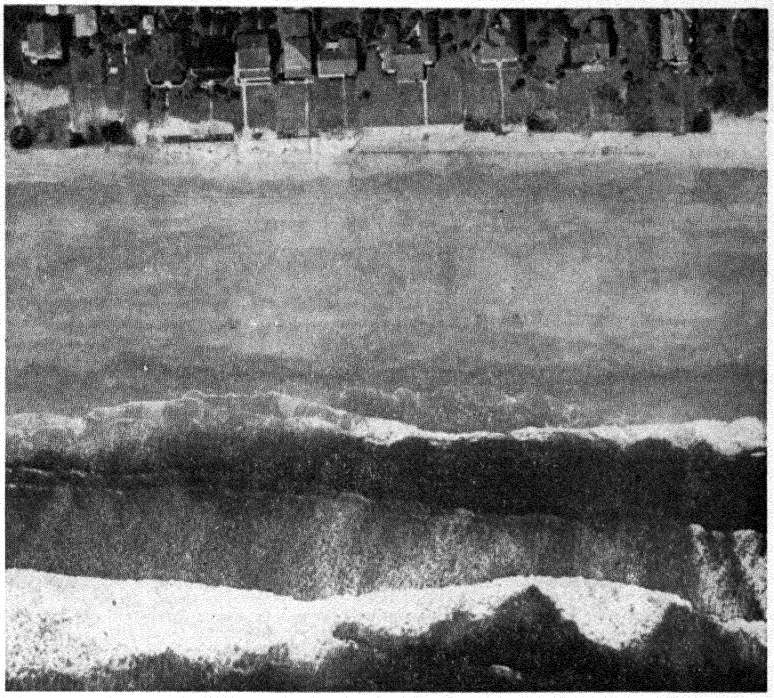
(a)

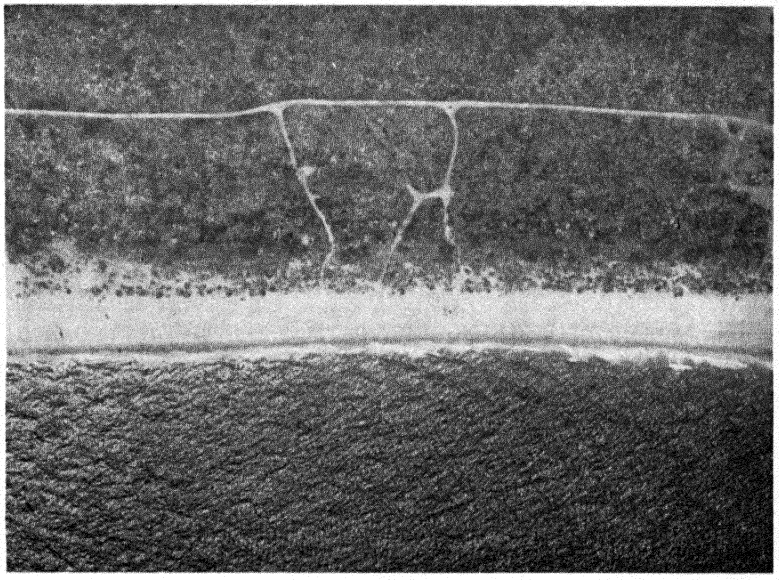


(c)

Fig. 11-9. Four pictures of beaches having various

(*b*)





(*d*)

characteristics, textures, and compositions.

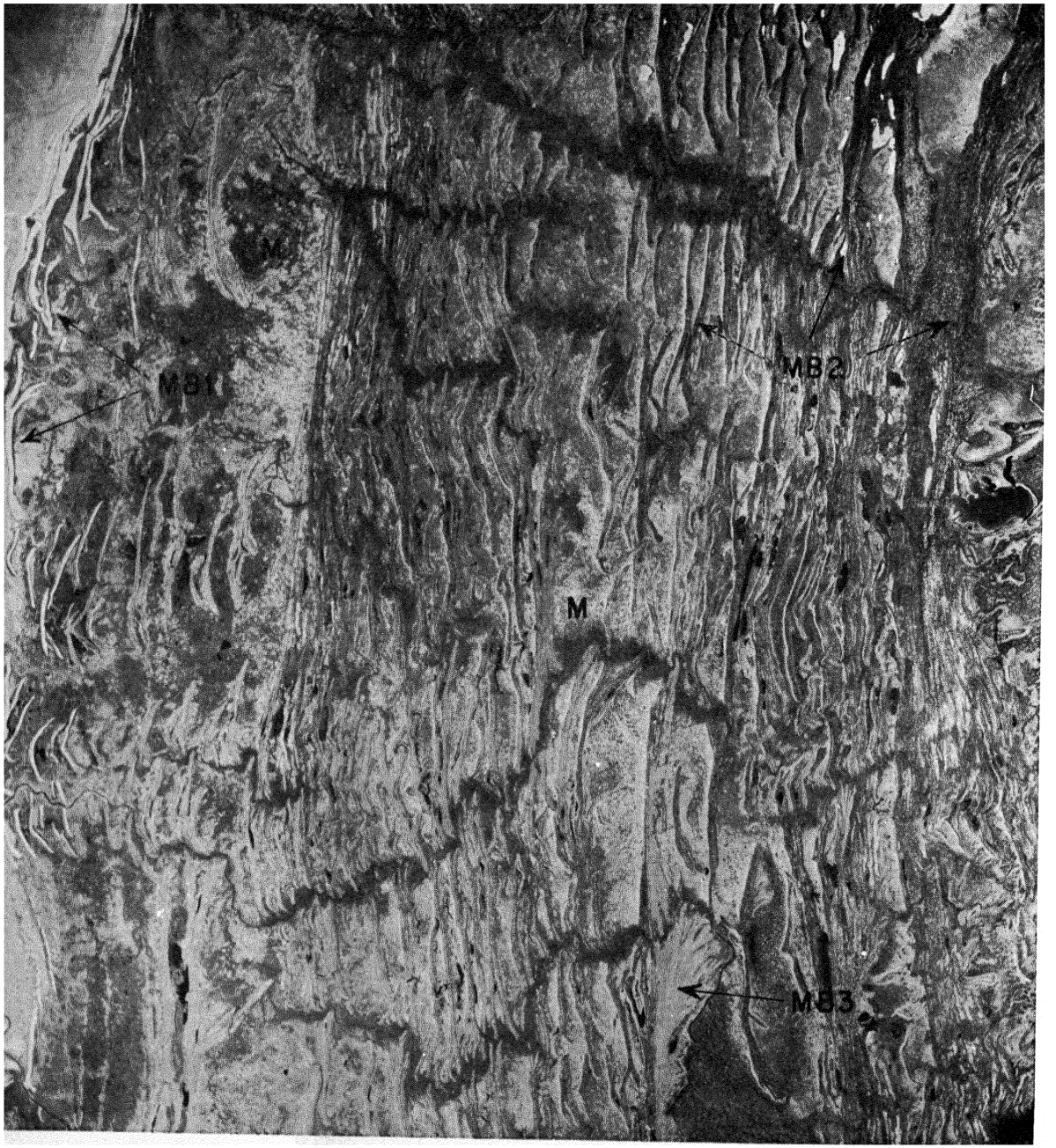


Fig. 11-10. This photograph (relief is so low that stereo vision is not required) shows a small portion of the magnificent beach-ridge developments in a portion of the Hudson's Bay region. Bare beach ridges, with their white tones (*MB1*), contrast with other single and coalescent ridges covered with conifers and moss (*MB2*) and a coalescent ridge which has been denuded by fire (*MB3*). The tonal differences are rather distinctive. Areas marked *M* are organic-mineral complexes (Chap. 15) which get deeper as one departs from the shore. Other views of this terrain appear as Figs. 11-3 and 11-4. (*Manitoba. RCAF.*)



Fig. 11-11. This single photograph illustrates the striped pattern typical of beach ridges in groups. The dark-toned areas are the interridge sloughs—marshy, swampy, or containing water. The light-toned stripes are the ridges themselves. To the left of the photograph is a portion of lake bed proper. The winding stream demonstrates its typical stability (no meander scars). At this scale, relief on the ridges is so low that it is almost indistinguishable. (*Indiana. USDA, Commodity Stabilization Service.*)

11-16. Formation of Lake Beds—Glacial.[2] Existing glacial lake beds, commonly known as proglacial lake beds, are formed when meltwaters, usually from a shrinking glacier, are impounded between the glacial front and high land beyond the glacial front. Into these basins of meltwater are discharged the heavy loads of sediment carried by the glacier and its meltwater streams. Proglacial deltas are formed along the lake boundaries, but great amounts of sediment are deposited beneath the water surfaces. Subsequently, as the glacier continues to retreat, or as topographic obstacles are breached, partial or complete drainage of the lake waters ensues, and all or part of the lake bed is

[2] In the interest of uniformity, the present tense is used in the above description. Actually, recent glacial lake beds, as visible landforms, are rare. The glacial lake bed is a relic of the past. In areas where existing relief was low, they extend over large areas. In areas where the relief was rugged, they extend over small areas, but are numerous. One of the greatest sequences of lake deposits is that accumulated along the front of the Wisconsin glacier in a general belt extending from Saskatchewan through the Great Lakes region to the St. Lawrence River. For inferred histories of the large glacial lakes, and their stages, the reader is referred to Flint (59). For additional inferences regarding one of these lakes (Glacial Lake Iroquois), the reader might be interested in the engineering report on a proposed harbor site in Hamilton Bay, Ontario, prepared under the author's direction for the Hydro-electric Power Commission of Ontario by the Engineering Division of Hunting Technical and Exploration Services.

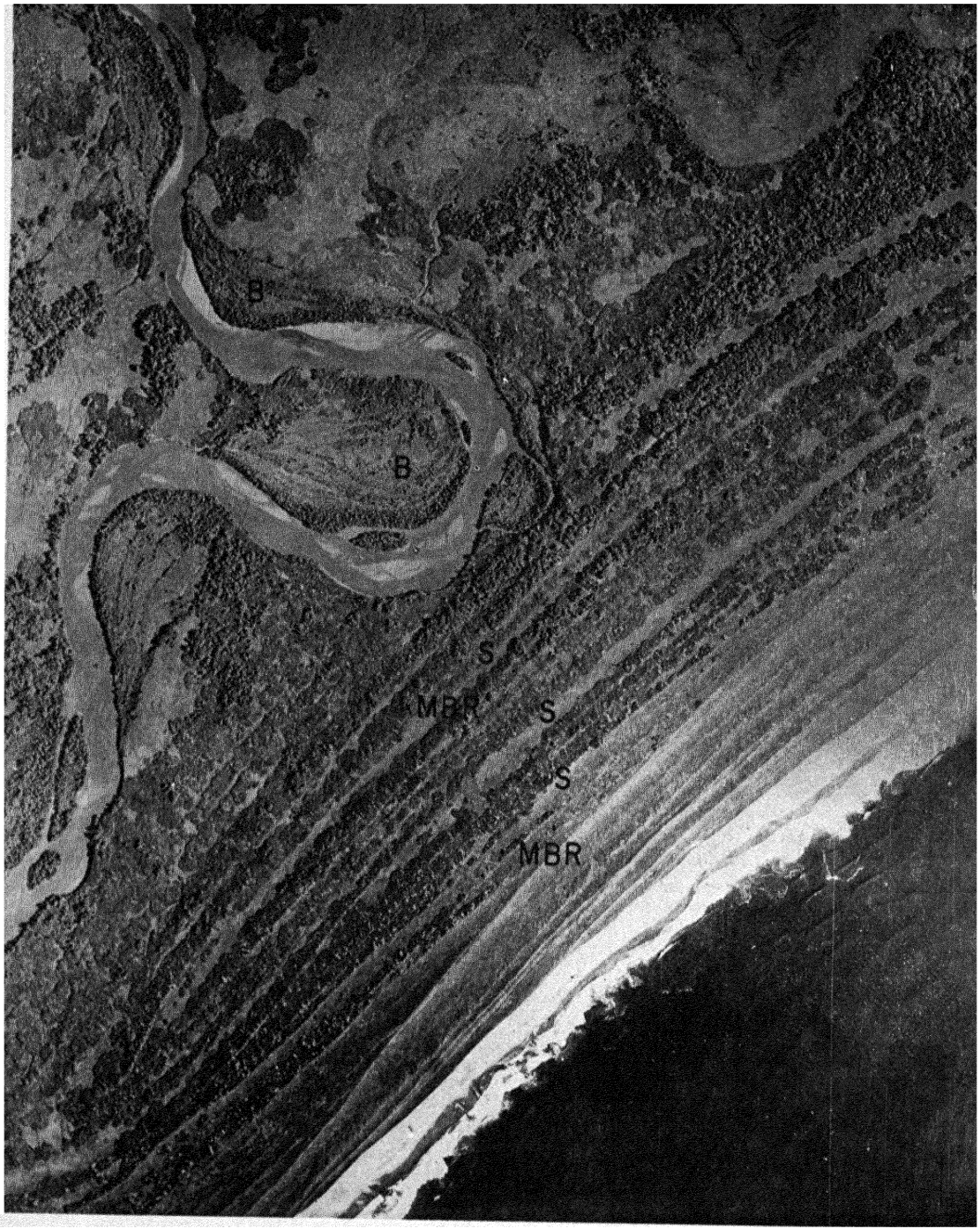


Fig. 11-12. An excellent low-level photograph of beach ridges *MBR* and sloughs *S*. The ridges nearest the water are barren. Those further inland are covered with tree cover. The swales are marshy. The beginnings of a meander floodplain are indicated by the point bars and scrolls *B*. An interpreter would conclude that these *ridges* are composed of gravel. (*Northern Asia.*)



Fig. 11-13. This stereotriplet shows a portion of the shore line and bed of glacial Lake Iroquois. The upland in which the shore line is carved consists primarily of glacial till *GT*. Point bars *LB*, created by the currents and waves of the old lake, are composed of sand and gravel (unfortunately developed). Below this occurs the glacial lake bed *GLL* consisting of a thin mantle of fine sand *S*, silt, and clay over till. A remnant of the preexisting till occurs at *T*. Old fillings of crevasses (?) in the underlying bedrock are indicated by the letters *CF*. After removal of the glacier, upwarping occurred and the level of Lake Iroquois dropped. This caused downcutting of the stream as shown by the deep valley traversing the lake bed. Fluvial bars *FB* are indicated. This stream has created a small meander plain (Chap. 9), upon which the point bars, scrolls, and abandoned channels are evident. *FB*1 indicates an upper fluvial terrace level. (*Ontario. Photographic Survey Corporation.*)

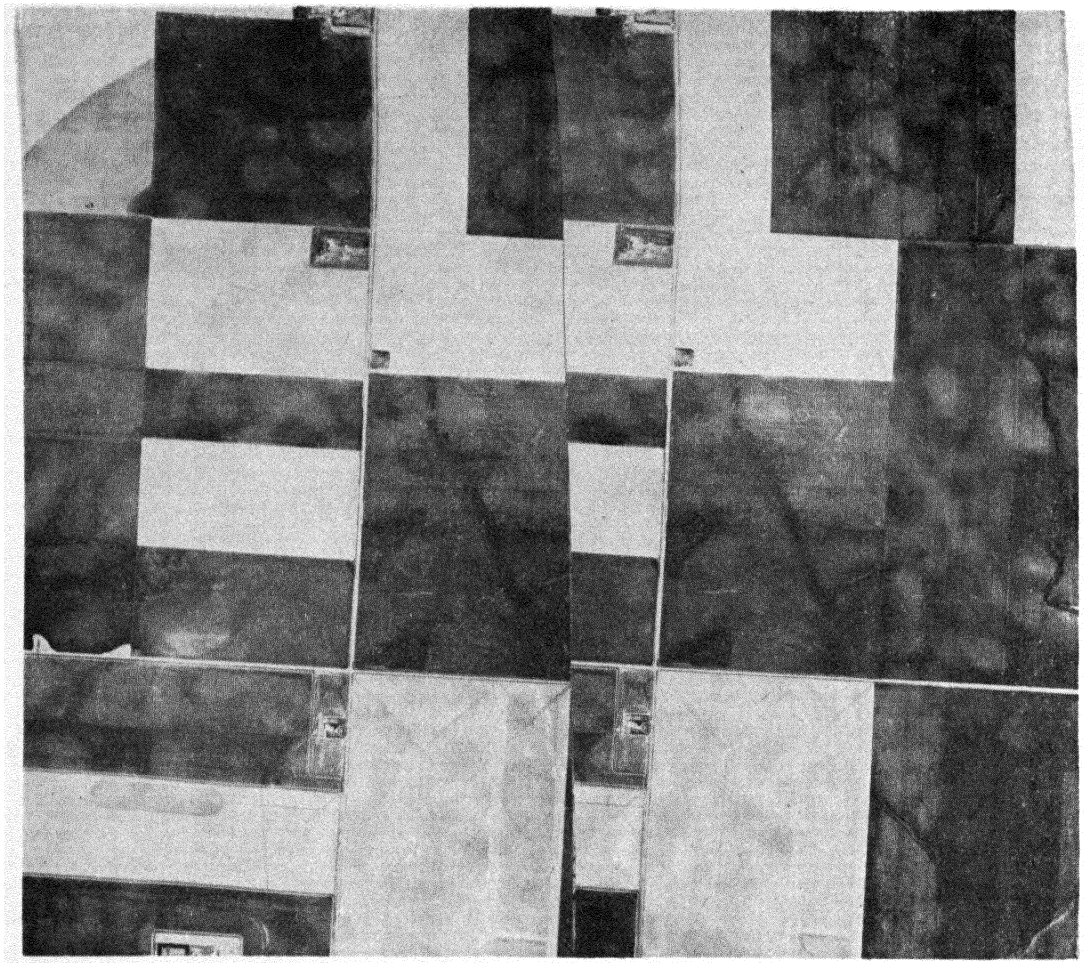


Fig. 11-14. Stereopair of a glacial lake bed having a highly impervious texture. The topography is more undulating than is normal for glacial lake beds and may reflect the preexisting morainic relief. Erosion has not progressed very far. Note the gradual tonal gradients (Chap. 5), regardless of the background tone (relative tonality). Also note the effect of the cultivation on the gray-tone pattern. (*Saskatchewan. RCAF.*)

exposed as a landform. If the drainage of the lake bed occurs in stages, strand and beach lines (Sec. 11-9) are created. Subsequent to the various drainage stages, glaciofluvial outwash (Chap. 13) may cover great portions of the original lake-bed surface.

The specific types of impoundment are complex. In most cases, normal drainage is blocked either by the glacier itself or by glacial accumulations such as marginal moraines (Chap. 12). In other cases, the weight of the glacial sheet is sufficient to depress the land surface temporarily and form a depositional basin.[3]

The sediments carried by glacial meltwaters are as variable as the load carried by the glacier feed-

[3] This depressed surface then undergoes elastic (plastic?) rebound, elevating the lake-floor sediments differentially, creating warped strand lines. Naturally, these processes of depression and rebound occurred during the great glacial ages of the past. It is conceivable, however, that they might occur in the future. The process of rebound is definitely still ocurring, e.g., along the south shore of Hudson's Bay (Sec. 11-13).

ing them. However, large amounts of the coarser gravels and sands are deposited in proglacial deltas, while the remaining sands and gravels accumulate relatively close to the shore line in conformance with the laws of velocity deposition. The remaining load, consisting of silt and clays, is deposited over the lake bottom proper, and, as a result, these textures predominate over the greater expanse of existing lake-bed landforms.

Obviously, most of the melting of glaciers occurs during the warm season (spring and summer in our present terms). Soon after entering the lake waters, the silt fraction, by virtue of its range of greater particle diameters, settles out in accordance with Stokes' law. The remaining clay fraction remains in suspension for a considerably longer period, also in accordance with Stokes' law, settling out gradually. With the advent of the cold season, melting and silt deposition cease, while clay deposition continues. During the following melting season, the entire cycle recurs. In this manner, alternating thin strata of predominantly silt sizes and predominantly clay sizes are built up on a yearly basis.[4] These layers are collectively called "varves." They are considered by Flint to be a product, almost exclusively, of fresh-water rather than saline-water deposition. His reasons have to do with the flocculating effect of the electrolytic saline waters, causing even the clay particles to aggregate and settle out relatively rapidly. Varves, though a feature of many glacial lake beds, do not characterize them all, particularly those of large extent.

[4] Some current opinion maintains that such strata can be accumulated on a daily basis.

11-17. Formation of Lake Beds—Alluvial, Playa, and Salina. Alluvial lake beds are found in all the present arid and semiarid regions of the world which possess natural basins. These natural basins were either formed by rock bodies or existed under arid conditions prior to the formation of lakes and were being filled by encroaching fans and bajadas (Chap. 10). The latter were the more common. Normal arid processes were interrupted one or more times by climatic changes (usually caused by the advance of glaciers during the ice age). The chief effects of the climatic changes were increased rainfall (and runoff) and decreased evaporation. As a result, surface runoff was ponded in the natural basins, creating lakes that increased in depth so long as the rate of runoff exceeded the rate of evaporation. Streams which emptied into

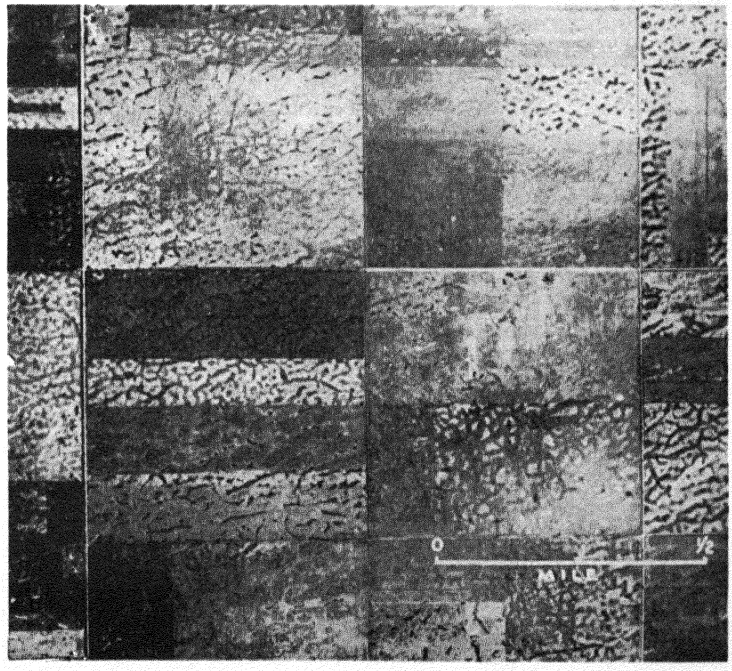


Fig. 11-15. A single view of the mottled pattern developed on glacial Lake Agazziz. Note the definite linears revealed in the lake sediments (Chap. 16). (*North Dakota. USDA.*)

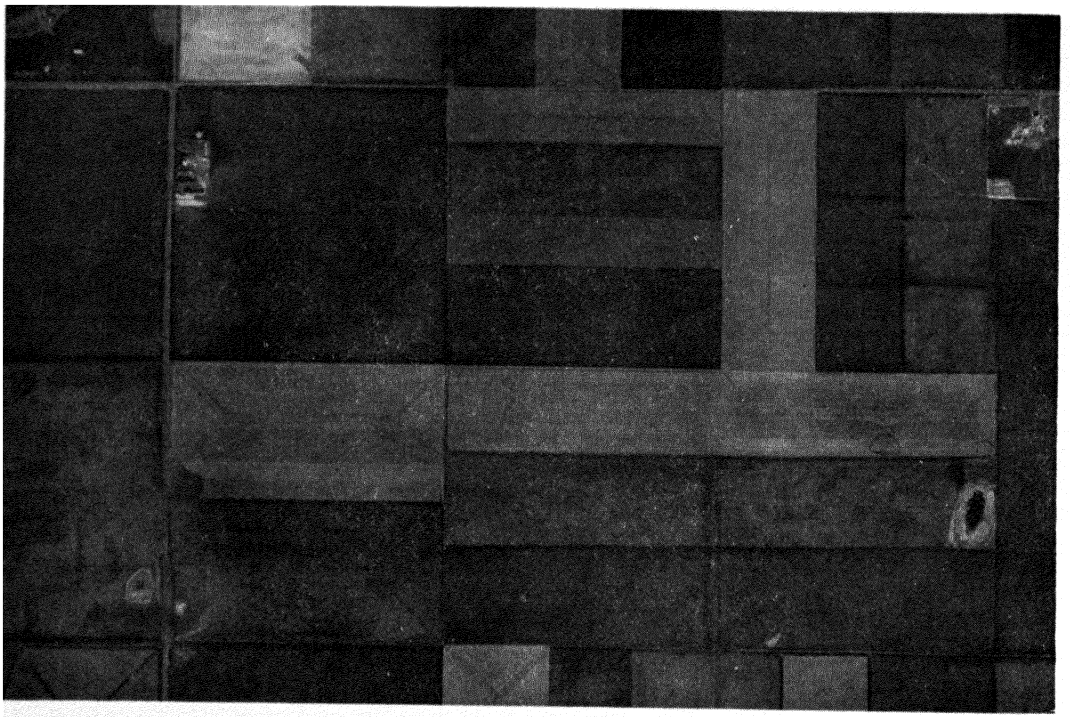


Fig. 11-16. This single photo shows features characteristic of a glacial lake bed composed of highly plastic clays. Topography is almost perfectly flat. Drainage and erosion are absent. The interpreter must depend upon tones and land use to evaluate the area. (Note the subdued mottled pattern and compare with Fig. 11-15. Without regional knowledge and experience, the interpreter might have difficulty in making an evaluation of this area.) (*Saskatchewan, RCAF.*)

the lake often built small deltas whose bottomset beds extended far over the pre-lake floor. Shore currents and waves also had an effect upon the underwater distribution of sediments. Eventually, the entire pre-lake floor was covered with layers of assorted sediments, generally fine-grained in texture. When the lake remained at one level for a sufficient time, wave-cut benches and terraces and belts of coarse materials were formed along the shores by wave and current action. Eventually, the climate changed again. Evaporation exceeded runoff, and the lake receded, isolating deltas and strand lines high upon the basin walls. As the lake receded, climatic fluctuations may have caused several pauses in lake level, each pause being recorded by a separate strand line. Ultimately, the lake waters evaporated completely, leaving an alluvial lake bed as visible evidence of its past. If, during the final stages of evaporation, it paused long enough, strand lines may have been formed on the lake bed itself. Following the disappearance of the lake, arid erosion again ensued, and fans and bajadas began to cover existing lake-bed deposits. Often, a salt playa, as discussed below, was formed. Later, because of more climatic changes, the lake may have appeared again, together with a repetition of the entire cycle. At present, however, most of the lake beds are completely dry, except for shallow playas temporarily created after exceptional storms. In a few lake beds, remnants of the old water body, such as Great Salt Lake, still persist, although even these are gradually drying away.

The playa is a special type of alluvial lake peculiar to arid areas of interior drainage. It is not formed as a result of climatic changes, like the alluvial lake bed, but is, instead, a normal land form created under constant arid conditions. Section 10-3 discussed flow of water over alluvial fans. It was found that, although appreciable

amounts of runoff were lost by insoaking and evaporation, a significant portion was often able to pass beyond the boundary of the fan, carrying fine sediments in suspension. If the area beyond the fan was surrounded by higher areas on all sides, a shallow, stagnant "playa lake" would be created and suspended fine sediments would be deposited on its bottom. Because of high evaporation rates, the water of this playa lake would soon disappear, exposing the exceptionally flat lake bed, or "playa." Since the waters of the playa lake originally contained appreciable quantities of dissolved salts (obtained from the chemical weathering of eroded rocks), surface crusts of salt would be deposited when the waters evaporated. The thickness of these salt layers would often be increased because of the evaporation of upward-moving, salt-bearing capillary ground water. In the lower depressions of some valley floors, salt-water lakes may exist throughout the year because of the constant inflow of ground water. Although the ground water may be relatively fresh, rapid surface evaporation swiftly creates and maintains the salinity of the water. Such a lake is called a "salina" (216).

11-18. Formation of Lacustrine Landforms—Strand and Beach Lines. Most lake beds fluctuate in level. Each fluctation, of any length, creates a strand line (beach ridge, terrace scarp) along its water boundary. Indeed, this is a distinguishing feature of lacustrine deposits and, in many cases, is of great practical importance.

The formation of strand, beach, and terrace lines associated with lake beds is similar to that of marine forms of the same character. Consequently, and for convenience, they are discussed in Sec. 11-9.

11-19. Aerial-photographic Characteristics of Lake Beds. The outstanding characteristic of all lake beds, glacial and fluvial, is their exceptional flatness. The surface is broken only by small to medium irregularities (salinas, remnantal or small beach ridges, current effects, salt mounds, gullies, etc.), but the over-all surface is flat. If there were pauses in lake level, well-developed beach-ridge and strand lines or lacustrine terraces (similar to marine terraces, Sec. 11-9) may occur. The flatness may be broken, usually in glacial lakes, by entrenched stream valleys and progressing gullies. Also, occasionally, glacial lake beds show very thin lacustrine mantles over the prelacustrine undulating till. The preexisting relief may persist in such a case. Around the edges of glacial lake beds, where the coarser materials occur, the surface may be characterized not only by strands, terraces, etc., but also by dune developments.

Surface-drainage patterns are characteristic. In

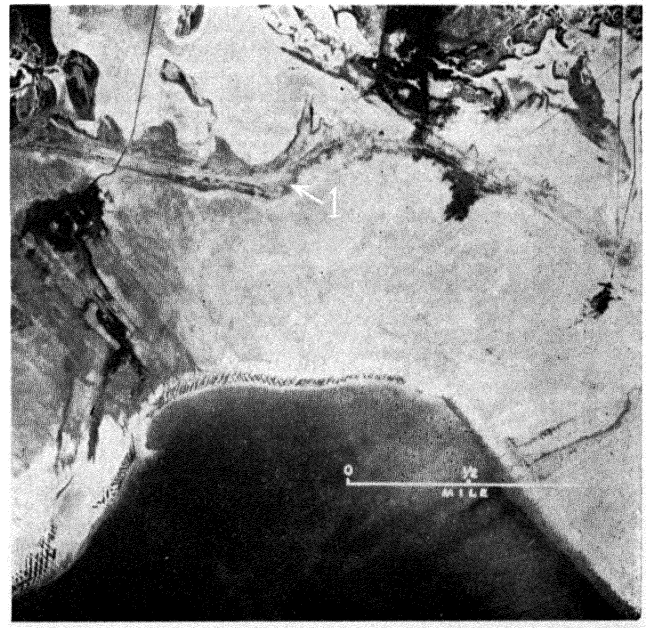


Fig. 11-17. Typical terrain around the shores of an existent alluvial lake. The flat topography, absence of integrated drainage, light-gray tones, and old strand line (beach ridge 1) are typical. The fine black line is a drainage ditch. The black areas are all water surface, either the lake proper or intersections of the water table. The black and white criss-cross pattern at the lake edge has some relation to runoff-ripple effects. Originally selected by the author while with the Cornell group. (*Utah. USDA.*)

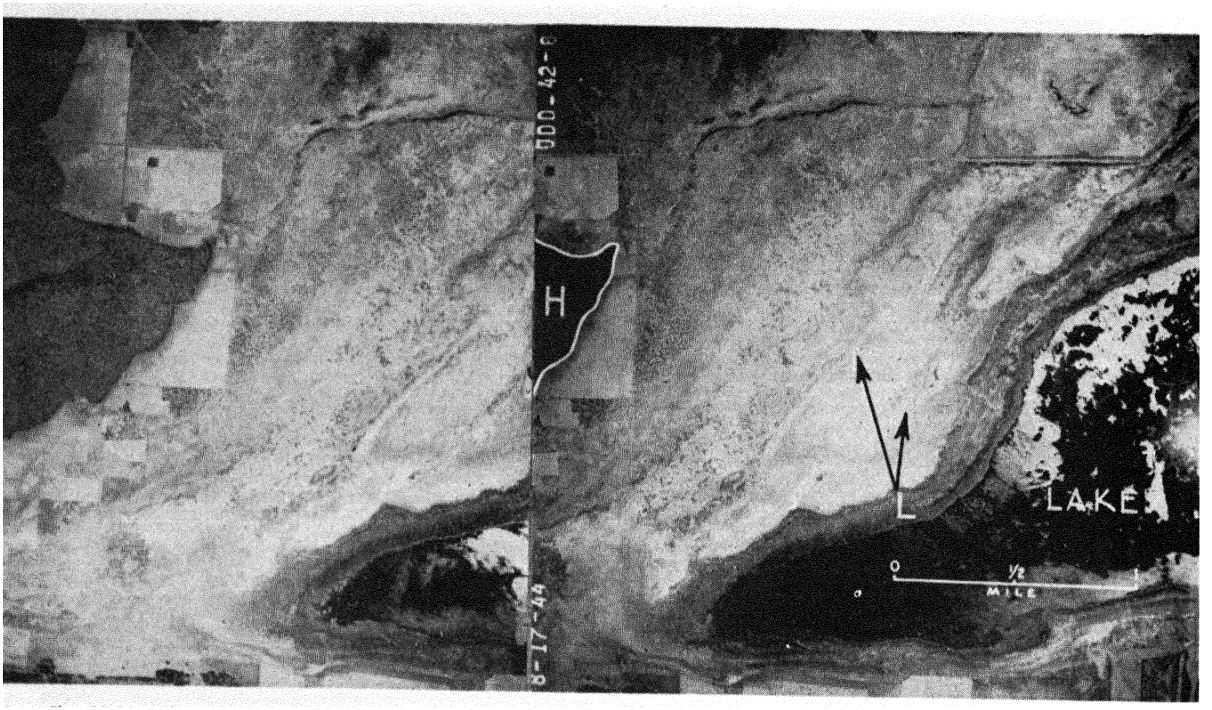


Fig. 11-18. This stereopair shows the water-laid surface of an old alluvial lake bed, together with its sharp break at the highland (*H*) boundary. In the right portion of the pair there appears a playa lake that is slowly receding, leaving a playa. A visible portion of the playa appears as a very light, flat area whose only relief features are small strand lines *L*. White patches within the lake are reflected sunlight, not salt. This pair was selected and annotated by the author while with the Cornell group. (*California. USDA.*)



Fig. 11-19a. A single aerial view of a playa, with its layer of encrusted evaporative salts of varying composition (indicated by the "scrambled-eggs" pattern), and two small salinas S. Selected and annotated by the author while with the Cornell group. (*Colorado. USDA.*)

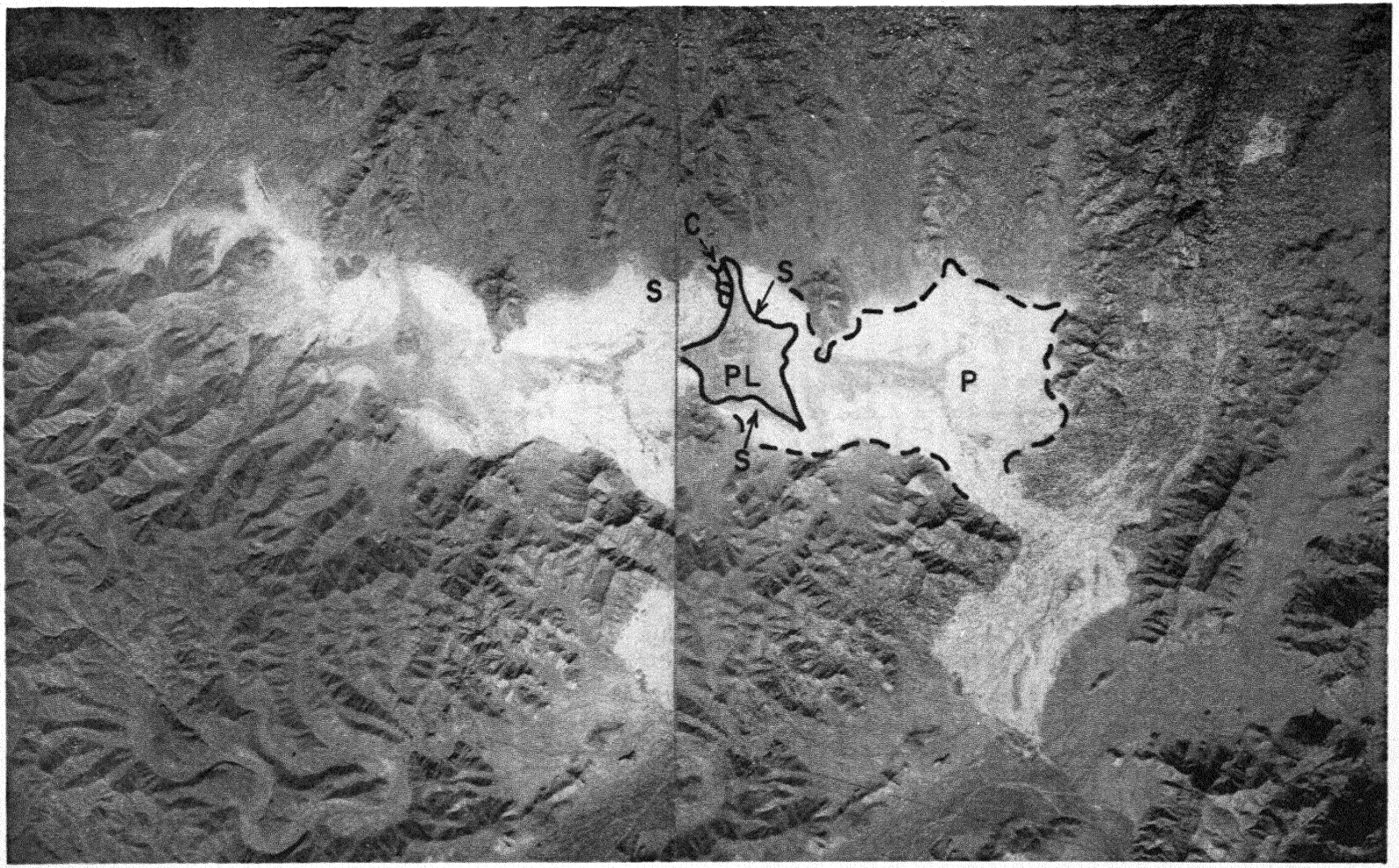


Fig. 11-19b. This photograph shows a playa lake *PL*, playa *P*, drying cracks **C** (note similarity to permafrost phenomena), and strand lines **S**. (*Far East Photographic Survey Corporation.*)

general, because of a low position with respect to local base level and a high ground-water table, integrated surface drainage is almost completely absent. This, of course, does not reflect perviousness, as it might on a terrace. Frequently, moderately large and well-established streams traverse lake beds without draining them by means of the usual sideward tributaries. These streams meander intricately, but their channels seem to be rather stable, as evidenced by the comparative lack of meander scars and abandoned channels. This meander pattern probably reflects a low local base level, and the resulting dominance of lateral erosion, counteracted by the highly tenacious character of the lacustrine clays. Of course, if the lake bed has undergone upwarping, such streams will be characterized by entrenchment and tributaries. Artificial drainage, using tiles, ditches, canals, and dead furrows, is a common feature, reflecting efforts to drain the lacustrine soils.

Erosion, unless upwarping has occurred or local base level has been breached, is absent. If present, it is typical (Chap. 4) of the lacustrine soils.

Both glacial and alluvial lake beds are characterized by generally narrow tonal ranges. In the case of glacial lake beds, these tend toward the medium and light grays. In alluvial lake beds, the range includes light grays to white. The word "generally" is important. Lake beds often display numerous tonal variations, but the visual *impression* is that they are minor. These variations may reflect many factors: variations in soil moisture and organic content, variations in depth to water table, wind-drifted sand, sand dunes, evaporative salt developments, the presence of strand lines, etc. The salt developments are quite striking (Fig. 11-18).

Vegetation is variable. In humid areas, farming is intensive and natural vegetation is absent. In arid areas, vegetation is completely absent or very sparse. When sparsely present, the over-all effect is a salt-and-pepper pattern. Irrigation may change the vegetative pattern of arid areas.

Field boundaries on lake beds tend to be regular and uniform.

Figures 11-13 to 11-19 illustrate the aerial-photographic appearance of lake beds.

11-20. Aerial-photographic Characteristics of Lacustrine Beach, Strand, and Terrace Lines. The characteristics of these lacustrine forms are essentially the same as those described in Sec. 11-13. Several illustrations are included in this chapter.

12 GLACIAL LANDFORMS

12-1. General Discussion of Glacial Action. Glacial ice masses still cover portions of the earth's surface and persist in most countries where appreciable elevations occur. These masses are the contemporary manifestations of the great ice sheets that covered large areas of the earth's surface during various ice ages of the past.

It is not the purpose, nor is it within the scope, of this book to consider the complex details of glacial action in terms of formation, physics, direction, history, location, movement, etc. Excellent references, including Flint's superb work (59), already exist on these facts of glaciology and glaciation. Nevertheless, to evaluate the aerial-photographic perspective of glacial deposits, some appreciation of glacial action in its most pertinent aspects must be had.

During various periods in the earth's history,[1] ice began to form or expand at high elevations in the vicinity of the poles (and probably elsewhere). Because of high snow nourishment due to a favorable climatic regimen, and partially generated by the ice masses themselves, the masses began to expand. They "spilled" (extruded?) from their initial high hollows and began a process of slow "plastic" flow down the valleys, eventually occupying them completely as "valley glaciers" (Fig. 12-1). During the process of expansion and flow, through a combination of abrasion and quarrying, they tended to sculpture the rock landscape in such a way that, following disappearance of the ice, typical features remained (cirques, cols, troughs, Fig. 12-2). Ultimately they reached the foothills and, still in a state of plastic flow, spread out, in a manner comparable to fluvial fans, to become "piedmont glaciers." Eventually, like fluvial fans, these glaciers coalesced and continued to advance until they became the great "ice sheets," or "continental glaciers," covering millions of square miles and having thicknesses exceeding several thousand feet. Finally, these ice sheets slowly wasted away, with numerous pauses, readvances, etc., until they almost disappeared—the condition that exists today.

During the stages of advance, through a combination of freezing and thawing, tearing and breaking (quarrying), and sheer basal pushing, wearing, and scraping (abrasion), the huge masses of slowly moving ice removed tremendous quantities of rock, unconsolidated deposits, and residual soils, working them into their own ice bodies. Within the ice bodies, the removed material was slowly carried along, usually for relatively short distances, but occasionally for hundreds of miles. In general, the material was carried within the *basal portion of the glacier*, within its *lateral* and *medial moraine belts* (Fig. 12-1), or (to a minor extent) *on its surface*. Some gouging and grooving of very competent rocks and sticky clays occurred during this advance, and frequently accumulations of drift were plastered (lodged) around small obstacles or in depressions and were overridden by the glacier to form "basal-till-deposits, drumlins," and "rock drumlins."

During the stages of wastage, the solid mineral particles carried within the ice were deposited because of one or more types of wastage action:

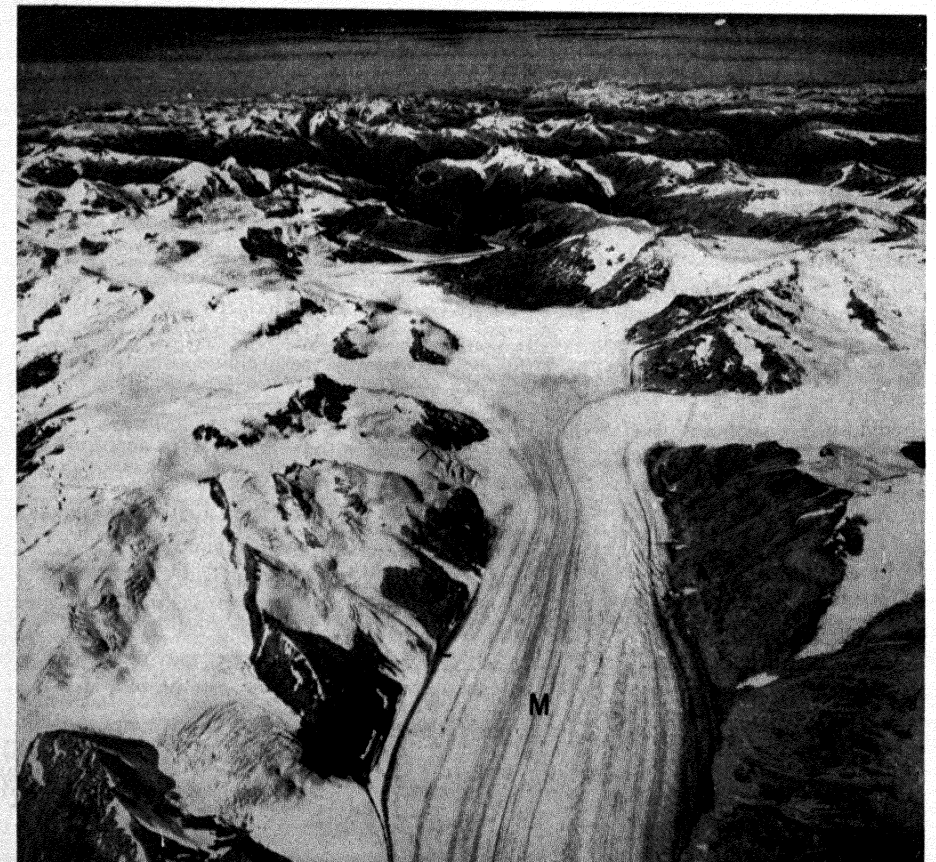
1. Removal in *suspension* by rapidly flowing glacial meltwaters of great volume
2. Deposition by dumping and pushing during "ablation" (in place wastage of the ice) with relatively little water action
3. Removal in ice blocks by "calving" and final deposition following wastage of the blocks

As mentioned in Sec. 2-17, the *glacial origin*

[1] Beginning as long ago as early Nebraskan time (1,000,000 years ago?), "ending" only in late Wisconsin time (9,000 to 15,000 years ago), and consisting of several glacial stages separated by several interglacial stages. It is quite posible that we are now in an interglacial stage.



(*a*)



(*b*)

may be assigned to those deposits that were accumulated by lodgment during advance of the glaciers or formed during their ablation.

The *glaciofluvial origin* may be applied to those deposits that accumulated by deposition from rapidly flowing, sediment-laden glacial meltwaters (Chap. 13).

Either of the two origins may be assigned to deposits resulting from the wastage of calved blocks and to deposits that combine fluvial and ablatory effects, on the basis of the situation and personal opinion or preference.

The formational history of most glacial landforms is open to debate (like most geomorphological phenomena in general). However, certain aspects are unanimously accepted, and others appear to have the advantage of greater reasonableness as based upon logic and common or specialized experience. The formation of the various landforms, as described in succeeding sections, is based upon these most widely accepted, and presumably more reasonable, views.

12-2. Drift, Till—Various Types. In speaking of glacial and fluvioglacial deposits, the words drift, till, stratified drift, basal till, boulder clay, superglacial till, subglacial till, etc., often occur. Since these words, properly used, refer to quite different materials, some discussion of their meaning may be of value. This is particularly true in view of the indiscriminate use of the terms and the attendant confusion in meanings that is common today.

In differentiating between the various terms, it is doubtful that a much better effort can be made than that of Flint (59). His words are here fully quoted:

> The term *glacial drift* embraces all rock material in transport by glacier ice, all deposits made by glacier ice, and all deposits predominantly of glacial origin made in the sea or in bodies of glacial meltwater, whether rafted in icebergs or transported in the water itself. It includes till, stratified drift, and scattered rock fragments.

The term "till" refers to the direct glacial deposit that results from lodgment or ablatory action with relatively little water action. Its name is ancient, coming from a Scottish word to describe "a kind of coarse, obdurate land"—the stoney clays of Scotland which were glacial in origin.

Till is a sediment, and it is perhaps more variable than any sediment known by a single name. Its outstanding characteristic is that it is not sorted. It may consist of 99 per cent clay, or 99 per cent large boulders, or any combination of these and intermediate sizes. Till takes on the complexion of the near-by bedrocks because it is largely derived from them, and in consequence it varies greatly from place to place. In shale and limestone districts, for example, the till is rich in clay and contains relatively few stones. In districts underlain by granite and quartzite, on the other hand, the till is very stony and the matrix that holds the stones together is poor in clay.

The term "boulder clay" refers to a particular type of till, namely, one rich in boulders within a fabric of tough clay. It is commonly misused to describe till in general. As Flint says,

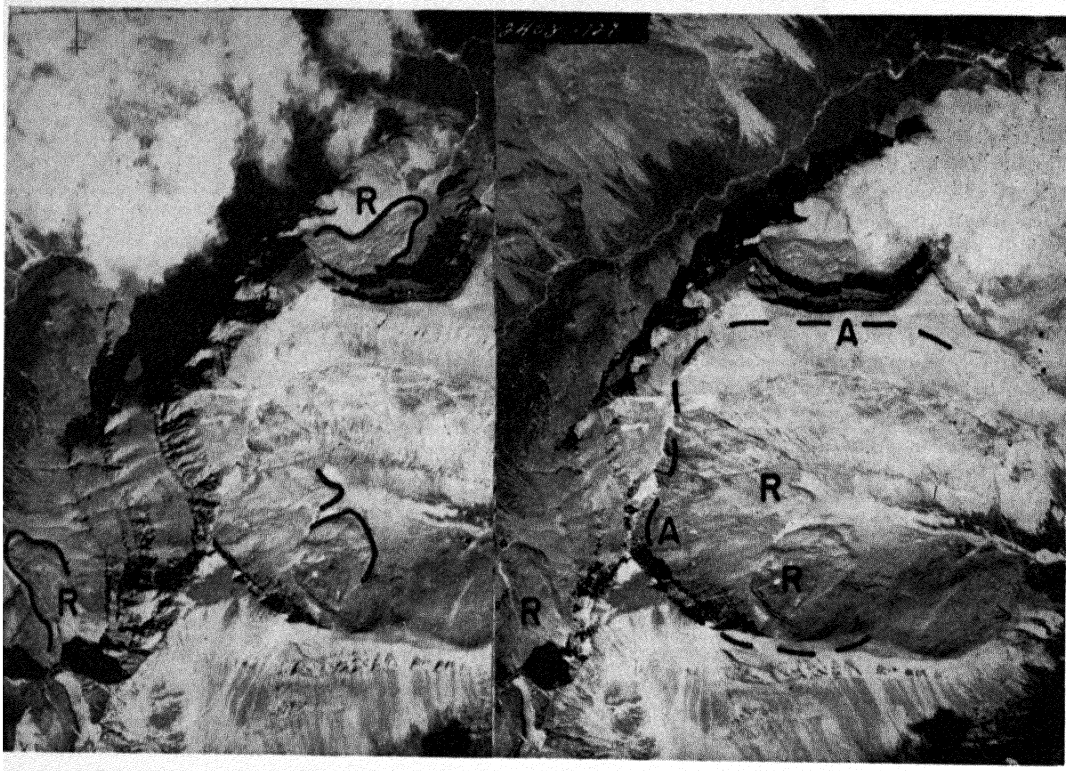
> Boulder clay is not a good designation for the whole range of deposits we know as till. It is not good because some till contains no boulders, some contains little or no clay, and some (though perhaps not very much) contains neither boulders nor clay, but only silt, sand, and small stones.

"Basal (or subglacial) till" and "superglacial till" are two other types of till having different characteristics and methods of formation. Again quoting Flint:

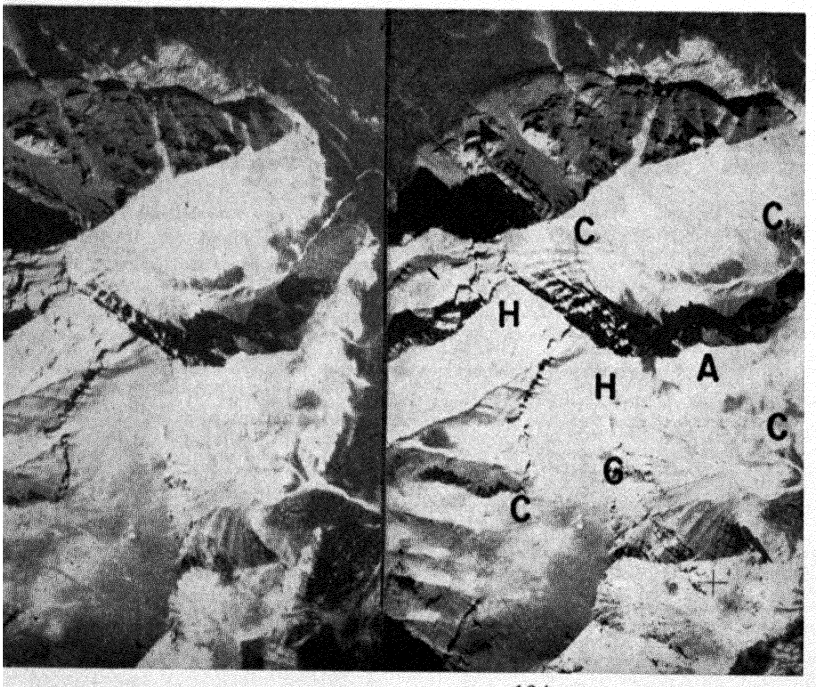
> As long ago as 1877 there were recognized, both in southern Sweden and in eastern North America, exposures of till that seemed to consist of two distinct members. The lower member was dense and clay-rich, with a good many glacially worn stones. The upper member included less clay and silt in proportion to sand, and the stones it contained were on the average larger and less worn than those in the lower member. Torell attributed the lower member to deposition, by lodgment beneath the ice, of the basal drift, and the upper member to the gradual letting-down of superglacial ablation moraine by slow wastage of the ice beneath it. At that early date he correctly recognized two very different processes of till deposition and thereby established a principle later adhered to widely.

Superglacial till overlying basal till has been identified at an increasing number of localities. The basal till is clay-rich because little or none of the finest sediment it contains had opportunity during deposition to be flushed away by running water. It is dense, tough, and compact because it has been pressed down by the weight of a great thickness of ice. Some of the

Fig. 12-1. Single vertical and oblique views of valley glaciers. Note the coalescing medial *M* and lateral *L* moraine strips, as well as the crevassing patterns at points of strain. (*British Columbia. Photographic Survey Corporation.*)



(a)



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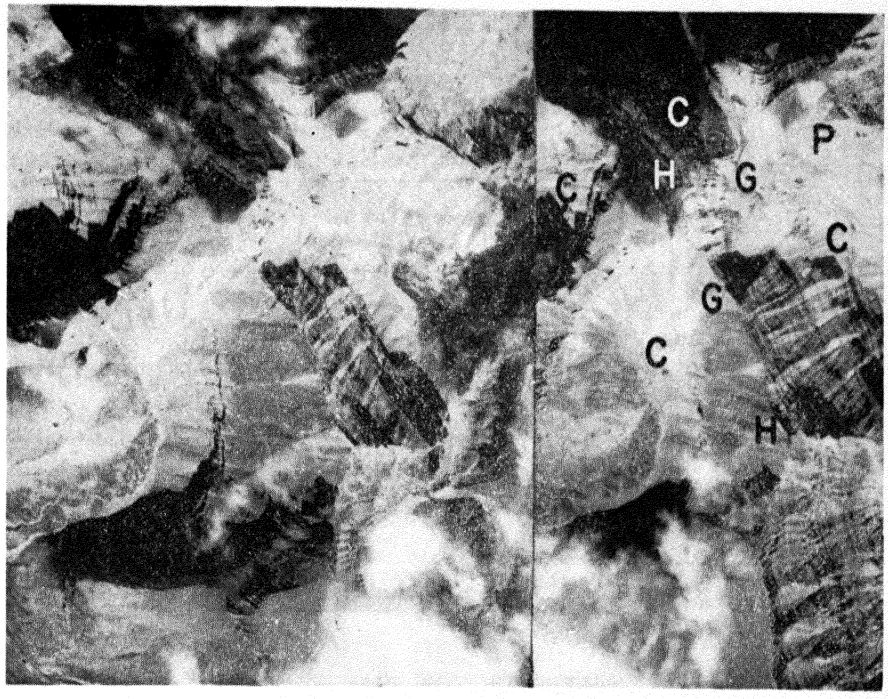

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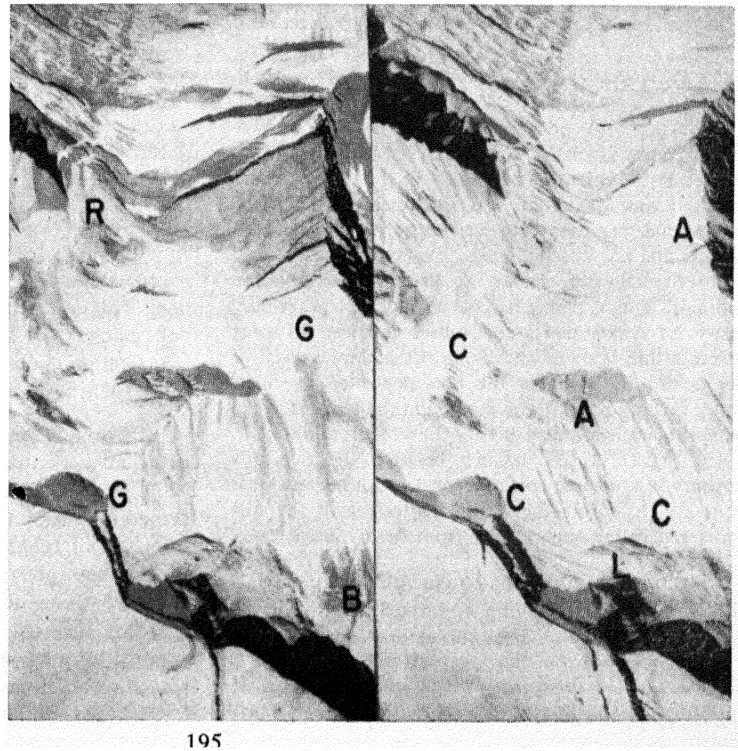


Fig. 12-2. These four stereopairs illustrate various features of alpine erosion as they have been developed in tilted sedimentaries, flows, etc., in the Canadian Rockies. More classical examples could be found, but these examples indicate the more common, irregular, and "non-textbook" appearances. Included are cirques *C*, horns *H*, cols *G*, the end of a hanging rock basin *B*, aretes *A*, and faceted spurs. Several rock glaciers *R* of irregular form, a snow avalanche *Av*, and a snow-debris avalanche are shown. The special tonal effects, and the associated strain imposed upon interpretation, of clouds, shadows, and snow are also indicated. (*Alberta. Alberta Department of Lands and Forests, Technical Division.*)

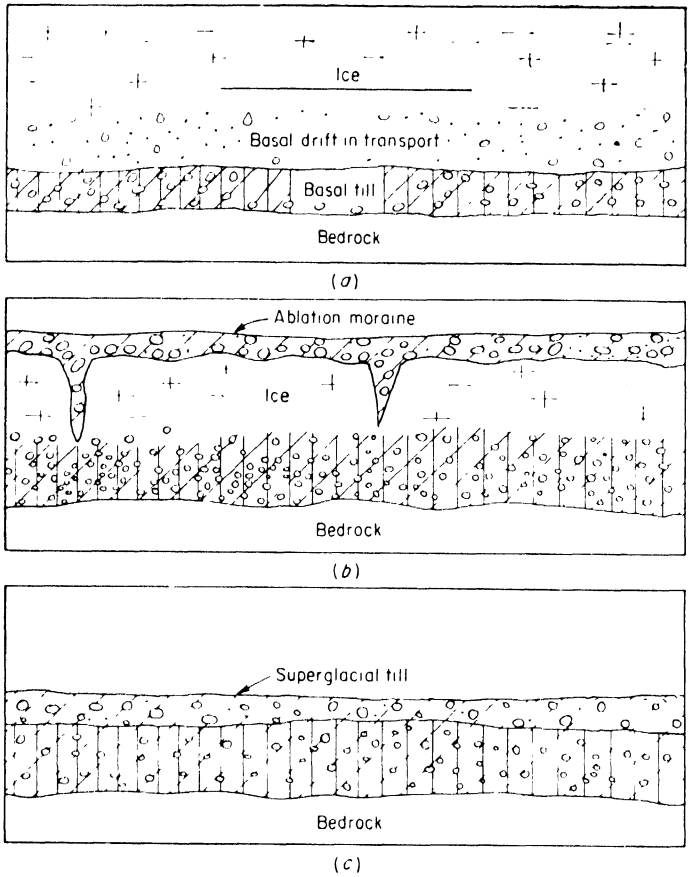


Fig. 12-3. A schematic illustration of superglacial and basal till deposition. [*After Flint* (59).]

stones show glacial modification because they were carried in the drift-rich basal part of the glacier where attrition was maximum. The superglacial till, on the other hand, has been subjected to no pressure and little attrition but was repeatedly washed by trickles and rills of meltwater during its existence as ablation moraine. This explains its coarser, average grain size, less-worn constituents, and looser texture. In some places a thin layer of stratified drift separates the two layers of till. Probably this was deposited by meltwater flowing beneath the thin ice in the terminal zone while ablation moraine was accumulating above it.

[In Fig. 12-3] the contact between the two tills appears as a distinct surface; yet it is not an erosional contact. This distinctness is characteristic of the surfaces separating superglacial from basal tills.

"Stratified drift" refers to glaciofluvial materials that are stratified, having apparently been carried and deposited by glacial meltwaters (Chap. 13).

12-3. A Classification of Glacial Landforms. If landform is considered in its broadest sense (shape of terrain, Sec. 2-27), glacial landforms may be divided into three major classes:

1. Sculptured landforms such as cirques, troughs, hanging valleys, cols, aretes, horns
2. Depositional-wastage landforms such as till sheets (plains), marginal moraines, drumlins, and rock glaciers
3. Combinations of sculptured and depositional forms such as rock drumlins

This broad approach to classification is not consistent with the "unit landform" concept (Sec. 2-27). It is true that the sculptured landforms, formed in consolidated materials by glacial erosive action, have typical topographic features regardless of their geographic location. Unfortunately, however, these features do not provide clues regarding the structure, texture and composition, or uniformity of the materials in which they are formed. Therefore they are not unit landforms. Rather, they are *erosion features* produced by the

removal of material and must be considered as such (Chap. 4), except that, unlike some erosion features, i.e., gullies, they do not even provide an aid to qualitative interpretation (Fig. 12-2).

If the glacial landforms are considered from the "unit" standpoint and, in accordance with the discussion of Sec. 12-1, are limited to those developed in close proximity to glaciers with relatively little effect because of water action, the following list may be enumerated:

1. Till sheets (or till plains)
   a. Sag-and-swell type
   b. Ablation type
2. Random ground moraine
3. Marginal moraines
   a. Valley-glacier lateral type
   b. Normal marginal types (end, recessional, interlobate, etc.)
4. Drumlins and rock drumlins
5. Rock glaciers

These landforms are discussed and illustrated in the following sections.

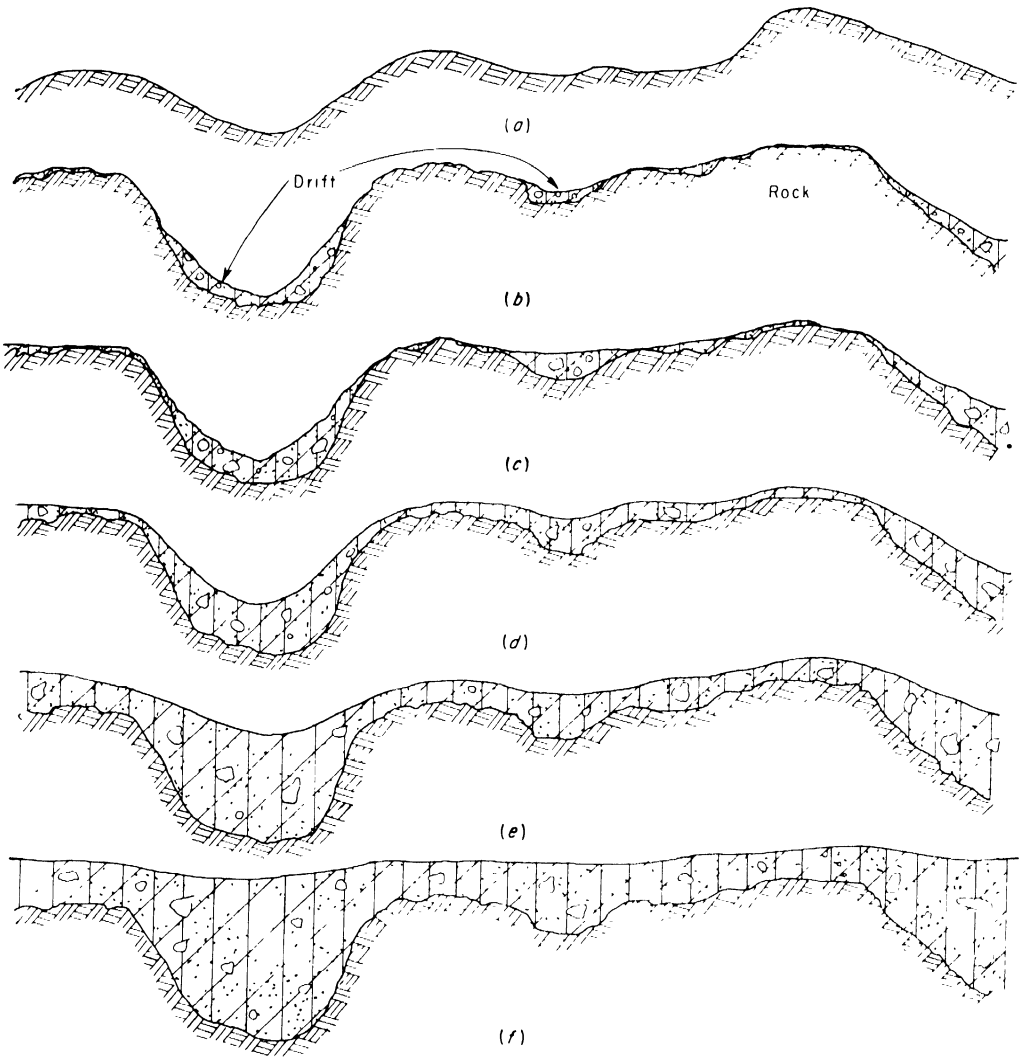


Fig. 12-4. A schematic representation of various degrees of drift deposition. Shown are (*a*) preglacial relief; (*b*) sporadic, random, ground moraine; (*c*) semicontinuous random ground moraine; (*d*) a thin (bedrock-controlled) till sheet; (*e*) a medium-thick till sheet; and (*f*) a thick drift-controlled till sheet. Note that the preglacial rock surface has been altered by deepening of the valleys and lowering of certain hilltops.



Fig. 12-5. A stereotriplet showing some sag-and-swell deposition with local knobby and ablation forms. The undulating topography is interrupted only by the occasional muck pocket *M*, bog *B*, and knob or ablation form *A*. These latter are potential sources of granular fill and show a certain distinctiveness of relief. The intervening areas include an undulating to gently rolling landscape. The furzy appearance on the surface of the ground is caused by high-growing crops (corn). Most of the mottling on this plain has been obscured by cropping, but some remains in parts of the photos. (*Illinois. Aero Service Corporation.*)

12-4. Formation of Till Sheets and Till Plains. As a glacier crept slowly over the land it abraded and quarried to bare rock. It also plastered and densified till on some of the terrain over which it passed. Most of this plastering, called "glacial lodgment," occurred on previously abraded surfaces and may initially have been concentrated in pockets, or in the vicinity of obstacles. Such pockets had a tendency to extend themselves, particularly if they contained appreciable quantities of clay. (Clay, especially if wet, sticky, and compact, has a definite resistance to plucking and quarrying and a contrary predilection to holding boulders, stones, and more silt-clay mixtures.) Because of these tendencies, the initial pockets of plastered till increased in depth and area until they may well have coalesced to form a "basal till sheet," also called a "subglacial till sheet." Such a till sheet may have been relatively thin, following the glacially accentuated, preexisting relief, or it may have been relatively thick, obscuring this relief by filling in the valleys to greater depths than the hills (Fig. 12-4). In either case, it had a more or less irregular to undulating surface existing beneath the ice.

Of course, it was also quite possible that no basal sheet would be formed at all, in which case the glacier would have been underlain by bare bedrock.

During some later stage in the history of the glacier, the supply of snow and/or precipitation fell below the level necessary to counteract the wastage actions (calving, dumping, pushing, melting) at the terminus of the glacier. The glacier began to retreat toward its point of origin. As it did so, some of its load was deposited upon the exposed basal till in the form of superglacial till. This was done through a process of ablation (Sec. 12-2, Fig. 12-3) involving gradual ice melting, together with a slow settling, dumping, and sliding of debris and modified to some extent by the pushing action of the basal glacier layer. Some of its load was removed by meltwaters as fluvioglacial materials.

Thus, as the glacier retreated, it left behind it a mantle of till. If this till was only slightly modified by ablatory action, a basal or subglacial till sheet may have remained. If the basal till layer was modified significantly by ablation phenomena, a "superglacial-basal till sheet" may have remained. If the basal till layer was lacking, or if ablation phenomena were dominant, an "ablation till sheet" may have been the result.

The first two types of sheets, provided conditions are suitable, may have a typical undulating topography, known as sag-and-swell topography, and the sheets may be called "sag-and-swell till sheets." The latter type of wastage action produces that chaotic, jumbled, but low-order topography of depressions, knolls, doughnutlike ridges and knolls, ridges, flow-oriented swale patterns, etc., that are known as ablation topography. The till sheets may be called ablation sheets.

In any of the cases mentioned, if the till sheets have a more uniform development over relatively large areas, they may be called "till plains"—basal till plains, ablation till plains, etc. They would correspond to one type of glacial plain described in von Engeln's classification of geomorphic units.

Occasionally till sheets and till plains are called "ground moraine." This name should be reserved for more random, sporadic, and irregular deposits of till.

12-5. Formation of Random Ground Moraine. In many areas over which a glacier passed, the till deposition was irregular in thickness, varying in texture and type, and sporadic or random in occurrence. The processes that deposited such till were the same as those responsible for the formation of till sheets and plains. However, conditions were such that widespread sheets and plains could not form. Rough topography, insufficient load, improper texture, lack of glacial movement (near glacial centers), etc., could have proved sufficient deterrents. These deposits should be called "random ground moraine," or more simply, "ground moraine." Although they cannot qualify as a unit landform, they are so widespread in Ontario, Quebec, Labrador, the northeastern United States, Scandinavia, and other mountainous to rolling areas that their occurrence should be fully understood.

12-6. Formation of Marginal Moraines. From a formational standpoint, there are two types of marginal moraine: (1) moraines maintained throughout the advance of valley glaciers (lateral and medial moraines), and (2) moraines created during the retreat of the glaciers (end moraines).

As mentioned in Sec. 12-1 and illustrated in Fig. 12-1, there are ridges of glacially eroded detritus that parallel the longest dimensions of valley glaciers. Some of these ridges (and the *only* ones that occur in connection with valley glaciers having no tributary glaciers) exist along the lateral contact between the glacial mass and the valley side.

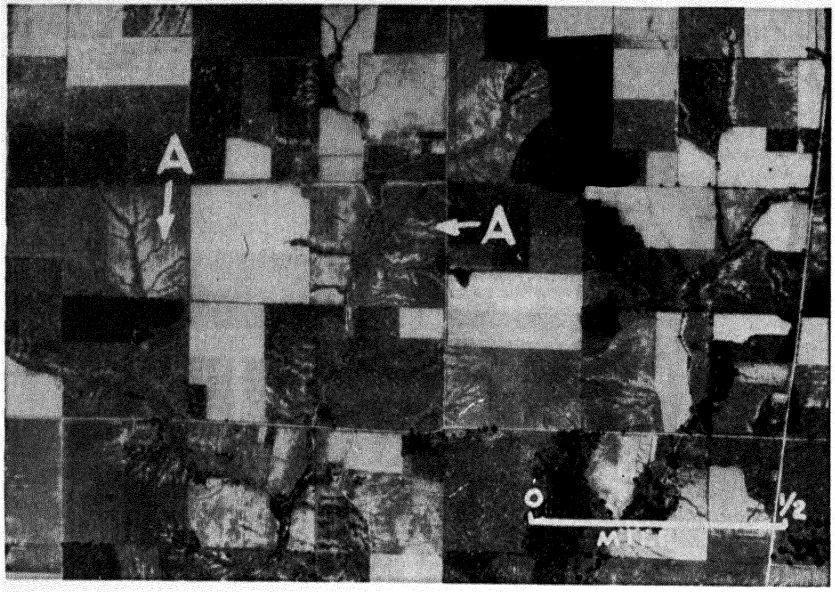


Fig. 12-6. A single aerial view of a flat till plain of Illinoian age. A long period of erosion (compared with deposits of Wisconsin age) has allowed the development of a considerably more integrated and dense pattern than would be expected in any but the most impervious late tills. The white-fringed, flat-bottomed, wide gullies *A* are an important criterion of identification for Illinoian till in this area, according to Belcher. The light areas indicate surficial silts some 10 to 14 feet in thickness over heavy claypan (dark bottoms), promoting lateral widening. This photograph was originally selected and annotated by the Cornell group (43). (*Indiana. U.S. Department of Agriculture.*)

Along this contact there occurs an accumulation of quarried and abraded rock fragments supplemented by colluvial and fluvial material from the valley walls above. Some of this belt, like the basal ice layer of the glacier, consists of an intimate mixture of detritus and ice. It is, of course, subject to melting and removal of running water along a level below that of the glacial surface. Sometimes this happens and "kame terraces" are formed (Sec. 13-4). This accumulation, in many instances, however, may be protected from melting by the dirty layer that covers the ice surface and acts as an insulation to the dirty ice beneath it. As a result, it may persist as a relative ridge along either side of a valley glacier and, as the cleaner portion of the glacier melts, portions of the ridge may slide and slump down toward the center of the valley, extending the lateral dimensions of the ridge. After the glacier melts, these lateral accumulations remain along the valley walls as "lateral moraines."

In active glaciers, the lateral moraines of tributary glaciers are incorporated into the body of the main glacier (Fig. 12-1). These are called "medial moraines." They seldom, if ever, persist as visible drift accumulations, being largely destroyed by ablation during glacial wastage.

Lateral moraines are much less important, as glacial deposits, than marginal moraines created during glacial retreat. At some time during the life of every glacier, the amount of glacial nourishment was insufficient to maintain the advance of the glacier in opposition to its terminal wastage. At this time, the glacier stopped advancing. If the nourishment was sufficient to balance wastage, the glacial front remained static. If the wastage exceeded nourishment, the glacial front retreated. In the first case (staticism), or, during general wastage, through a series of minor retreats from and readvances to the same general locale, an accumulation of wastage products was formed. This accumulation may be called an "end moraine." It is formed by the normal ablatory action (dumping, sliding, melting) at the glacial terminus, probably supplemented by upriding and upthrusting of the glacial ice sheet as it continued to flow toward the moraine. The topographic form of end moraines is fairly variable, but may be described generally as

a broad, relatively high ridge with a surface that ranges from irregularly undulating to a jumbled knob-and-kettle, or chaotic ablatory, type.

End moraines are composed predominantly of unassorted material (till), although stratified drift, in the form of local strata and pockets, is almost always present and occasionally may be dominant (kame moraines, Sec. 13-4). The ratio of till to stratified drift is dependent upon the proportion between rate of flow and rate of melting.

End moraines are qualified by a number of terms such as "terminal end moraine" (formed behind the terminus of glacial advance during a relatively static period of glacial retreat) and "interlobate end moraine" (formed between two lobes of an ice sheet, between two piedmont glaciers, etc.). Some end moraines may have come into being largely through a process of ablation, in which case they may be called an "ablation end moraine."

12-7. Formation of Drumlins and Rock Drumlins. There are three outstanding observational facts about drumlins:

1. They almost invariably occur in groups and fields that display definite, large-scale orientation (Fig. 12-15).

2. They usually have a typical streamlined shape resembling a half-submerged cigar or elongated tear drop (Fig. 12-15).

3. They are frequently (perhaps always?) composed of compact till surrounding a core of slightly to greatly dissimilar material (usually other compact till, but frequently rock and occasionally semistratified drift).

These facts imply fairly definite things about drumlin formation.

The large-scale orientation implies that drumlins were formed by advancing ice sheets. This general orientation usually parallels that indicated by striations, eskers, etc., which are believed to be rough indicators of advance direction. In addition, it would seem reasonable to assume that a melting ice sheet would provide only rare large-scale orientations because the ice would be too thin to maintain its flow across topographic obstacles and would therefore have diverse orientations. Against this hypothesis may be set the fact that most large drumlin fields occur in areas of

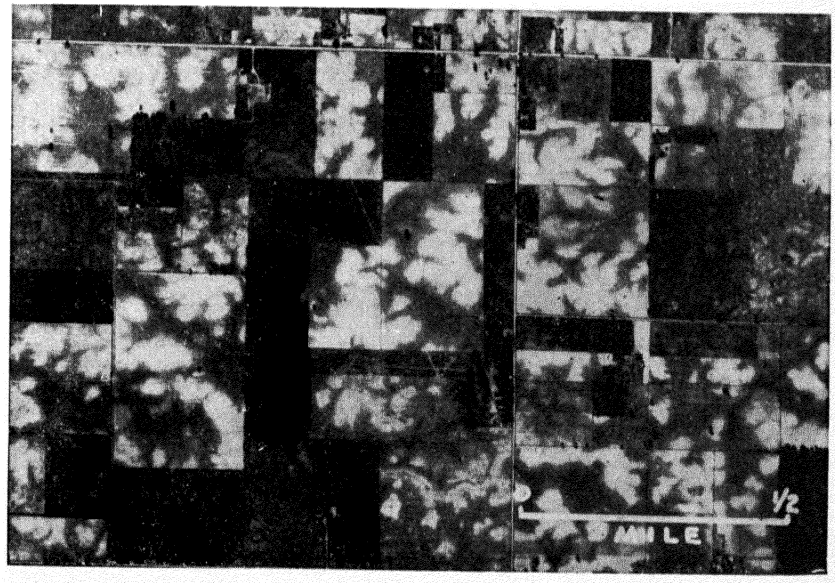


Fig. 12-7. This striking tonal pattern is typical of certain portions of Wisconsin till plain in the Middle West. The sag-and-swell topography is present but has a very low order of relief. A detailed soil map of this area may be almost completed by outlining the dark- and light-toned areas. A sample taken in one or two of each type will be representative of all the others. Note the semigradual tonal boundaries (Chap. 5). A striking pattern such as this is developed almost solely in the Middle Western United States and should not be considered representative of Wisconsin till plains in general. Originally selected and annotated by the Cornell group (43). (*Indiana. U.S. Department of Agriculture.*)

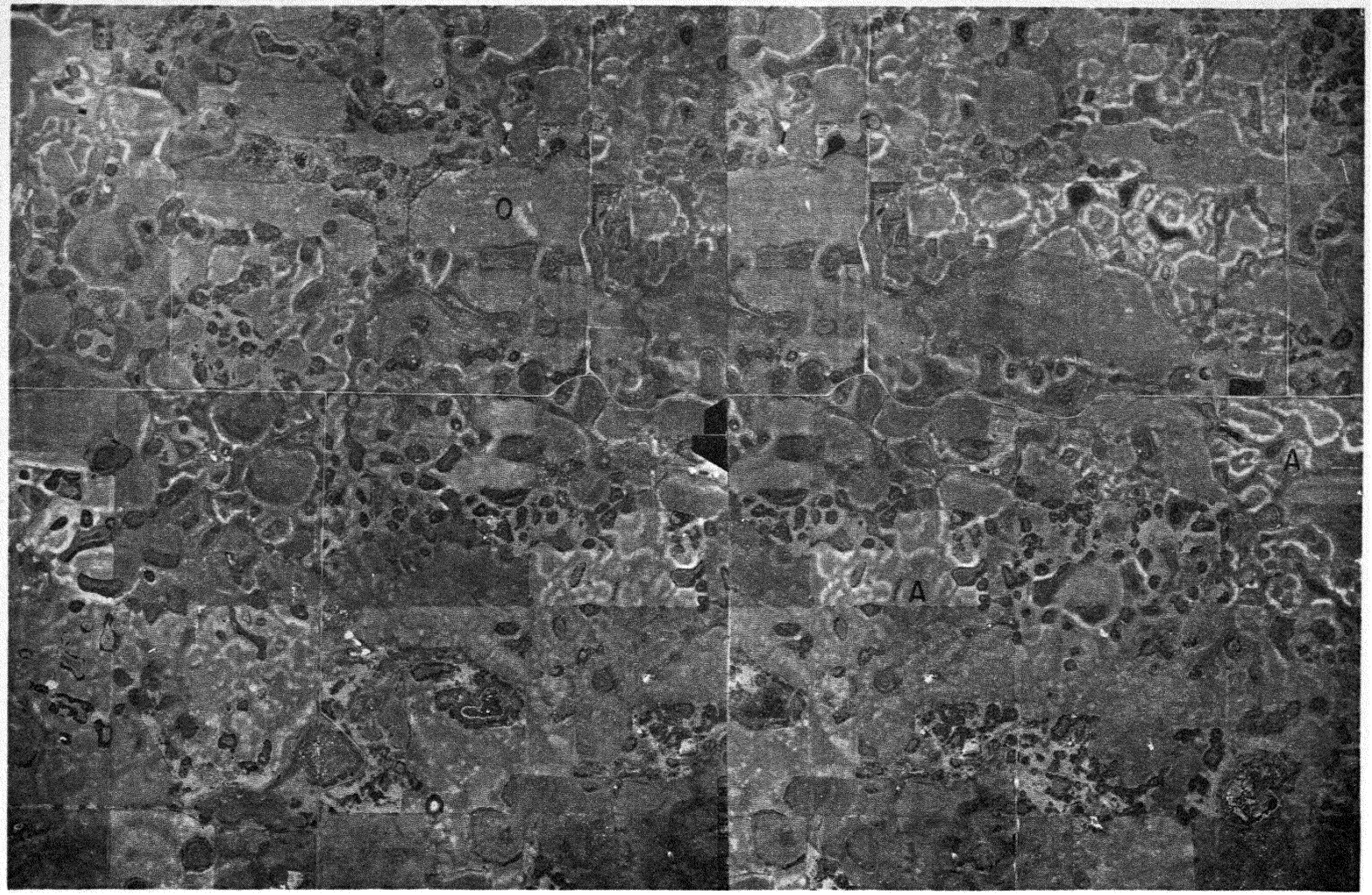


Fig. 12-8. A superb example of large-scale ablation features (*A*) developed on a till plain. At various places, particularly in the vicinity of *O*, surficial glaciofluvial sorting has occurred. (*Saskatchewan. RCAF.*)

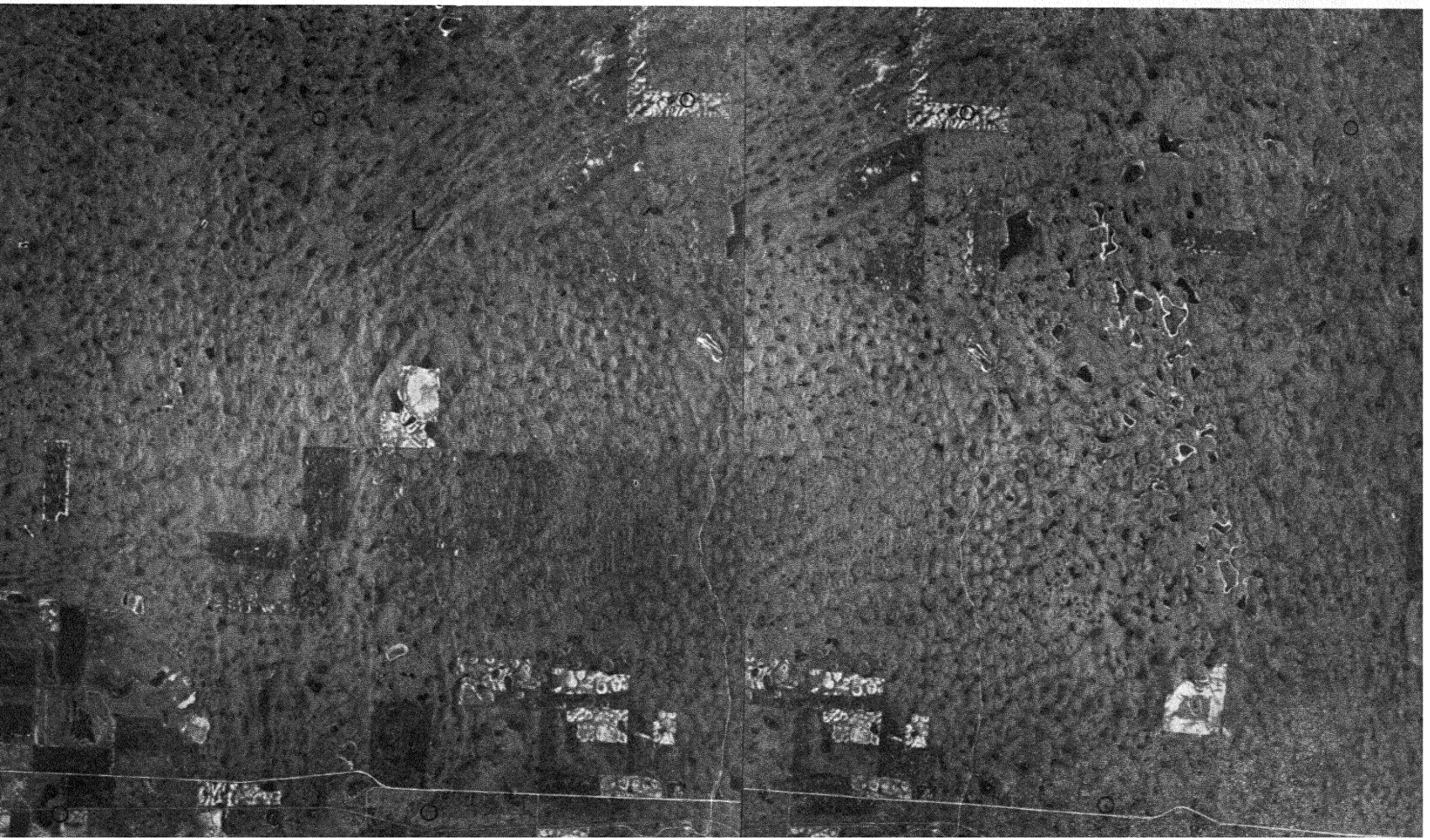


Fig. 12-9. This stereopair shows a view of the amazingly chaotic jumble that characterizes much of the central Canada ablation till plain. The hummocks with their little central pits and doughnut shapes are superbly illustrated. So also is a lineal area *L*, possibly representing a stagnant deposit of crevassed ice or recessional moraine. The origin of these mounds and pits is unknown, though it may have been a slow kettle stagnation followed by a secondary more rapid ablation, the pits being small kettles (sort of a case of the holes outdoing the doughnuts). Numerous ablation lakes and marshes (Chap. 15) are discernible. The drafted circles are survey control points. (*Alberta. Alberta Department of Lands and Forests, Technical Division.*)

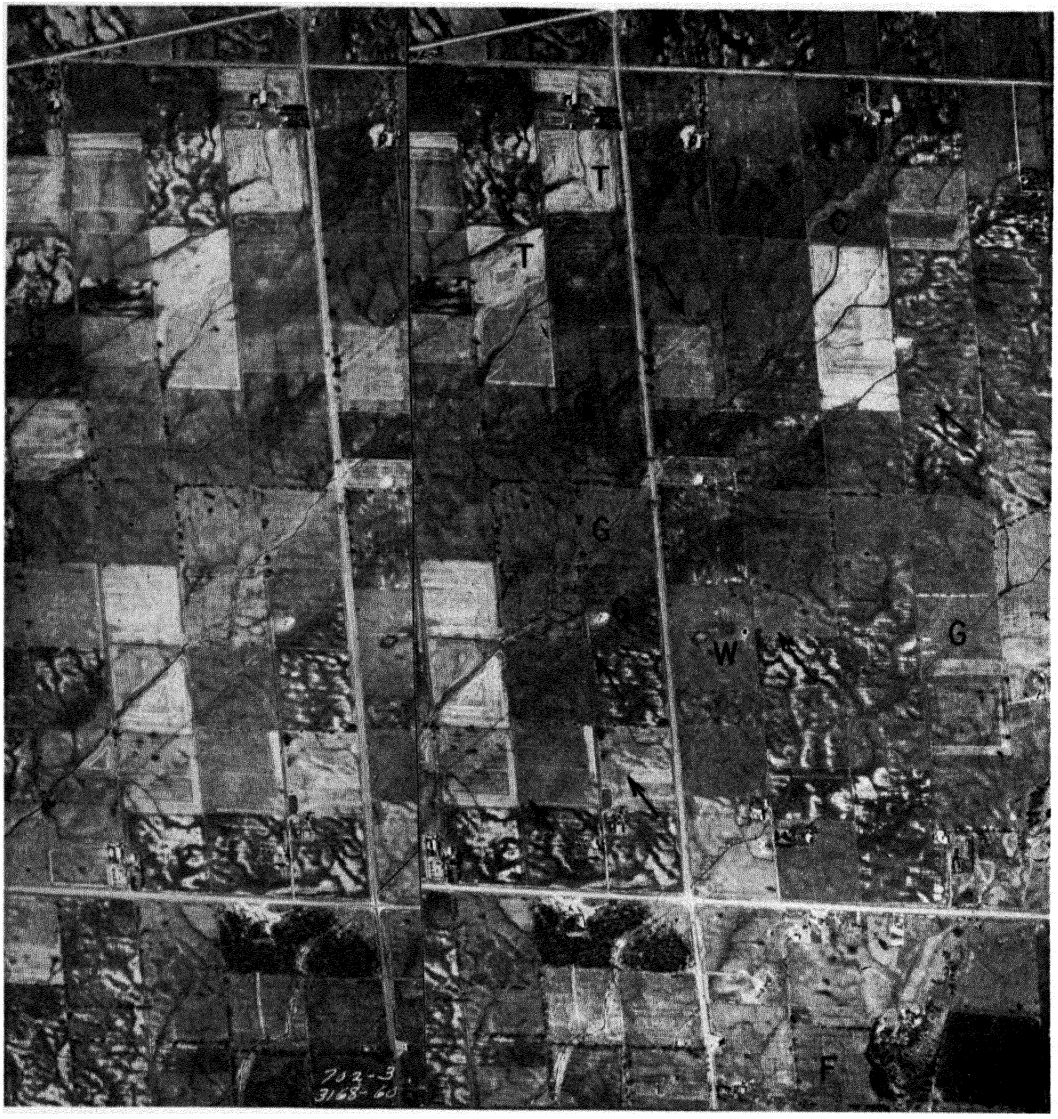


Fig. 12-10. A stereopair showing the appearance of an ablation till sheet in southern Canada. The low order, but chaotic state, of relief is very well known. The linear depressions *G* are believed to be glacial grooves (Chap. 4) and are slowly being exploited by stream flow to create an oriented drainage pattern throughout the region. Note the dark tones present in these depressed areas, as well as in the low depressions throughout the till. These indicate soggy, impervious soils (Chap. 5). Also note the impression of drainage orientation given by the ablation knolls (in direction of arrows). These indicate the direction of flow from local segments of the wasting glacier. Also shown on the photo are many land-use features such as standing water in small pondlets *W* and furrows *F*, motor-cultivation patterns *T*, contour farming *C*, and drainage layouts *D*. The pattern of light and dark tones, with their sharp boundaries, is very striking, particularly since it is not easily explainable. The materials are silty clays, and such lightness and sharp boundaries are inconsistent with this texture. Two possible explanations are the existence of limy horizons or a special state of evaporation, precipitation, and capillarity (Chap. 5). (*Ontario. Photographic Survey Corporation.*)

low, drift-controlled relief where topographic obstacles may have been obliterated or covered by basal till. Perhaps the safest thing to say is that orientation implies that drumlins were formed by *flowing* ice having a mass direction of movement. This does not tie drumlin formation to either advancing or regressing glacial stages.

Formation by flowing ice is also implied by the typical streamlined shape. This implication seems indisputable. The shape also suggests that the ice sheet *overrode* an obstacle of some sort that it could not remove by quarrying, plucking, or abrading.

The two-phase cross sections support the idea that some obstacle, of heavy, clay-rich till, rock, or occasionally something else, served as the nucleus for drumlin formation.

With these probabilities in mind, it seems reasonable to say that, as an ice sheet flowed slowly over the terrain, it occasionally lodged (Sec. 12-1) some till that was resistant to plucking (Sec. 12-1) or encountered bedrock that was resistant to quarrying and abrasion. If the former occurred, the lodged till would tend to extend itself by further lodgment, becoming in the process a streamlined drumlin core. Around this core would be deposited successive layers of drift, each one adhering to the streamlined form and eventually forming a "drumlin." If the latter situation occurred, the bedrock may have been partially eroded and smoothed, or even have been virtually unaffected. Regardless, basal till would have been lodged in its lee, and the process of forming a "partially rock-cored drumlin" would have begun. In certain instances, where bedrock was encountered, the bedrock itself may have been streamlined, and then thinly veneered with glacial drift, to form a "rock drumlin."

12-8. Formation of Rock Glaciers and Rock Streams. As mentioned in Sec. 10-2, rock glaciers have a disputed origin. Because they generally occur in mountainous glaciated regions, relatively close to existing glaciers, they are included in this chapter.

Flint (59) says this of them:

> Various theories of origin of rock glaciers have been advanced. The one that has met with general favor ascribes the debris to avalanching from the cirque walls onto the surface of a waning true glacier. The resulting thick superglacial drift is slowly carried forward and deposited as successive ridges of end moraine. Even after wastage causes the underlying glacier ice to disappear, the formation of interstitial ice from local precipitation may induce continued slow movement in the mass through a long additional time.
>
> According to this theory most rock glaciers consist essentially of end moraine and ablation moraine, which has been subjected in some cases to post-glacial movement.

Cotton (44) also discusses them and refers to observations by various scientists.

12-9. Aerial-photographic Characteristics of Till Sheets, Till Plains, and Ground Moraine. The outstanding aerial-photographic characteristics of a till sheet are its extent, order of local relief, nature of topography, and repetitiveness or uniformity of landscape.

Because they were originated by large, glacial masses; had a type of formation responsive to area environment in terms of glacial direction, glacial load, type of preglacial topography, and nature of materials being eroded; and were the direct result of a subglacial, lateral enlargement process; till sheets have a broad extent. Till sheets, to be properly classified as such, should have an area of at least 10 to 20 square miles. Most exceed this figure, and areas of 100 to 200 square miles are not uncommon. Above the *arbitrary* figure of 200 square miles, the till sheet may be termed a till plain. Such plains, under favorable conditions, may reach thousands of miles in extent. It might be said, then, that till sheets and till plains should fill the major part of any photographs except those of the smallest scales.

The order of local relief that exists on till plains and sheets is invariably quite low. Local differences practically never exceed 100 feet unless there has been some special type of process in operation, such as deep erosion. On most till plains the usual local orders of relief are less than 20 to 50 feet, and on some till plains, large areas may have maximum-height differences of less than 10 feet.

The nature of topography on till sheets and plains is fairly characteristic. It is difficult to describe. However, because of extent and low order of relief, it may be classified as ranging between gently undulating to gently rolling, with *possible* knolls, hills, and kettle-like depressions. In certain cases, the typical sag-and-swell or ablation types of topography are developed (Sec. 12-4).

The repetitiveness and uniformity of topography usually make an impression. Different areas look alike. Where topography is undulating, the impres-

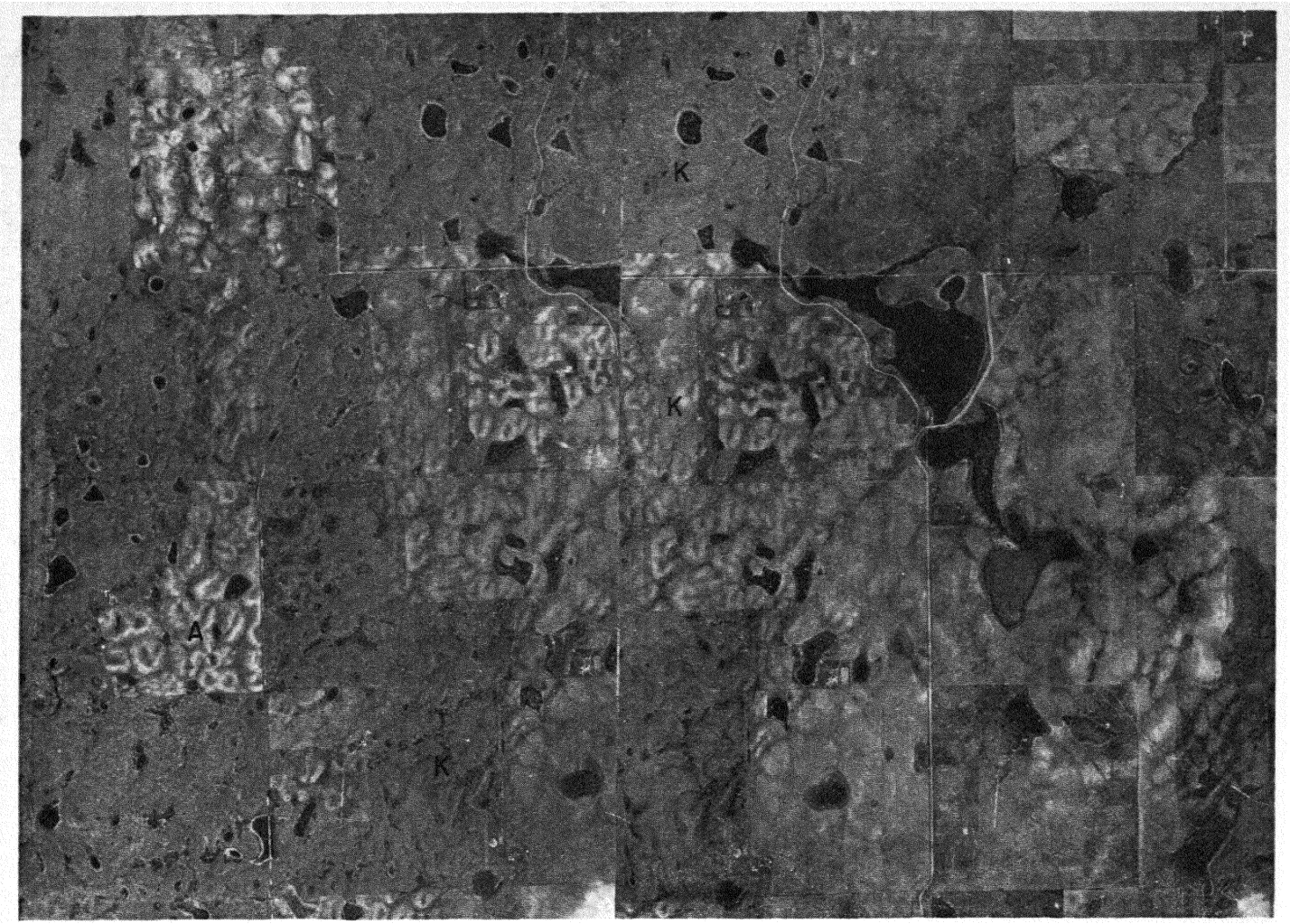


Fig. 12-11. An excellent illustration of knob-and-kettle topography *K* developed on a till plain. Ablation phenomena *A* also seem to be present. Note the tonal changes indicative of land-use practices. Also note the gradual tonal gradients. (*Saskatchewan. RCAF.*)

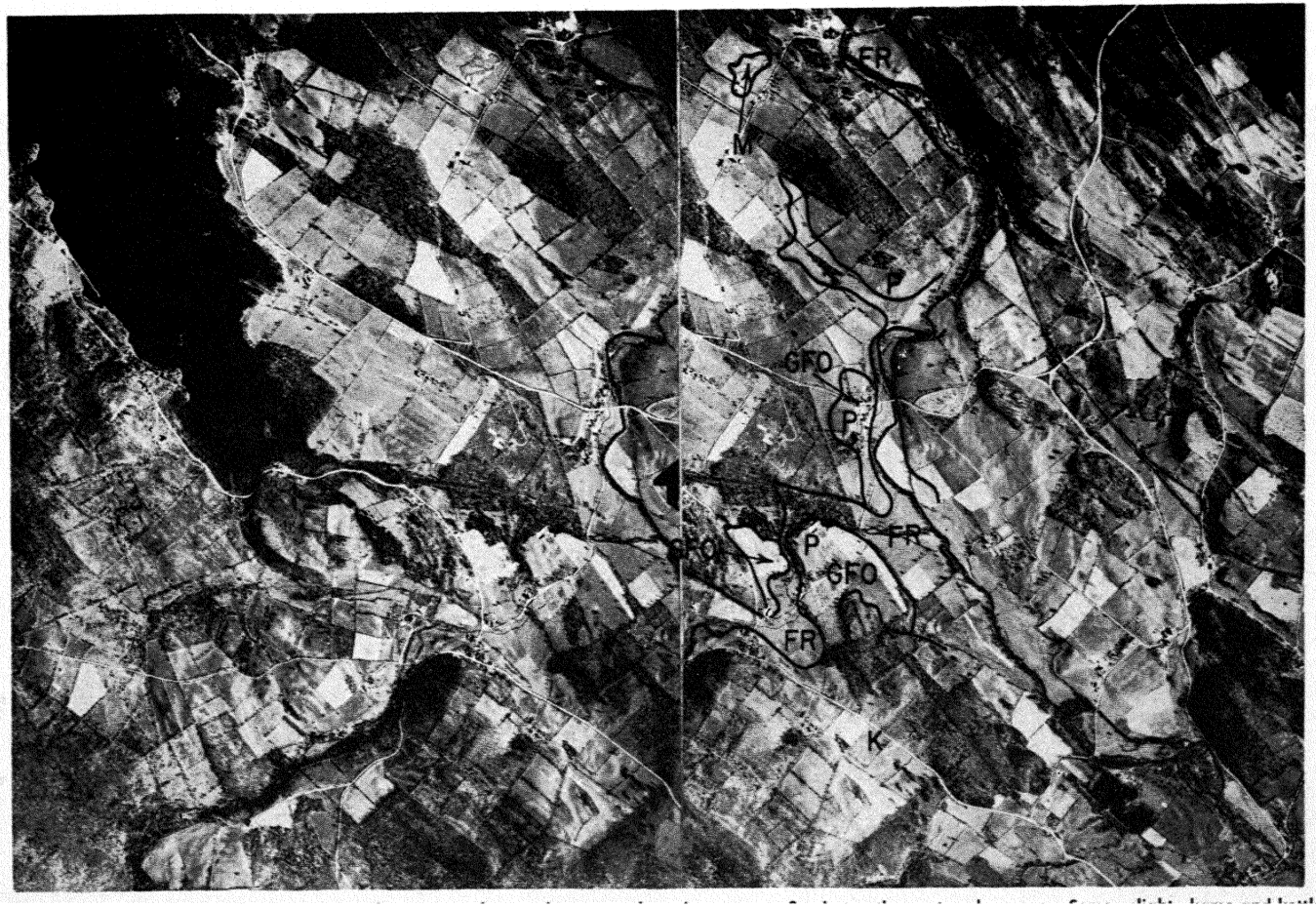


Fig. 12-12. This stereopair shows semigranular to granular random ground moraine deposited with varying, but generally small thickness, over the preexisting bedrock. The relief is markedly controlled by the rock rather than the drift. Local areas of sheet-wash collection and recent fluvial plains *FR* (very young streams developed in weak rocks), as well as local granular outwash deposits *GFO*, are also shown. Notice how the successfully exploited pits are confined to the outwash areas. Some slight kame-and-kettle topography occurs at *K*, and a glacial muck pocket appears at *M* (Chap. 15). Random ground moraine is infinitely variable in appearance. *For other examples in this book see Chaps.* 13, 19, *etc.* (*New Jersey. Aero Service Corporation.*)

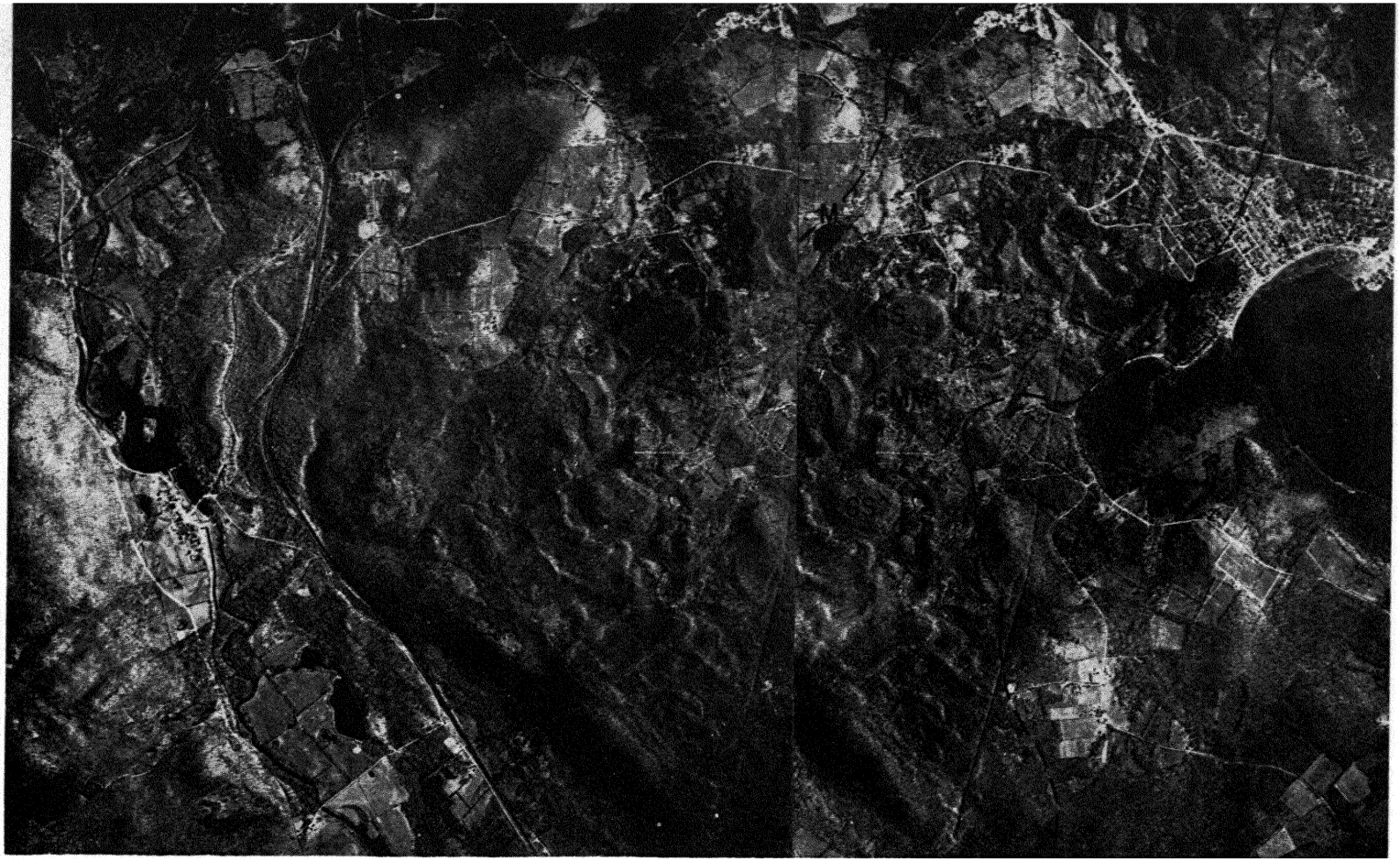


Fig. 12-13. An example of a tree-covered moraine belt *GMM* traversing some rather high and bold gneissic hills (covered thinly with random ground moraine). This moraine shows the typical, difficult-to-describe topography of the marginal moraine. In this case the topography is of the knob-and-kettle type, predominantly granular, with numerous steep-sided ridges, pause fronts, knolls, and flat-topped accumulations of till and local stratified drift *GS*. Old kettles are frequently occupied by organic-mineral complexes (Chap. 15) having marsh *M* or swamp *S* cover. A knoll has been opened for sand and gravel *P*. (*New Jersey. Aero Service Corporation.*)

sion is one of dull monotony. Where it is rolling, or has sag-and-swell and ablation topography, the impression is one of "regular irregularity," a "statistically isotropic landscape." [2]

Surface-drainage patterns, except for major streams, have not usually established themselves on any but the oldest (Illinoian?) till sheets and plains. In many cases, surface-drainageways are almost completely lacking. In others, the drainage pattern is elemental, fragmental, and nonintegrated, while density and uniformity are nonexistent. On most plains, a repetitive condition of blind or impeded drainage is common and organic areas may be frequent. On some of the old till plains, a nonoriented pattern of drainage has been started, which shows signs of ultimate integration, uniformity, and density (and probably orientation, as it eats into bedrock).

Gully patterns are usually also absent on till sheets and plains. Elemental ones may be forming and, on the older plains, will be the advance elements of stream development. Such gully patterns are indicators of local composition rather than identifying features of landform.

Tone patterns are of little significance, except in special cases. Illinoian and Wisconsin till plains of Indiana have striking and significant tonal patterns (Figs. 12-6 and 12-7). However, these are not typical of other areas. The most general thing that can be said about the tonal pattern is that it is drab and relatively uniform or repetitive and striking and, like topography, "regularly irregular."

Vegetation and land-use patterns are largely a function of climate. Sag-and-swell sheets and plains are usually intensively farmed because of topography and, unrelatedly, because the texture of the soils is favorable. Vegetation is often associated with organic areas, though this is not a rule. On ablation till plains, topography and drainage are usually so chaotic, blind, etc., that land use is poor. Figures 12-5 to 12-11 and others in Chaps. 9, 14, and 15 illustrate various aspects of till plains.

The aerial-photographic characteristics of random-ground-moraine deposit are difficult to describe because they are so variable. More often than not, deposits occur in topographic lows, toward the bottom of slopes, etc., and tend to smooth relief without covering the bare rock at all places. They are subject to all kinds of slump, ablation, and erosion activities, tonal properties, etc. Their characteristics are best learned through regional experience. Some of their aspects are illustrated in Fig. 12-12. See also Chaps. 9, 13, and 15.

12-10. Aerial-photographic Characteristics of Marginal Moraines. The dominant identifying characteristic of marginal moraines is their landform, both as a whole (unit landform) and in terms of surficial expression. As mentioned in Sec. 12-6, the topographic form varies exceedingly, but may be described generally as a broad, relatively high (100 to 500 feet) belt having an irregularly jumbled surface composed of anything from gentle or undulating slopes, hills, valleys, through steep, sharp knob-and-kettle topography, to chaotic jumbles of ablatory forms. Ridges may or may not be a major component of the over-all topography. The belt, as a whole, frequently rises abruptly from the adjacent terrain. Somewhat less frequently, it has a gradual transition zone. Generally, the component hills, knobs, and ridges of the moraine are fairly small, as are the individual depressions and valleys. There is no accordance and few flat areas, in association with the hilltops and valley bottoms.

Surface drainage may be completely absent or developed to a high degree of density. If surface drainage is present, and regardless of density, it is almost invariably poorly integrated, nonuniform, unoriented, and characterized by no control, angles of juncture, or angularity. Even constructional patterns are lacking. It is a type of drainage that is vaguely termed "disordered."

Erosion details may or may not be present. In any event, their presence, absence, and characteristics are not elements of identification, but indicators of the physical nature of the component materials.

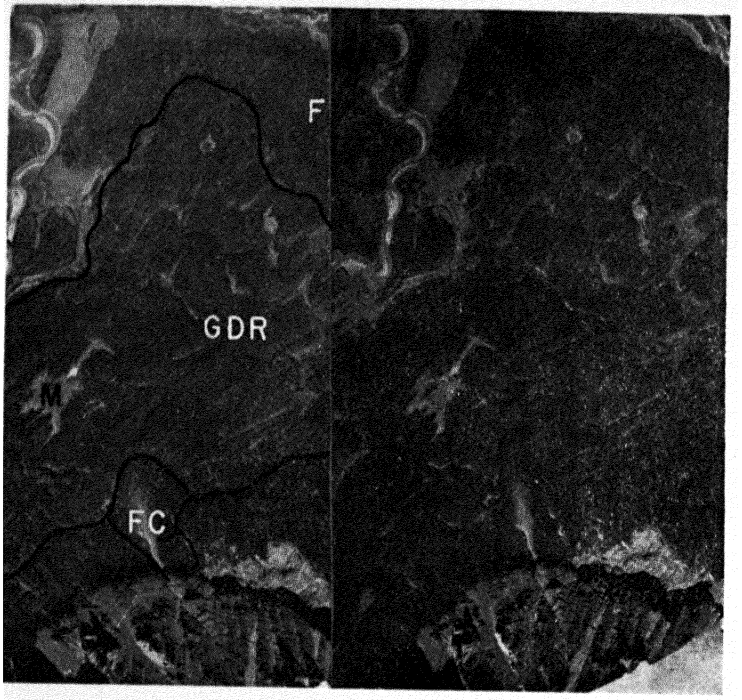
Tonal patterns also show wide variation. They may be uniform or heterogeneous. The latter is more common than the former because of the many differences of elevation, slope, texture, drainage impedance, organic accumulation, and existence of local perched water tables.

Vegetation and land use are also variable. Forest, pasturage, and grass, scrub, or brush are common covers in all but the most populous areas, where some tillage may be present. However, tillage is limited by slopes, variability of surficial and subsurface moisture, generally poor soils, etc.

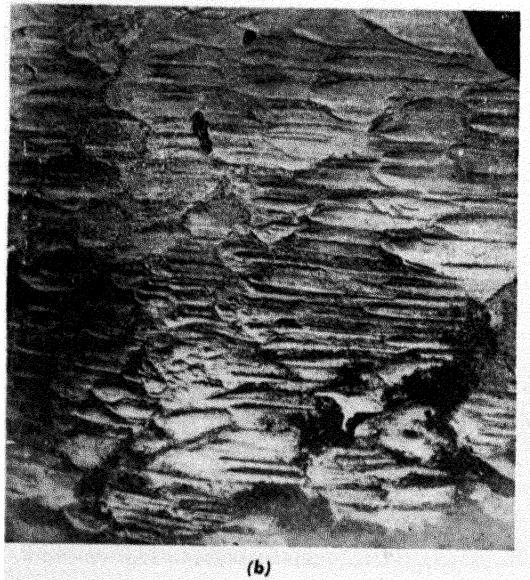
A marginal moraine appears in Fig. 12-13.

[2] Because of the nature of till, there may be something to be said for the idea that true tills also approach the soil-mechanics concept of a statistically isotropic material.

12-11. Aerial-photographic Characteristics of Drumlins and Rock Drumlins. The aerial-photographic characteristics of drumlins and rock drumlins are identical. The fact that they have aerial-photographic (or ground) characteristics. Occasionally, under favorable conditions of environment, inferences regarding *probable* rock drumlins may be drawn correctly.



(a)



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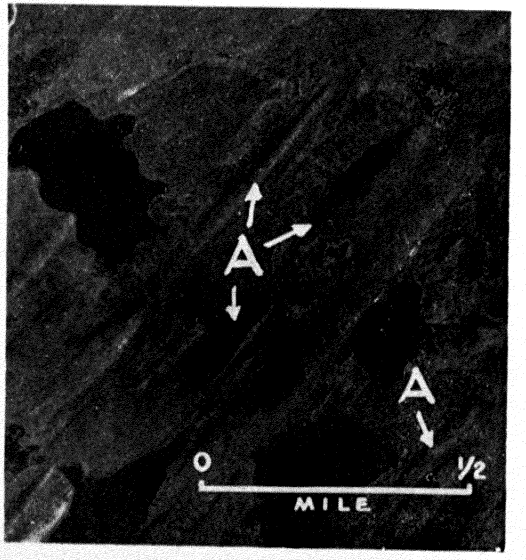


(c)

Fig. 12-14. This composite of stereopairs and singles illustrates the general appearance of drumlins and drumlinization. The upper stereopair (*a*) shows the drumlinization *GDR* of rocks, rather than true drumlins. Also included in this photo are a marsh *M*, fluvium *F*, and a colluviofluvial cone *FC*. All of the photographs show the orientation variations in width, shape, and length, and the difference between the wide (stoss) and tapering (lee) ends. In (c) typical cigar-shaped drumlins are shown by *A*.

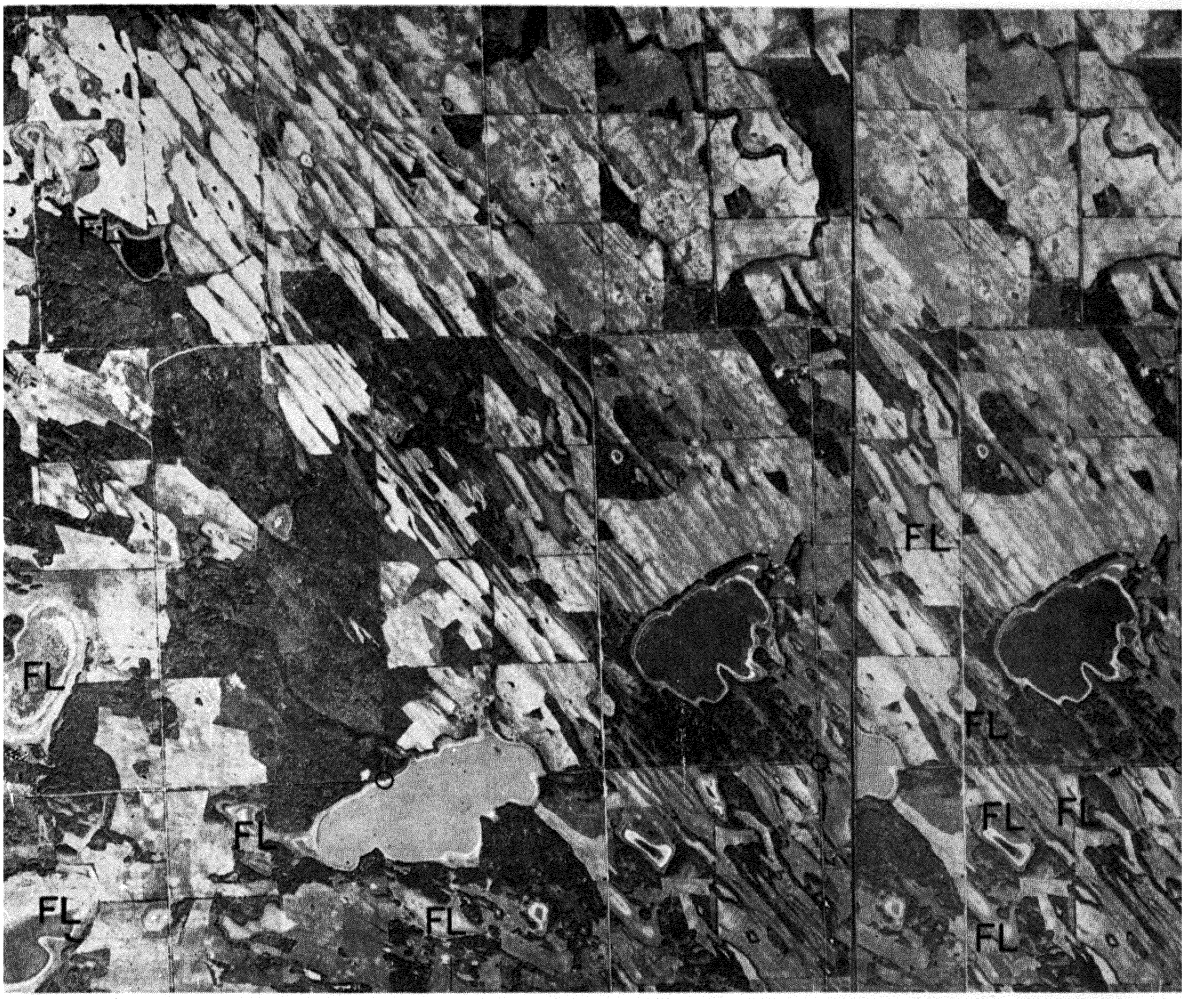


Fig. 12-15. This stereopair shows an excellent view of drumlinization on the glacial plains of Alberta. The drumlinization is almost unique because of its density—individual hills are almost overlapping. The direction of movement is quite distinctive in the area of concentration, dying out to a great degree on either side. Also shown are numerous filled and filling lakes *FL* with their lake margin, floating or filled marshes, and bogs (Chap. 15). The drafted circles indicate points of survey control. (*Alberta. Alberta Department of Lands and Forests, Technical Division.*)

The dominant visible characteristics of drumlinoid forms, like the observational facts indicating their origin (Sec. 12-7), are their occurrence in groups and fields, their general parallelism, and their streamlined shapes. These characteristics are adequately discussed in Sec. 12-7, although it might be said that the half-submerged cigar shape is an idealization. Actual drumlins range from very narrow and long, through the ideal shapes and modifications of occurrences in terms of blunt stoss ends, blunt sides,[3] etc., to squat cigar shapes and oval shapes. Further, drumlins are often coalescent in pairs, triplets, and even groups. Frequently, they occur *en échelon*.

Sizes of drumlins vary. Lengths may range from 100 feet to several miles, with several thousand feet being common. Widths are exceptionally variable, with 800 to 1,500 feet being frequent occurrences. Heights range from 15 to 250 feet, with those of 50 to 100 feet being dominant. Steepnesses of sides vary[3] but are generally greater than the stoss end.

[3] There is a possibility that the steepness of the sides and stoss ends is indicative of the compositional nature.

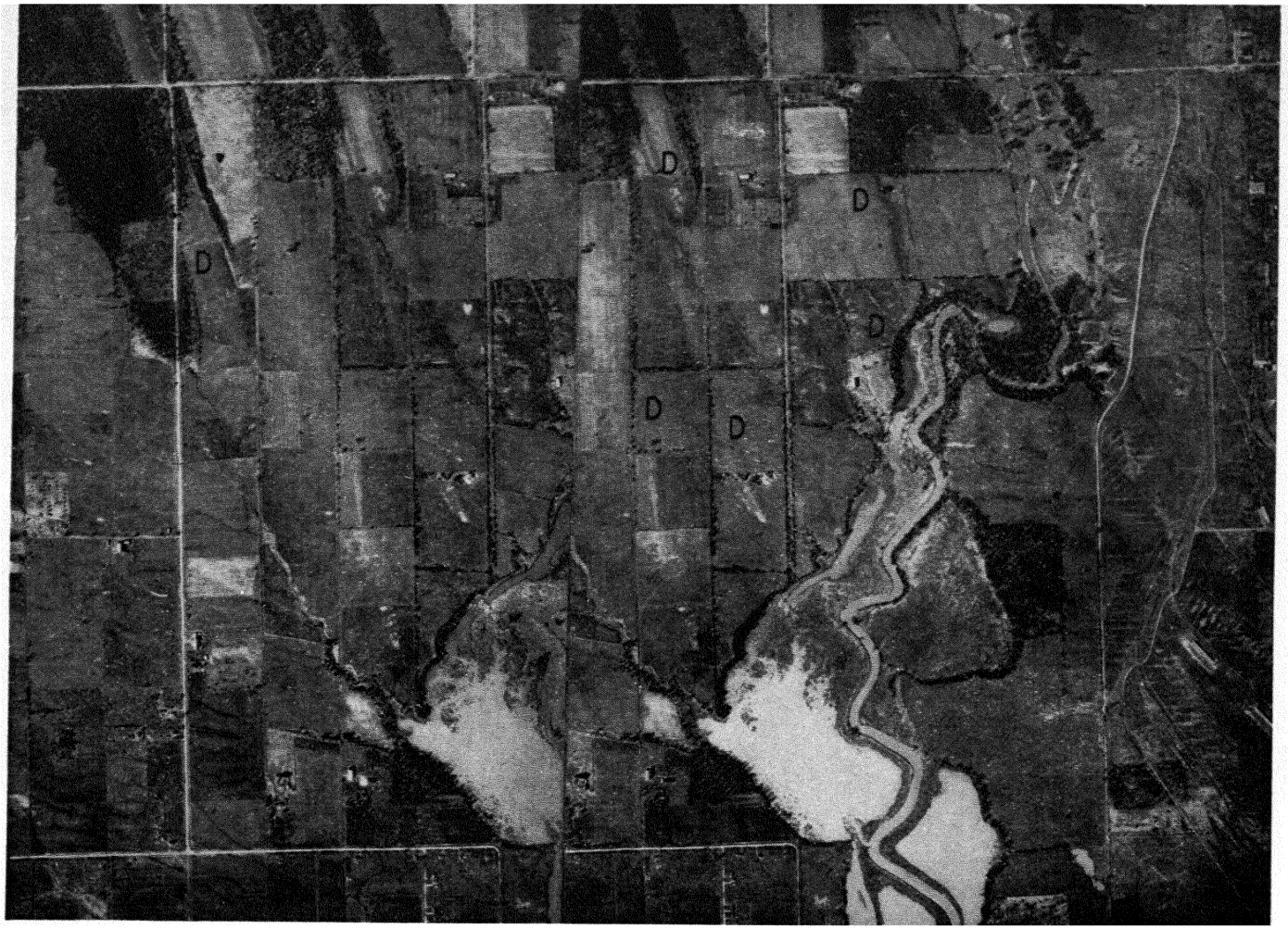


Fig. 12-16. Stereopair showing drumloidal forms *D* formed in silty-clayey till. Various shapes, widths, and heights are illustrated. This area is also known for its glacial grooves. (*Ontario. Photographic Survey Corporation.*)

Drumlins are seldom characterized by any surface-drainage development of significance.

Erosion features are limited to landslide scars or slumps [4] along the drumlin sides (not uncommon) and occasional texturally indicative gullies. In areas of cultural development, pits have often been dug, in the never-ceasing search for sand and gravel. Occasionally, these pits have succeeded in uncovering small, poorly stratified deposits. Usually they have been failures.

Gray tones are generally even-toned dark to medium grays.

Vegetation and land use are superfluous to drumlin identification. In any event, they vary in accordance with the normal-area vegetative and land-use differences due to topography, climate, and microclimate. In areas where farming is extensive, drumlins are usually cleared and farmed.

Figures 12-14 and 12-16 illustrate drumlins and rock drumlins.

12-12. Aerial-photographic Characteristics of Rock Glaciers and Streams. The only photographic characteristics of these forms are their shape, topography, location, and tone. Their shapes range from long narrow lobate tongues to viscid swellings at the tongue ends. The topography consists of a series of lobate-shaped rolls or coalescing ridges that give an impression of an extremely ropy, viscous fluid slowly oozing down a valley. These forms are usually found near the heads of high valleys, usually in regions where glaciers are still active. They are almost invariably characterized by even, medium-gray tones and display no signs of drainage, erosion, vegetation, or land use. They are best described by illustration. Figure 12-2 includes some typical but not ideal shapes.

[4] Possibly because of the rough laminations or rough stratifications that have been observed in many drumlins to surround the core concentrically, i.e., roughly parallel to the surface.

13 GLACIOFLUVIAL LANDFORMS

13-1. General Discussion of Glaciofluvial Action. In Sec. 2-18, it was stated that glaciofluvial deposits are composed of particles originally eroded and carried by a glacier but having a present position, lithology, and landform resulting primarily from the constructive action of glacial meltwaters.[1] Further, except for eskers, the position may be expected to be beyond the terminus of the glacier at the time of deposition.[2]

The formational origin was shown to be one of fair simplicity.

The formational origin, to be effective, requires (1) the nearby presence of a glacial mass—preferably a wasting one, (2) an adequate supply of glacially transported debris, (3) a supply of glacial meltwaters competent to carry the available debris, (4) a suitable environment for deposition.

The nearby presence of a glacial mass should not be interpreted specifically. Some glaciofluvial forms, as will be discussed subsequently, are created in immediate contact with the ice front. Other glaciofluvial deposits—of outwash—occur at distances of tens to hundreds of miles from the terminus of the glacial masses that apparently supplied their creative meltwaters. For usual purposes it may be assumed that glaciofluvial materials, except for valley trains (Sec. 13-7), will occur within 0 to 75 miles of the nearest correlatable glacial terminus; and that valley trains will not occur much beyond 200 miles away.

Since some part of a glacial mass is always melting, glaciofluvial deposits may be formed while a glacier is advancing, stagnant, or regressing. Deposits built during advance should be covered by subsequent till deposition for the most part. Deposits built during stagnation might be appreciable and form constructional landforms of considerable size. However, they also might be buried by ablatory materials that are not glaciofluvial in the strict sense. Deposits built during regression should prove to be the most important for a variety of reasons. These include increased supply of meltwaters, ever-fresh supply of terminal glacial debris, and lack of subsequent covering. The fact that the inner marginal belts of drift deposited by the Laurentide and Scandinavian ice sheets contain more outwash and ice-contact deposits than the outer belts would seem to support the hypothesis that deposition is primarily related to glacial regression (62).

An adequate supply of glacial debris refers to both quantity and textural nature. Obviously, meltwaters from a glacier bearing no debris will deposit none, and it may be said that, all other things being equal, the greatest glaciofluvial deposits are associated with glacial masses having the greatest quantities of debris.

Textural adequacy of debris implies that the mineral matter available within the glacier, or transportation and deposition by meltwaters therefrom, must be large enough in size so that the meltwaters will deposit them rather than sluice them away. Many areas bordering glacial termini are largely devoid of glaciofluvial deposits. This is because the glaciers in such areas provided debris that was so fine-grained, it was carried far away, probably into the sea.

Competency of the glacial meltwaters should imply that the flowing waters have the characteristics required to handle the volumes of sediment available. Therefore, should debris be overlarge, it would not become a glaciofluvial material. The rarity of boulders in glaciofluvial deposits indicates that competence is of real importance. However, it should be mentioned that boulders may

[1] The word "constructive" is intended to eliminate superglacial tills and certain other ablatory phenomena from the glaciofluvial category, to which they might otherwise belong.

[2] It must be remembered, however, that such glaciofluvial forms may have been covered by readvancing glaciers and, reciprocally, that glaciofluvial deposition may have covered previous terminal deposits.

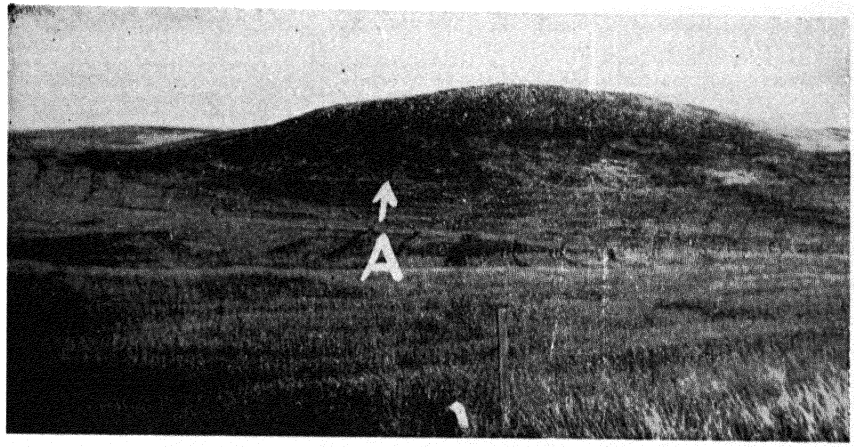


Fig. 13-1a. A ground photograph of an individual kame showing its prominent knobby shape. The arrow *A* indicates the limit to which cultivation has been carried out. Droughty soils and excessive slope make cultivation unfeasible. (*Saskatchewan. J. D. Mollard.*)

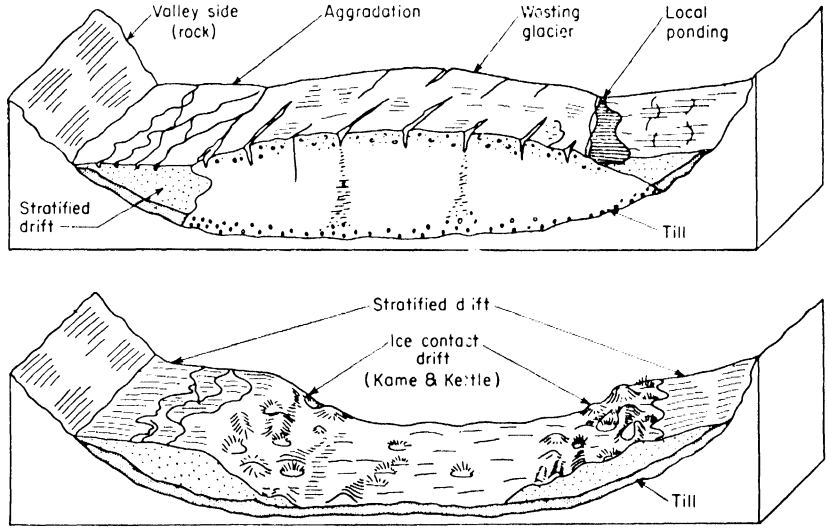


Fig. 13-1b. Kame terraces in the process of formation and following the disappearance of the glacial mass. (*After Flint.*)

occasionally be glaciofluvial sediments. The author is acquainted with certain boulder deposits of the Manicouagan River of Quebec that almost certainly were deposited by flowing water.

A suitable environment for deposition implies that a reduction of velocity in the sediment-transporting water must have occurred for a glaciofluvial deposit to come into being. Such a reduction may occur when flowing waters enter a fresh or saline body of water (glacio-fluvio-lacustrine and glacio-fluvio-marine deposits, Secs. 11-9a, 11-15, 10-2). It may also occur along streams and on plains (Sec. 13-7) or at any place where reductions in slope, sheltered waters, or excessive load accumulations are likely to be present. Of course, if the slopes leading away from a glacier are high enough, glaciofluvial deposition will not occur, even if all other conditions for deposition are present.

13-2. Types of Glaciofluvial Action. There are two fairly distinct types of glaciofluvial action,

both of which require the proper combination of the factors discussed in Sec. 13-1.

These types may be called "ice-contact action" and "proglacial action."

As might be suspected, ice-contact action takes place in direct contact with the ice, either at its front or beneath it. One or more boundaries of the flowing glacial meltwaters are provided by the glacial mass itself. It should be obvious that this fact should distinguish both the types of deposition (Fig. 10-1) and the characteristics of the materials or landforms developed from those of other types of glaciofluvial action. Flint (59) describes ice-contact action admirably:

> Whether accumulation takes place upon, against, or underneath the wasting terminal zone of the glacier, it is likely to be sporadic and irregular, with no intervening distance to smooth out the differences between summer and winter, noon and midnight, in rate of melting and the release of sediments. The same site may successively see a rushing stream, a quiet pool, a small avalanche of boulders, and actual overriding by slowly flowing ice, folding or faulting the layers of sediment or smearing till upon them. Ice is likely to melt out from beneath the accumulating sediment, or from a supporting position beside it, causing sagging, collapse, slumping, land-slipping, earthflow, and a variety of other distortions and disturbances. In such a place, in short, anything can happen, and it usually does.

Proglacial action occurs beyond the glacial front, away from direct contact with the ice. In all respects, except possibly volume and texture of load and volume and velocity of flow, it is identical with fluvial action of the type that creates bar meander and bar plains (Sec. 9-7) and fans, bajadas, or piedmont fluvial plains (Secs. 10-3 and 10-5), deltas (Secs. 10-1 and 10-2), and subaqueous beds (Secs. 11-9a and 11-15).

13-3. Glaciofluvial Landforms. Glaciofluvial landforms may be classified generally according to the type of action that produced them:

A. Ice-contact forms
  1. Kame-type deposits
     a. Kames
     b. Kame groups and terraces
     c. Gradational forms
  2. Kettles
  3. Eskers, crevasse fillings, esker trains
  4. Deltas and deltaic fronts

B. Proglacial forms
  1. Outwash-type deposits
     a. Miscellaneous outwash and outwash plains
        (1) Unpitted
        (2) Pitted
     b. Valley trains
        (1) Unpitted
        (2) Pitted
  2. Terraces
  3. Deltaic deposits
  4. Subaqueous deposits

13-4. Formation of Kame-type Deposits and Gradational Forms. Individual "kames" are small ice-contact landforms, built by ice-contact action (Sec. 13-2) within the body of the ice mass. The glacial debris was deposited in cavities, short crevasses, etc., or as small outwash deposits resting upon the body of the ice. After the ice melted, these forms slumped to some extent, but not enough to prevent their being left as knolls, short ridges, etc., scattered here and there over the landscape (Fig. 13-1*a*). Kames are generally associated with kettles (Sec. 13-5) and being indicative of thin, fragmental, crevassed, and stagnant ice, are most frequently found in the vicinity of lateral and marginal moraines (Sec. 12-6), kame terraces

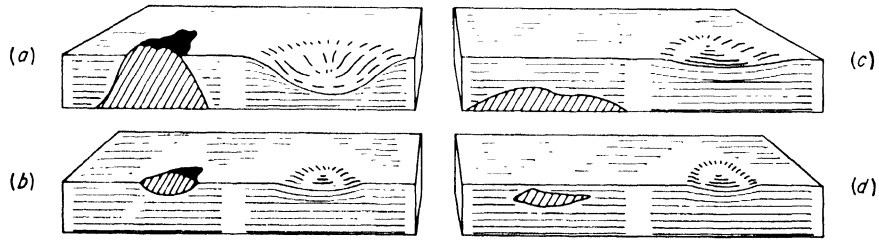


Fig. 13-2. Inferred formation of various types of kettles from (*a*) large projecting ice mass, (*b*) small projecting mass, and (*c*, *d*) floated-in masses at two depths. Note the topographic resemblance between kettles *b*, *c*, and *d*. (*After Flint.*)

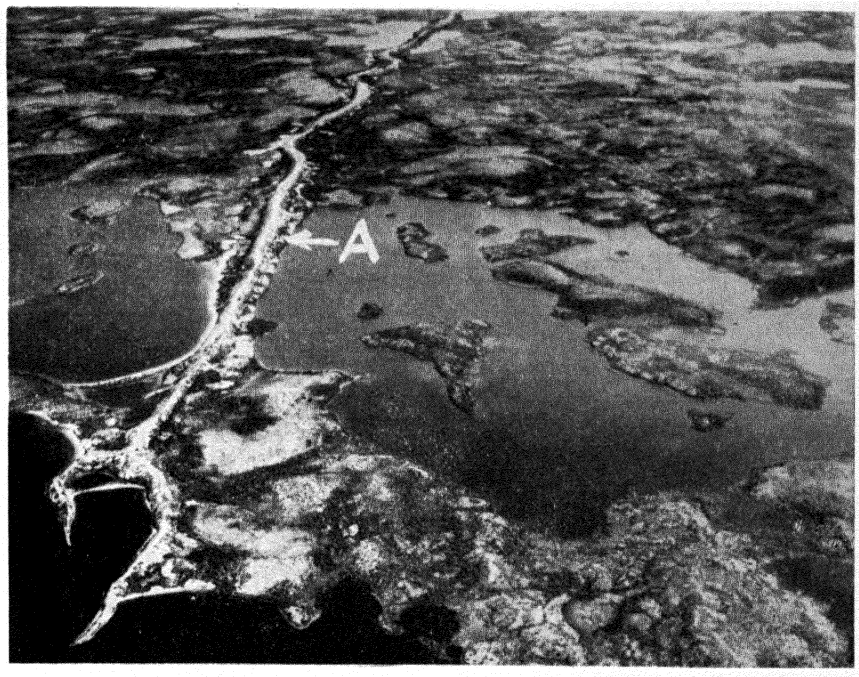


Fig. 13-3. This well-known oblique illustrates most of the features associated with an esker, its sinuous ridged landform, light tones, tendency to cross lakes (*A*), occasional branches, and frequent disappearance beneath the surface of water bodies. (*Northwest Territories. RCAF.*)

(below), and pitted outwash and valley trains (Sec. 13-7).

Naturally, kames may occur in pairs and more or less coalescent groups, rather than singly. Such occurrences may be termed "kame groups," for lack of a better name.

"Kame terraces" were formed, similarly to lateral moraines (Sec. 12-6), along the lateral boundaries of valley glaciers. As the valley glacier wasted away from one, or both, sides of its confining trough, heavily loaded meltwaters accumulated between its front and the valley sides. These meltwaters engaged in typical braided stream deposition (Secs. 9-7 and 13-8). One side of such deposits was supported by the ice face and was therefore directly subjected to ice-contact action. After the main ice body melted away, this support was removed, and the inward side of the kame terrace slumped. Since some stagnant ice fragments were thereby usually covered, the slumped face is often distinguished by kettles. The process is depicted in Fig. 13-1*b*. It might be noted that kame terraces differ from fluvial or glaciofluvial terraces, mainly in that they are not erosional remnants of deposits that once filled a valley but are solely constructional (Sec. 2-28) landforms that never had much greater extent. Normal terraces result from *complex* fluvial constructive action (Secs. 9-2 to 9-4), while kame terraces are created by *simple* depositional fluvial constructive action. Of course, it is possible for kame terraces to be eroded subsequently by fluvial action.

As must be apparent to the reader, it should be possible for kame deposition to occur at the ice-contact sides of marginal moraines, or cover previous morainic deposits of till, or, under proper conditions, to form a "kame moraine" composed of innumerable kames, kame groups, etc., mixed with local outwash, kame-terrace-type forms, etc. Such kame moraines are standard, and frequent, marginal morainic occurrences.

It must also be apparent to the reader that kame-like deposition may occur in any environment where glaciofluvial sediment can be accumulated under ice-contact conditions. Such environments may occur in association with the deposition of till sheets, marginal moraines, or random ground moraine, for example. Kame deposition, in

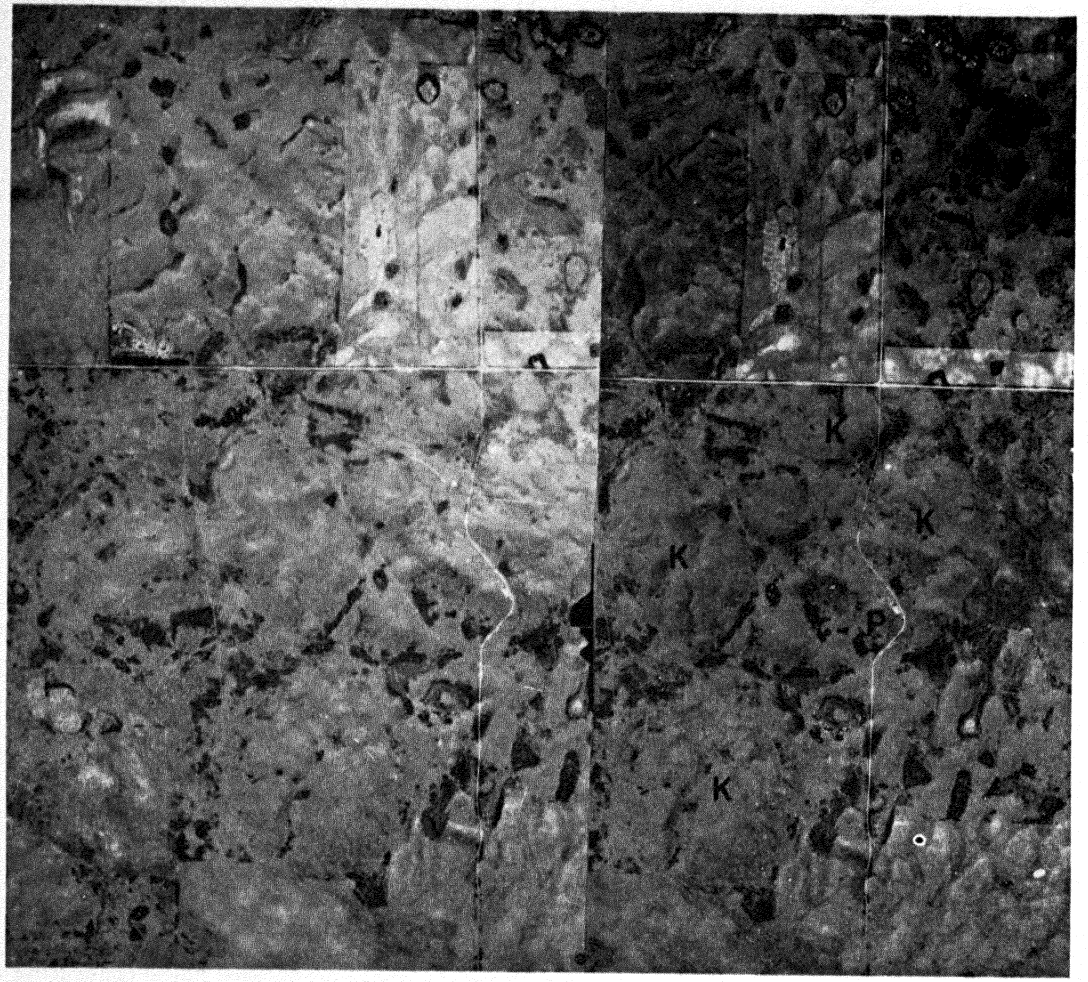


Fig. 13-4. Some superb examples of large kame groups *K*. Note their height and steepness, as well as the borrow pit *P*. Their form is not only steeper, but is higher, than the till knolls of the surrounding till plain. Only a knob and kettle or some type of ablation moraines have similar forms. (*Saskatchewan. RCAF.*)

other words, may often be gradational in character, giving rise to various deposits that are unclassifiable by any other name than kame-like.[3]

13-5. Formation of Kettles. Kettles are distinctive terrain depressions that occur mostly in water-assorted drift but occasionally in till. Their major significance is their association with stratified materials.

[3] Some geologists would eliminate the use of the word "kame," because it has been misused. Yet the rude stratification of kame deposits is distinctive, and it would seem foolish to eliminate a distinctive word with a properly distinctive meaning only to substitute for it a word like "moraine," which can be equally applied to quite different deposits.

The formation of kettles is simple. Chunks and blocks of stagnant ice (Fig. 13-2) are buried by variable depths of sediment (usually water-laid because of the improbability that the glacial mass would readvance over the chunk, simply burying it, instead of removing or incorporating it). These ice blocks melt, at which time the overlying materials slump, leaving a more or less circular [4] depression of varying depth and steepness.

In some areas, kames and kettles may be so closely associated that a "kame-and-kettle topography" results. Along probable old meltwater channels "kettle chains" may develop.

[4] The minimum surface area of a wasting ice block being provided by a sphere.

13-6. Formation of Eskers, Crevasse Fillings, and Esker Trains. An esker is probably the most striking of all glacial and glaciofluvial landforms. In general, it consists of a long, narrow sinuous ridge that tends to follow valleys, but also climbs low hills and crosses divides, usually at low points.

Flint (59) has an admirable description of the hypotheses concerning esker formation, which would be most difficult to improve upon. It is here quoted almost in entirety:

As Hummel was apparently the first to point out, it is almost universally agreed that eskers are the deposits of glacial streams confined by walls of ice and left as ridges when the ice disappeared. It is further agreed that as the eskers in any district parallel the striations and other records of the latest direction of glacier flow there, and as they are closely related to deltas, kames, and outwash, they are late deposits having been built in the terminal zone of the glacier shortly before it disappeared from the district. However, not all eskers were built under just the same conditions, although all are constructional rather than erosional features. It is probable, in fact, that eskers are formed in several rather distinct ways, of which two seem more common by far than the others.

The most common mode of origin appears to have been in tunnels (less commonly open canals) at the base of the glacier, during so late a phase in the deglaciation process that the ice was thin and stagnant or nearly so. It is unlikely that tunnels could easily form or, once formed, stay open unless the ice that inclosed them was nearly motionless. If stagnant, the ice must also have been thin. Water derived chiefly from surface melting worked its way downward through crevasses and other openings and at the base of the ice enlarged systems of openings to form tunnels. The lowest possible channelways were sought (which is why eskers generally occupy valleys). Flowing through these openings, chiefly under hydrostatic pressure, the flowing water emerged in ponded water (a glacial lake or the sea) at the glacier's terminus. . . .

Another, much less common, way in which eskers originate was first suggested by Shaler and later detailed almost simultaneously by De Geer in Sweden and by Hershey in North America. De Geer showed that certain eskers in Sweden consist of short segments, each segment beginning upstream with coarse gravel and grading downstream into fine sediments. The coarse upstream part is narrow, but downstream the esker broadens into a distinct delta. From these facts he inferred that each segment represented the deposit made during one year (chiefly in the summer melting season). The narrow part of the esker was

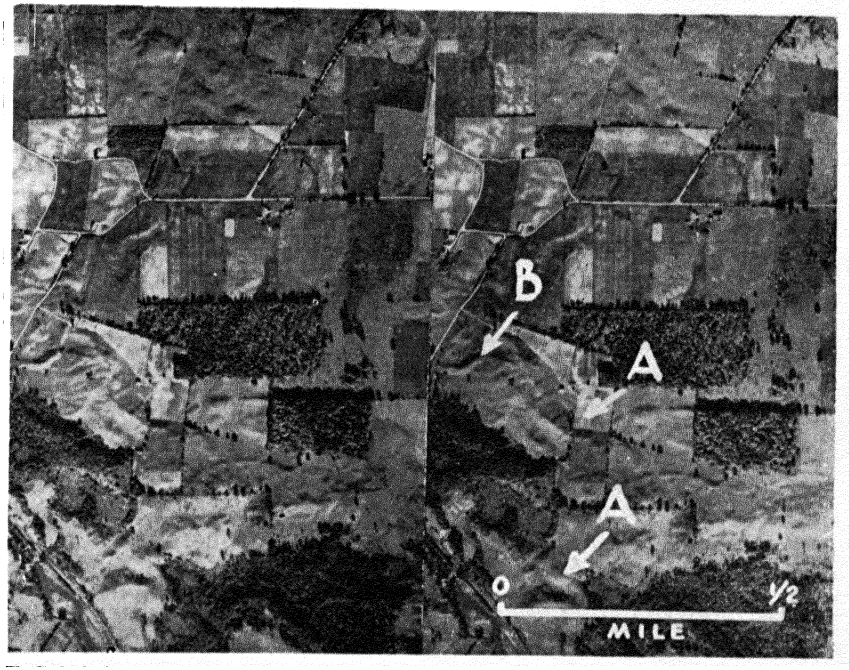


Fig. 13-5. A stereopair showing kames *A* and a small portion of esker *B*. All these forms are composed of dirty sand and gravel. Originally selected and annotated by the Cornell group (43). (*New York. U.S. Department of Agriculture.*)

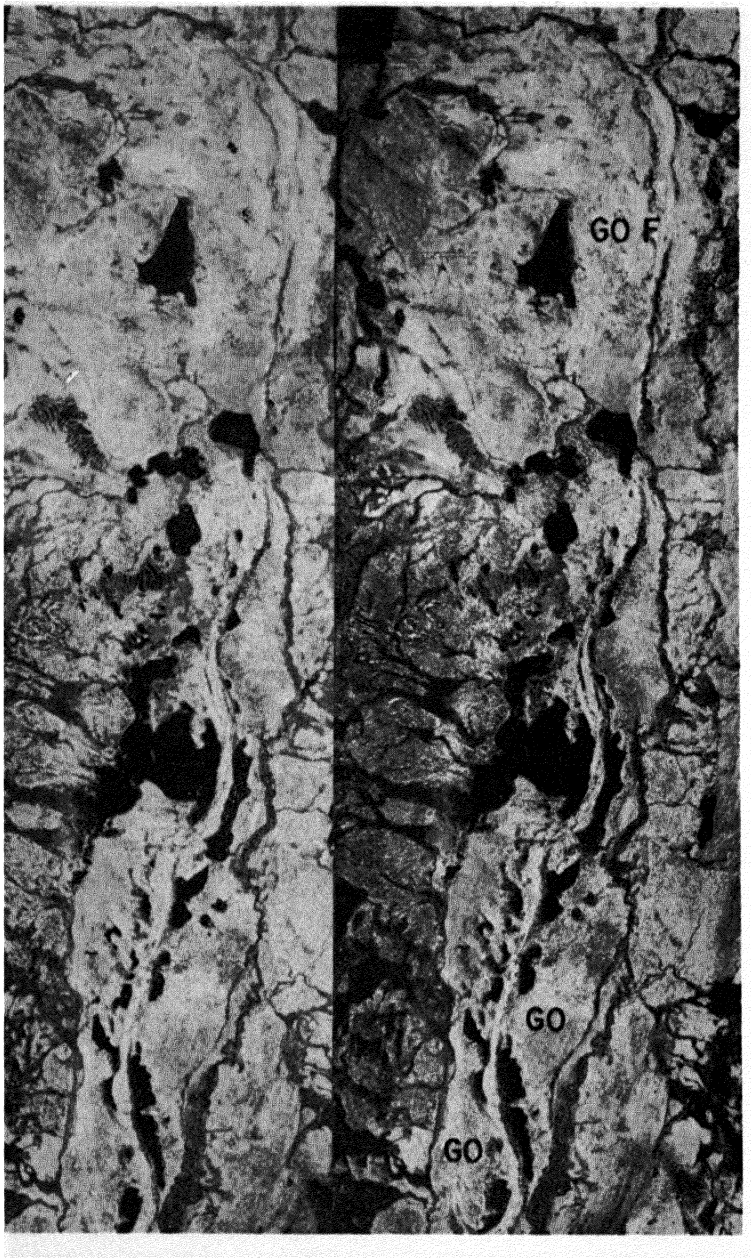


Fig. 13-6. This stereopair shows an esker trending along the floors and sides of valleys, as well as up and over low obstacles. Sharp-crested ridges predominate, but in one area a flat-topped crevasse filling *F* plus its associated pitted outwash *GO*, both a reflection of advanced wastage, is well shown. Other outwash deposits *GO* are shown at the bottom of the figure. (*Quebec. RCAF.*)

made in a short subglacial tunnel leading to the glacier terminus, at which the delta was built and beyond which the tunnel stream was free to spread beyond the confining walls of the tunnel. Small eskers in northern England and in southwestern Quebec have a similar character, broadening into deltalike mounds at intervals of a few hundred feet. In the examples cited there is clear evidence that the ice terminus constituted one shore of an extensive glacial lake. All the important conditions favor this mode of origin: the well-defined clifflike terminus characteristic of a glacier margin in standing water, the rapid wastage that occurs under these conditions, and the preserving effect of submergence of the esker segments as fast as they are abandoned. Probably all clearly segmented eskers were formed in this way, though they constitute a small minority of all the eskers on record. . . .

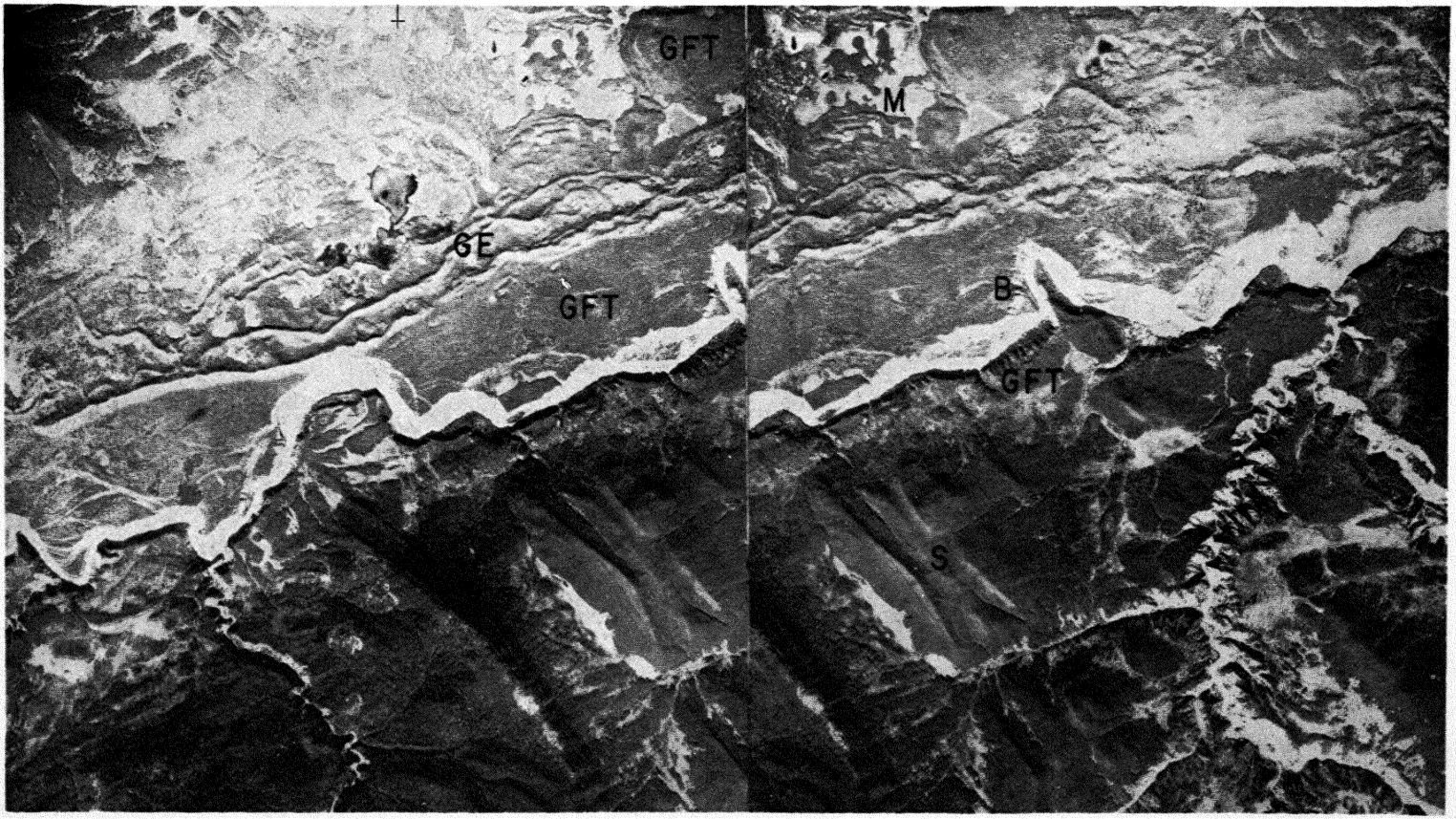


Fig. 13-7. This fine stereopair shows an esker train. Three major eskers intersect in a complicated pattern *GE*. Numerous smaller ridges also are included in the complex. All the esker features, including their valley location, are apparent. Large areas of marsh *M* are also shown, as are three levels of glacial outwash (valley trains), now existing as isolated streamside glaciofluvial terraces (*GFT*). The entrenched stream that is dissecting the terraces is in its early youth (Chap. 9) and has not yet begun to meander. The bend *B* is due to some unconformity, resistant layer, or structure. The hills *S* are composed of sedimentary rock. (*Alberta. Alberta Department of Lands and Forests, Technical Division.*)

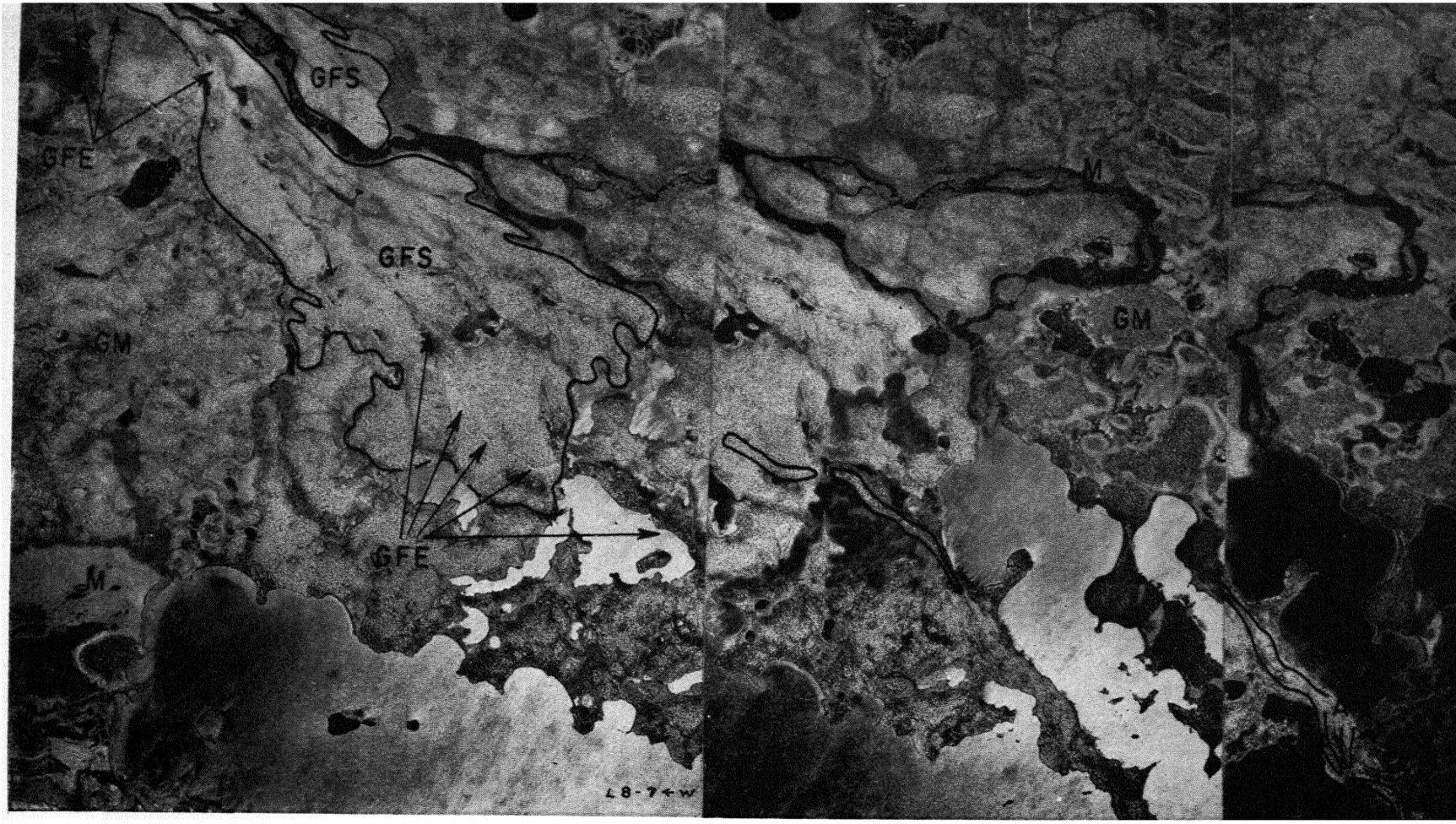


Fig. 13-8. This stereotriplet shows an area of relatively thin till *GM* (random ground moraine), over bedrock. The depressions are filled with typical muskeg *M* in this area. The light-toned "strings" in the muskeg area are ridges of sphagnum moss. In the center portion of a triplet there is a local area of glaciofluvial stratified drift *GFS*. This is either glacial outwash, glaciodeltaic, or a combination of both. Partially buried and interrupted, but nevertheless discernible as a definite landform, are portions of an esker *GFE*. This becomes more continuous toward the bottom of the photograph, and braided at one place (*A*). At the bottom, a transverse-trending esker is just visible. The sharp sides that are occasionally apparent in the *GFS* area are ice-contact faces. Note the difference in vegetative difference on and off the *GFS* area.

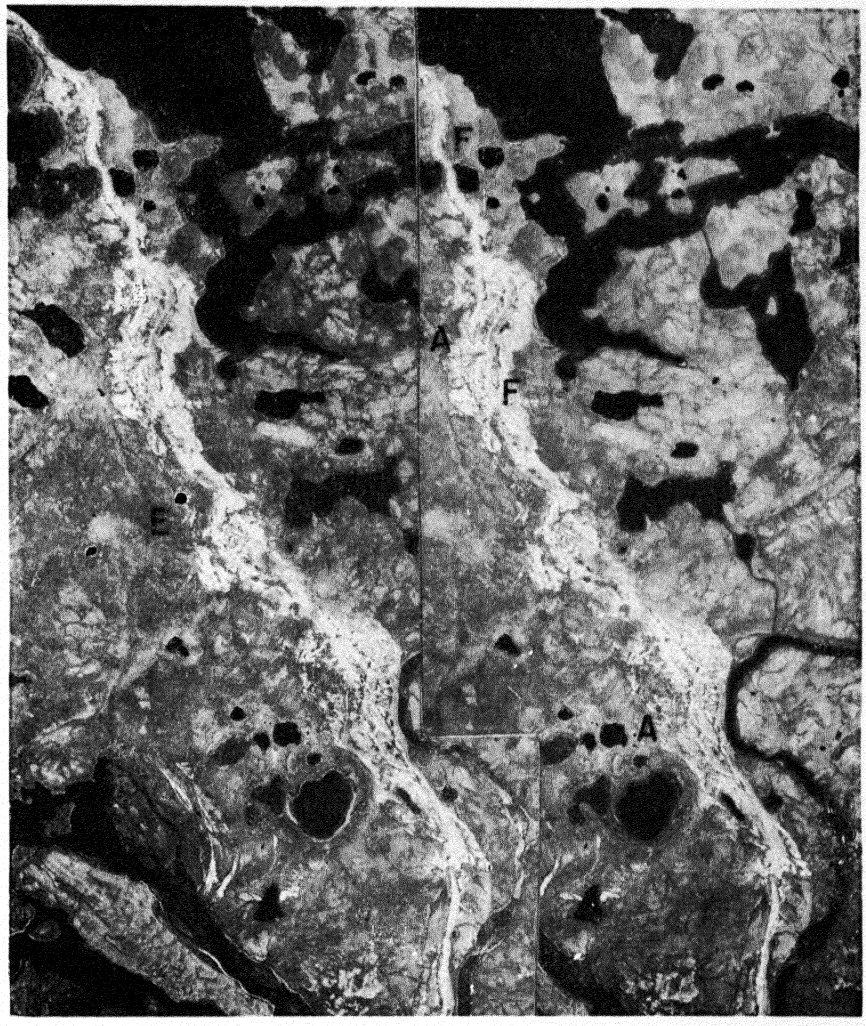


Fig. 13-9. A stereopair showing a long esker-crevasse train (*E*) crossing a rolling, thinly till-covered bedrock plain. The esker is anastomose at *A*. Most of its length has a knife-edged crest, indicating subglacial deposition. Some stretches, however, have flat tops (*F*) and may indicate local areas of subaerial crevasse filling. The light tone reflects both an absence of vegetation and high porosity. (*Manitoba. RCAF.*)

In summary, it appears likely that many eskers are subglacial tunnel deposits, and that a few were built headward in successive segments, each marked by a delta where the esker stream entered a glacial lake.

Eskers are largely composed of poorly sorted, stratified drift. Gravel and sand are major constituents, but silt, till, and boulders occur in lenses, pockets, and irregular strata. Cross sections of eskers show that layers tend to parallel the surface around a central horizontal series of foreset beds. The constituents of eskers are similar to the constituents of the till in the *nearby* vicinity.

"Crevasse filling" is a name that may be given to eskers, or portions of eskers, that were deposited in crevasse channels open to the sky. Sediments were constantly deposited upon their surfaces from the melting ice on either side and were reworked by the waters flowing along the crevasse to yield narrow, fairly linear, partially flat-topped ridges that usually grade into deltas or outwash at their



Fig. 13-10. Portion of a thin outwash valley train (spillway) GO carved in, and overlying, a till plain *GM*. Small till hills *T* protrude through the outwash. Flow markings *F* are apparent. Fluvial action is slowly destroying the outwash by virtue of expanding fluvial plains *FP*. Note the orchards, lack of surface drainage, and absence of erosion, as well as the gravel pit *P* developed in reworked outwash. (*Ontario. Photographic Survey Corporation.*)



Fig. 13-11. A ground view of sandy outwash S_d, reworked by lacustrine forces and adjoining an esker with its larger cobbles. (*Ontario, Manitoba.*)

lower ends, and, perhaps, eskers at their upper ends.

Esker trains may be formed when subglacial streams occur near to each other. Such streams may occasionally intersect, creating an anastamosic pattern of esker ridges.

13-7. Formation of Outwash Deposits and Valley Trains—Unpitted and Pitted. As stated in Secs. 13-1 and 13-2, outwash deposits are proglacial, created by an optimum combination of load, velocity, and supply. Their formation is essentially quite simple. Debris-bearing glacial ice melts. The flowing water transports the debris in accordance with hydraulic laws. Eventually, the loaded waters emerge from the glacial terminus and spread outward or flow down valley. In either case, their velocity and quantity of flow are reduced by insoaking, irregularities in their path (horizontal and vertical), and, commonly, a reduction in slope. When flow characteristics are reduced, load is dropped, blocking the channel, and remaining or future waters tend to bypass it. The end result is a form analogous to a fluvial fan, bajada, or bar plain.

Flint (59) again describes the sequence well:

> The streams that eventually build outwash do not ordinarily come into existence at the glacier terminus. On the contrary, they begin as far back on the glacier as the neve line, the upper limit of melting. From this line on down to the terminus, a distance that may reach many miles, melting of the top and flanks of the ice leads to dozens and even hundreds of little streams. In high latitudes these streams flow only in the summer season and only in the daytime; in lower latitudes they are more persistent. But, large or small, intermittent or otherwise, they find their way downward toward the base of the ice and emerge at the terminus chiefly from the base and along the lateral margins of the glacier. Within the terminal zone of the glacier they have picked up a load of sediment. In a valley with a very steep gradient the meltwater can sluice away all the sediment it had acquired while flowing through the terminal zone. But ordinarily the gradient is insufficient, the coarser part of the load is dropped, and aggradation begins. This interpretation is demonstrated by the fact that the upstream parts of some outwash bodies reach hundreds of feet in thickness.
>
> Aggradation occurs largely because the streams flowing through the marginal zone of the glacier have steep gradients or very efficient channels or both, whereas the gradients beyond the ice are very often smaller, and the proglacial ("beyond-the-ice") stream channels are conspicuously inefficient, being very broad and very shallow.

If the outwash deposition takes place over areas that have never been glaciated, or from which the

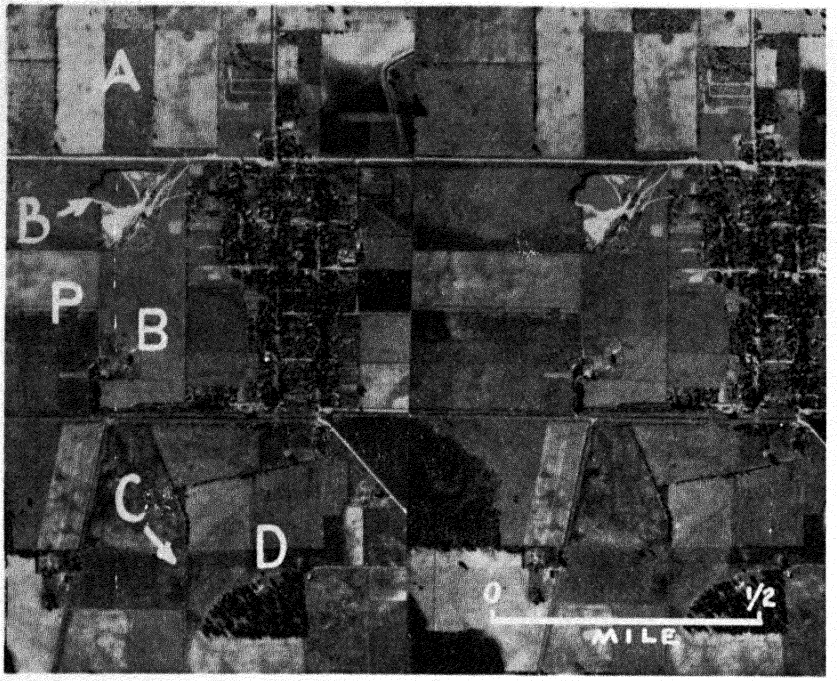


Fig. 13-12. This stereopair shows the appearance of a typical large-scale outwash plain deposited over an area largely without stagnant ice. In such an area, the outwash has either spread out widely or has been confined to broad valleys, in either case covering the landscape to considerable depth and creating a flat landscape. The only features that modify this landscape are an occasional kettle, the remnants of abandoned distributaries, small, recent, infiltration pits *A*, and the gravel pits *B* opened by man. Drainage and erosion are absent. Tones tend to be light unless recent rains have saturated the soil and raised the water table (the case in this illustration). Even so, the white area above the orchard shows a granular soil. An organic accumulation is indicated by C. This is related to an old distributary *D*. This photograph was selected and originally annotated by the Cornell group (43). (*Indiana. U.S. Department of Agriculture.*)

glaciers have long disappeared, kettles do not have an opportunity to form (Sec. 13-5), and unpitted outwash is the result. If, however, outwash occurs over stagnant ice of one type or another, burying it, kettles do form because of ice wastage, and pitted outwash is the result. The stagnant ice may consist of the slowly melting remnantal ice blocks of a more advanced glacial position, or it may include the thin, slowly wasting terminal zone of a glacier proper. In any case, it is covered by deposition, in either a forward or headward direction, and pitting ensues. Thwaites (201) has a fairly elaborate presentation on pitted outwash that could well be studied by a serious photo interpreter.

13-8. Formation of Proglacial Outwash Terraces. These forms are the remnants of former valley trains (Sec. 13-7), and in practically every respect, their original formation is analogous. They also are, in essence, identical with glacial-fed bar plains (Sec. 9-7). Their ultimate form is that of fluvial and glaciofluvial terraces (Sec. 9-8).

13-9. Formation of Ice-contact and Proglacial Deltaic Deposits. Deltaic deposits formed in connection with glaciofluvial action are discussed, for convenience, in Sec. 10-2.

13-10. Formation of Ice-contact and Proglacial Subaqueous Deposits. The formation of these deposits is discussed in Sec. 11-9a (marine subaqueous) and 11-16 (fresh subaqueous glacial lake beds).

13-11. Aerial-photographic Characteristics of Kame-type Deposits, Kettles, and Gradational

Forms. The dominant identifying characteristics of these forms are their geomorphic locations and their topographic form.

As explained in Sec. 13-4, they are invariably features of a glacial landscape, being most prominent along glacial valley walls, near marginal moraines, and comprising marginal moraines (kame moraines). Frequently, they occur as isolated forms on till plains, in ground moraine, or in association with pitted outwash and valley trains where rafted ice blocks were able to provide the essential ice-contact condition.

Topographically, the kames consist of knolls and short ridges which may stand alone, in groups, or coalescent terraces. Usually, the boundary with adjacent lowlands is abrupt. The knolls and ridges usually have steep but occasionally moderate sides. Conical and flat tops are both common. Individual occurrences tend to be low (less than 50 feet in height) and of relatively small horizontal extent (less than 500 feet in diameter or length). Kame groups, terraces, and moraines may be much larger.

Surface drainage is almost invariably absent. Erosion features may occur around the upper edges of kame-type deposits, particularly where the tops and sides have been cultivated, burned-over, or grazed. However, such features are not characteristic or important as an identifying characteristic, unless, by chance, they have developed texturally indicative gullies (Chap. 4).

Tonal ranges tend to be light because of the porous nature of the materials.

Vegetation usually consists of grass (in the prairies) or trees (in humid-temperate areas). Cultivation is extremely rare because of poor nourishment, droughty profile, and steep slopes.

Figures 13-4 and 13-5 illustrate some aspects of kame occurrences.

13-12. Aerial-photographic Characteristics of Eskers, Crevasse Fillings, and Esker Trains. The most important identifying characteristics of these forms are their geomorphic location, shape and topography, and relation to the general terrain.

Like kames, eskers are always associated with a glacial landscape. However, they never occur *on the surface of the most recent proglacial forms.* In

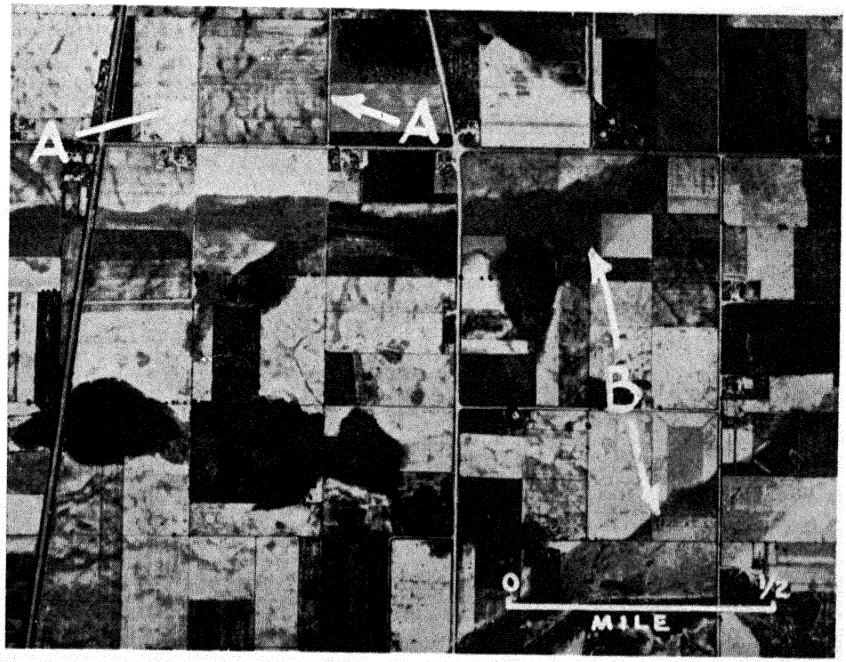


Fig. 13-13. Another area such as that shown in Fig. 3-18, showing the flat surface; shallow, flat-bottomed, muck-filled, abandoned distributaries *B*, some of which consist of chains of ovals (ice-block pits?); light tones; sharp boundaries between tones; and channel scars and infiltration pits *A*. Photograph originally selected and investigated by D. J. Belcher. (*Indiana. U.S. Department of Agriculture.*)



Fig. 13-14. A fine stereopair of valley-train outwash topography. Note the current scars on the surface, the flat surface, lack of drainage and erosion, and the light tones. (*New York. U.S. Department of Agriculture.*)

rare cases, they may have predated the proglacial form, subsequently being buried.

Typically, eskers are long, narrow, smoothly sinuous to subangular ridges, frequently broken into segments of varying length. Crevasse ridges tend to be shorter. Esker trains are braided, usually shorter, and considerably wider at points.

Topographically, the eskers tend to have steep sides and sharp to narrow, but rounded, crests. Occasionally, they have smooth, more gentle, rounded shapes. Crevasse fillings have occasional lengths characterized by flat tops, as do esker trains. Occasionally, the esker train will display a corrugated surface.

The eskers tend to follow generally low areas of terrain, but they *do go uphill and over divides,* generally at or near the low points of the latter (Sec. 13-6). They often lead to nearby regionally prominent areas of stratified drift and trend in the same direction.

Surface drainage and erosion features are almost completely absent.

Tonal ranges tend to be lighter, but do show variation, largely because of grassy vegetative cover (like dunes).

Vegetative cover is either grass or trees. Land use is insignificant. Pits have often been opened for sand and gravel. Finally, organic deposits often flank one or both sides of the deposit, being associated with the final wasting of the esker and crevasse boundaries, i.e., elongated kettles.



Fig. 13-15. This triplet shows an area of granular, pitted glaciofluvial outwash deposited as a valley train. The kettles *K* are even interpretable as to whether they were formed by ice beneath the surface, exposed to the air, etc. The outwash *GFO* has the typical flat surface, light tones, lack of drainage and erosion, and abrupt break with the higher materials that are characteristic of water-deposited materials. Some of the kettles are filled with muck *M*. The heavily forested, rough areas in the valley are steeply dipping hard shales, while the valley sides are composed of gneiss with a shallow mantle of random ground till *GM*. Sheet erosion is beginning at *S*. Borrow pits *B* were used to build the railway embankment. Around the edges of the shale in the valley and the rolled edges, there are deposits of knob-and-kettle till. (*New Jersey. Aero Service Corporation.*)

Illustrations of esker-type occurrences appear as Figs. 13-3 and 13-6 to 13-9.

13-13. Aerial-photographic Characteristics of Outwash Deposits, Valley Trains, and Outwash Terraces. Outwash landforms are identified by their geomorphic location, topographic location, topography, surface-drainage pattern, gray tones, and miscellaneous features.

Geomorphically, the outwash forms are related to a glacial landscape, but as was discussed in Secs. 13-1 and 13-7, they have a tendency to extend beyond the edges of the glacial plain, sometimes for great distances. They also occur within the plain, and local deposits are frequently associated with marginal moraines. In glaciated regions of high relief, the outwash follows major valleys, forming valley trains and their remnants, outwash terraces. In areas of low relief, the deposits are either bounded by slightly higher areas or spread outward like alluvial fans, ultimately passing imperceptibly into the surrounding terrain.

Topographically, the major characteristic of outwash deposits is a flat surface. Unpitted outwash displays an almost featureless flat surface, interrupted by a few existing and remnantal abandoned channels and/or channel scars. Pitted outwash displays numerous kettles. Usually, however, these do not occupy the greater part of the surface, which has the same accordant, flat aspect as the unpitted plains. Occasionally, pitting is sufficient to destroy the flattish aspect and yield a confused jumble of semiaccordant ridges, hills, and mesas. The surface form of both types resembles "unpitted and pitted" fluvial fans, bajadas, and filled valley forms (Chap. 10) or, in the case of valley trains, bar plains (Chap. 9).

Surface drainage is largely absent, because of the very porous nature of the deposits. However, even in such cases, there are likely to be remnants of broad, flat-bottomed, partially organically filled (except in arid climes) abandoned channels.

Occasionally, these channels are numerous and interlaced to a certain extent. These channels represent the original temporary loci of stream flow that were either abandoned because of diminishing over-all flow or blocked by dropping stream load in the manner of bar plains, fans, etc. (bar plains, Sec. 9-7, if glacial-fed, may be considered forms analogous to valley trains).

Erosion is generally absent, but may occur if conditions are favorable.

Tonal ranges are important. Over-all tones tend to be in the lighter ranges and sometimes are extremely light. However, medium grays, indicative of vegetative cover, also occur. Very-dark- to dark-gray tones, with abrupt boundaries, occupy the abandoned channels and swales. Occasional "tapioca" patterns may be present. These have been said to reflect the presence of "infiltration basins" (17). Channel scars, indicative of past rapid flow, may also be coincident with tonal changes.

Vegetative cover and land use are direct functions of the general climatic regimen as associated with the granular nature of the deposits, plus the topographic character of the surface.

Figures 13-10 to 13-15 illustrate the photographic appearance of outwash. Outwash terraces are discussed and illustrated separately in Sec. 9-11.

13-14. Aerial-photographic Characteristics of Ice-contact and Proglacial Deltaic and Subaqueous Deposits. These characteristics are discussed and illustrated in Sec. 10-7.

14 AEOLIAN LANDFORMS

14-1. General Discussion of Aeolian Action. In Sec. 2-20, it was said that the aeolian origin could be assigned to unconsolidated deposits of material that had been transported by winds and deposited as a result of a reduction in wind velocity. The formational chain of origin was shown as one of relative simplicity, while the complete, or lithological, chain of origin could be either simple or complex.

Only the formational chain of origin is of interest in so far as landforms are concerned. This chain, in order to become operative, requires (1) a satisfactory source of materials, and (2) a satisfactory topographic and/or climatic environment for effective wind action.

A satisfactory source of materials is present wherever there exists an accumulation of relatively fine grained, discrete particles, at least occasionally in a dry state and relatively free of encumbrance by vegetation.

The stipulation concerning fine grains limits satisfactory sources to those composed of sand sizes (medium to very fine), silt sizes, and clay sizes.

The stipulation concerning discreteness refers to a requirement that the particles must not be adherent, one to the other, aggregated, etc. This eliminates *clay* sizes for the most part because particles of clay size are affected by physicochemical forces that tend to make them cohere, wet or dry, into particles of silt size or larger. (These aggregated particles are, of course, subject to wind action if small and discrete enough.)

The stipulation of dryness recognizes the fact that wind action is not effective upon materials that are held together by moisture (apparent cohesion, Sec. 4-10).

The stipulation regarding vegetative encumbrance recognizes the stabilizing effect of vegetation in changing an otherwise suitable source to one providing little supply of materials or no supply at all.

In terms of the above definition, with its stipulations, it is safe to say that any deposit of weathered residual material or transported unconsolidated material may provide a suitable supply of material to transporting winds. Naturally, some deposits tend to be more favorable sources than others. These include fluvial deposits (river plains, deltas, fans), glaciofluvial deposits (outwash, terraces), marine and lacustrine deposits, and other aeolian expanses.

A satisfactory topographic environment implies that the source of supply should be situated so that winds traverse its surface with sufficient velocity and adequate duration. Such a situation is not common in mountainous and hilly areas, although it occurs occasionally. Rather, it is related to locations where the winds have a long *fetch* over relatively flat areas of considerable expanse (plains around lakes, along broad river valleys, and adjacent to seas and oceans).

A satisfactory climatic environment implies that winds of sufficient sustained duration, direction, and velocity will act upon the source of materials. Actually, such winds occur practically everywhere, except, possibly, in the mountains, but they do have a tendency to be more pronounced in areas of diurnal extreme (arid and polar regions), in areas bounding large water bodies (oceans, seas, lakes), and on second-order relief features (Sec. 2-25, group A).

The climatic situation is also related to effectiveness of wind action as a function of vegetative cover. In arid and polar regions, where vegetation is sparse, effective aeolian action is most probable.

14-2. The Aeolian Landforms. Wherever the proper conditions for aeolian action exist, it is reasonable to expect that aeolian landforms will occur to the leeward at distances ranging from a few hundred yards to several hundred miles.

These landforms may be divided into two

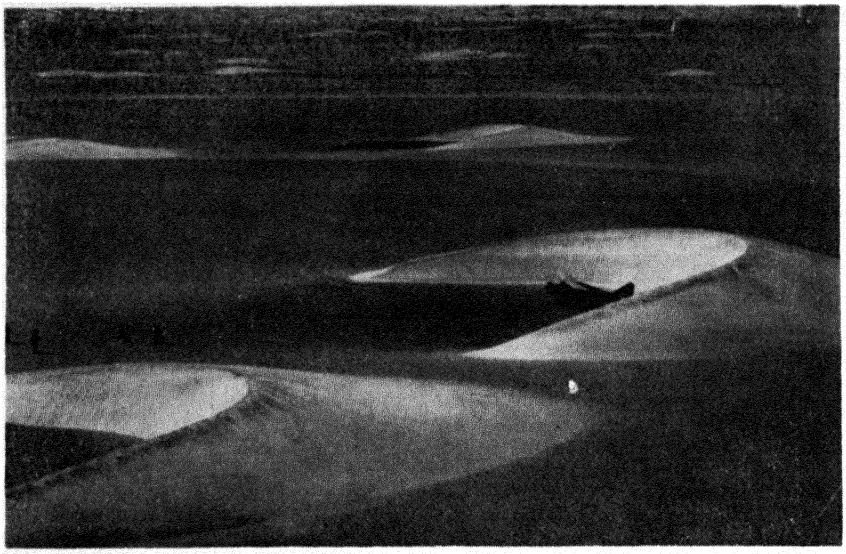


Fig. 14-1. This well-known photograph shows isolated barchanes developed to an almost complete state of perfection and symmetry. Note that the intervening areas are devoid of sand and largely devoid of vegetation. (*Peru.*)

classes, depending upon the types of material that comprise them. The classes may be divided into distinct unit landforms (Sec. 2-27), as follows:

A. Landforms composed predominantly of sand sizes
  1. Sand sheets
  2. Sand dunes
    a. Transverse
    b. Longitudinal
    c. Barchane
    d. Coastal
    e. Blowout and wind drift
  3. Sand ridges and complexes [1]

B. Landforms composed predominantly of silt sizes
  1. Loessial plains [1]
  2. Lunettes

14-3. Formation of Aeolian Landforms—Sand Sheets. Assuming that the conditions for aeolian action have been satisfied, winds pick up the sand in their usual gusty fashion and transport it in relatively short leaps over, but close to, the ground.

There are situations where the source of supply, nature of winds, and topography are such that sand sheets or sand drifts are formed. It has been said by Cotton (44) that these sheets and drifts may occur as thin smooth sheets or thick sheets with irregular surfaces called dunes.

The thin smooth sheets, presumably, are covered with small wind ripples similar to those that occur on the backshores of beach areas. Further, the sheets apparently advance as a whole over large areas, provided that the aeolian conditions are long enough satisfied. Cotton describes a record, by Cockayne (36), stating that such sand drifts have ascended fairly steep hills and even cliffs over 700 feet high.

These sheets should logically represent nothing more than accumulations of migrating sand. On irregular or vegetated ground, dunes should form. On smooth, and particularly smooth rocky, terrain, the continual transporting action of the wind should be dominant. In the latter case, a thin smooth sheet could exist provided that it served as a locus of transitory accumulation and migration, any unit volume of sand spending only a brief time (compared to dunes) upon its surface.

Thicker sheets, with surficial dune developments, are easiest to understand. If, in the process of blowing across irregular or vegetated terrain, the sand encounters a favorably situated small or large obstruction, an eddy occurs on the leeward side of the obstruction, the velocity of the wind is temporarily reduced, its transporting power is

[1] Sand complexes are not unit landforms, but are included for completeness. Also, there are loessial deposits, of thin or random nature, that do not qualify as loessial plains on the basis of unit landform.

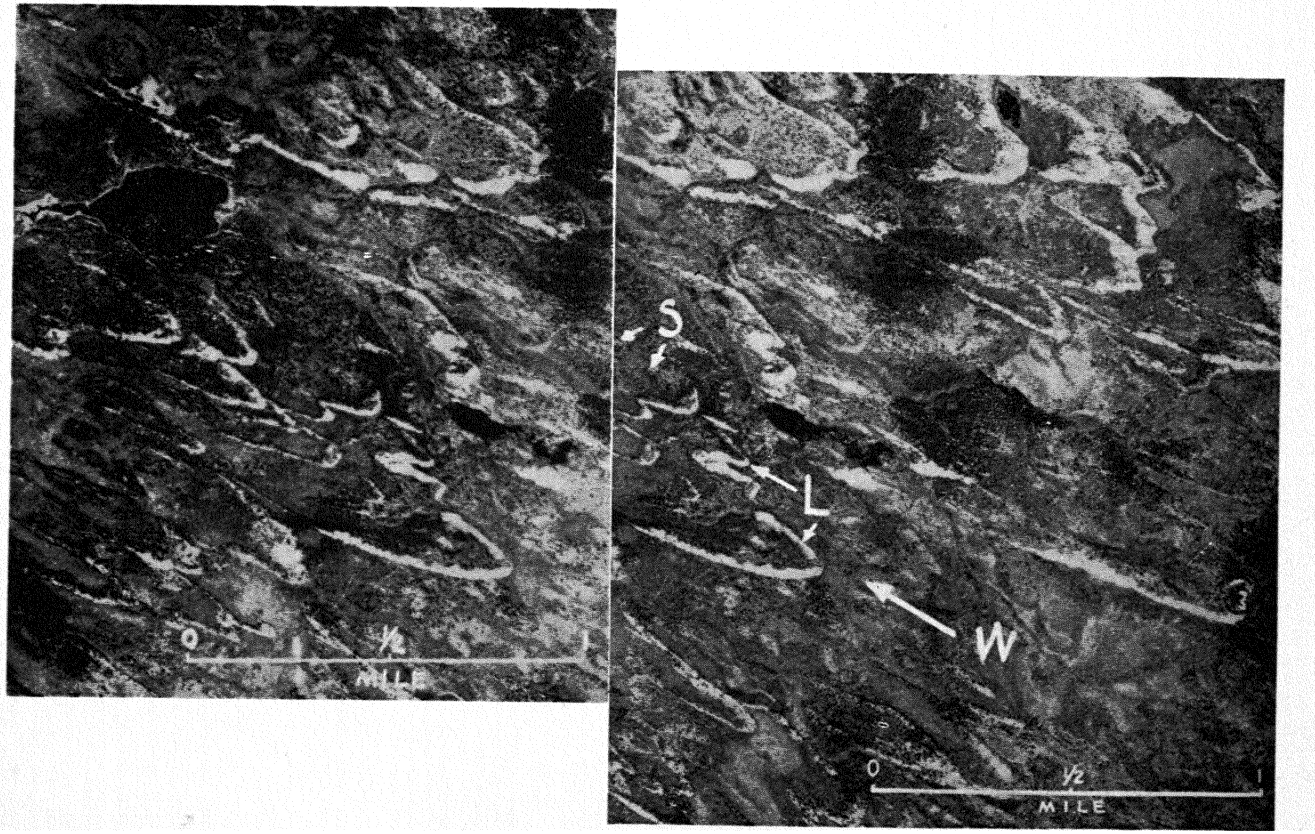


Fig. 14-2. Barchane dunes similar to those displayed in Fig. 14-5. Note the stabilization (on the smaller dunes, S). The barchanes show some lengthening, and the possibility of longitudinal dune formation is apparent. The larger dunes *L* are devoid of vegetation, and the distinctive white tones are striking. Wind direction is indicated by *W*. The areas between the dunes are occupied by sluggish streams and marshes, with occasional swamps (Chap. 15). (*Canada. Photographic Survey Corporation.*)



Fig. 14-3. A stereopair showing a striking development of well-stabilized barchanes in the north country. The dunes are surrounded by flatland marsh (Chap. 15). (*Yukon Territory. U.S. Army.*)

lessened, and sand falls, beginning a sand dune. Von Engeln (212) advanced an alternative and quite plausible hypothesis that some dunes may be caused, without benefit of obstacle, by irregularities in the wind action itself. Both hypotheses appear sound from the standpoint of anyone who has watched the drifts and flurries of a snowstorm. It is probable that their *combined* operation is always present in the formation of dunes.

In any event, once the initial deposition has occurred, it tends to perpetuate and enlarge itself by creating better and better opportunities for eddy deposition. Eventually the accumulations may be dignified by the term "dunes." At this stage they are at least 10 feet high, commonly 20 to 50 feet high, and occasionally more than a hundred feet high. It can be expected that, under favorable conditions, the gently tapering windward slopes (2 to 10°) of these dunes will be overlapped by other dunes in such a manner that thick sheet characterized by dune developments will result. However, it is also common to find that the wind action has stripped all the sand from between the dunes, leaving the dunes as more or less isolated forms resting on a dissimilar material.

14-4. Formation of Aeolian Landforms—Transverse and Longitudinal Dunes. Dunes have been observed to develop both transverse and parallel



Fig. 14-4. A view of a barchane complex showing small, poorly formed barchanes *ADB1* and large, wide dunes *ADB2*, having tendencies toward the formation of longitudinal ridges. Much of the gray tone of these dunes is caused by stabilizing vegetation. The dunes are developed upon the surface of a glacial till plain (Chap. 12). (*Alberta. Alberta Department of Lands and Forests, Technical Division.*)

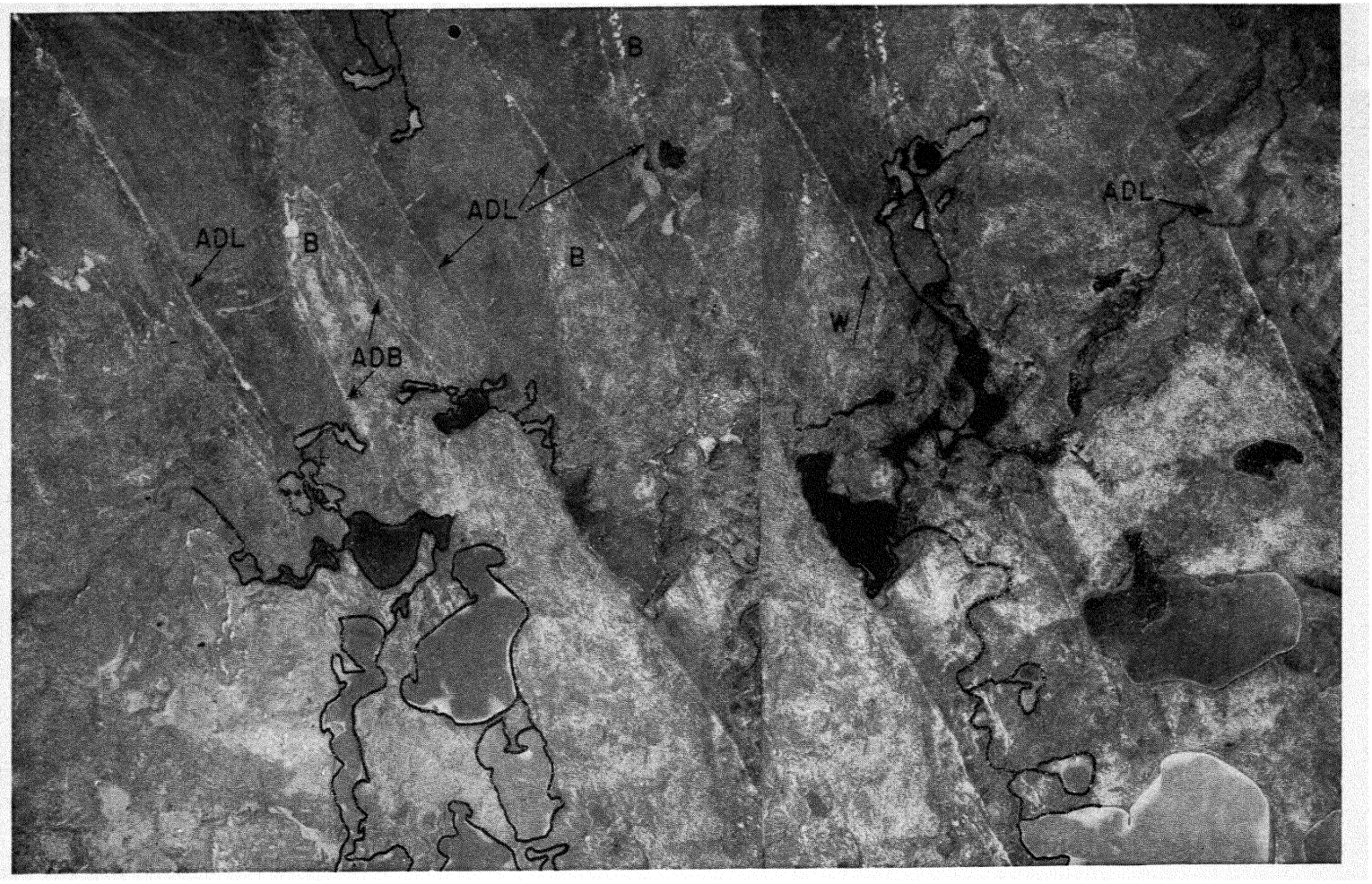


Fig. 14-5. A superb example of longitudinal dunes *ADL* that show every sign of having been created by the extension of large, wide barchane dunes *ADB*. In this area the dominant wind is parallel to the axis of the dunes, but the uneven slope on the ridges, plus additional lineations, indicates the secondary effectiveness of diagonally oriented winds *W*. All the dunes are stabilized by vegetation, except in the vicinity of blowouts *B* (Chap. 4). The entire dune system has been developed on a complex of glacial water-laid materials surrounded by organic deposits. (*Alberta. Alberta Department of Lands and Forests, Technical Division.*)

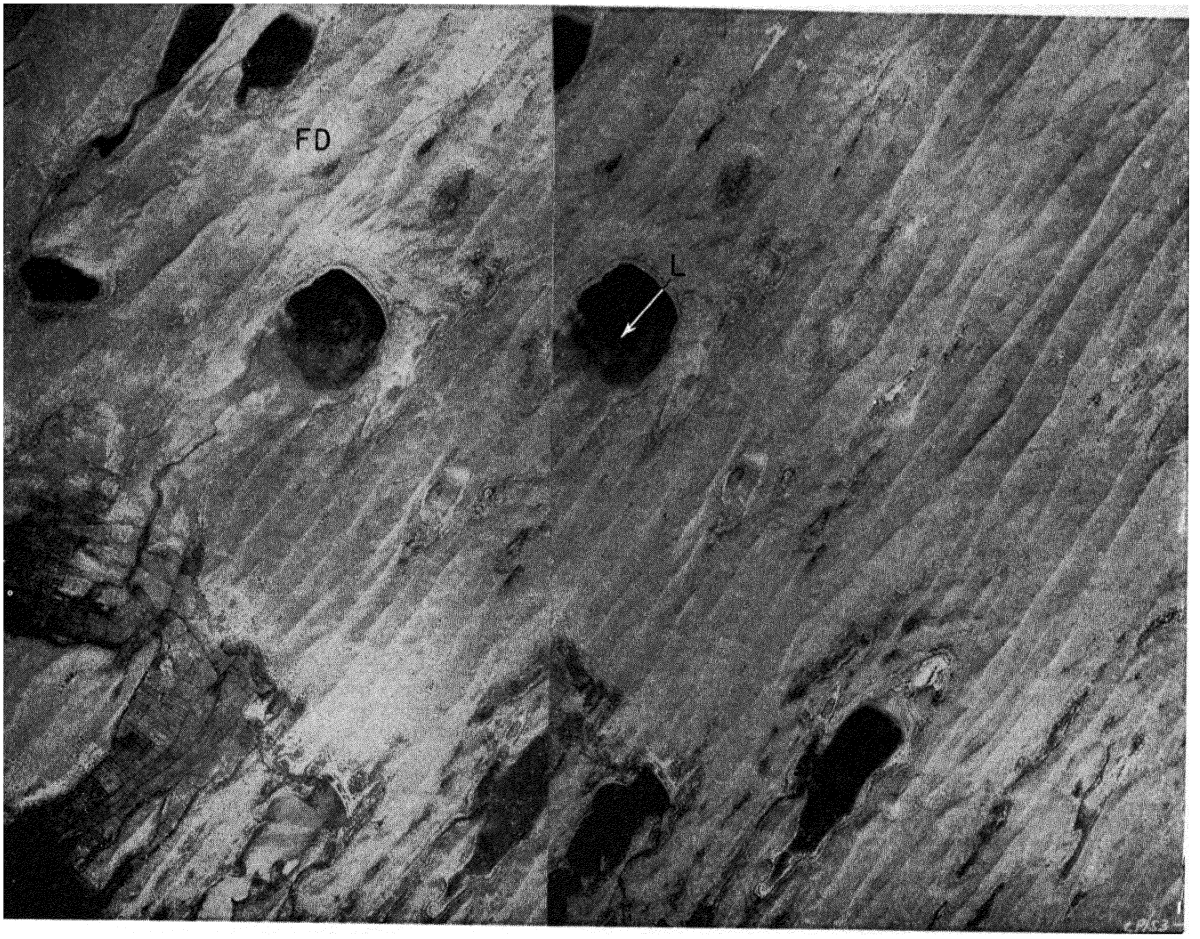


Fig. 14-6. Very thick longitudinal dunes with well-developed parallelism enclosing lakes *L*. A small fan delta *FD* is also present. The small black dots are shrub-sized trees. (*Middle East. Photographic Survey Corporation.*)

to the direction of prevailing winds. There is considerable opinion that transverse dunes are formed in association with moderate winds, and longitudinal dunes by strong winds. Lobeck (101) says the following:

When a moderate wind blows upon deep sand, the conditions are favorable to the production of great transverse ridges. The eddy on the near side of the ridge, and to windward of it, burrows sideways along the base until the finer material is removed. A small hollow is thus elongated into a trough. The forward-flowing current passing over the top of the ridge has insufficient power to move the coarser grains of which the ridge is gradually becoming composed. The height of the transverse ridges and the distance between them depend upon the force of the wind and the amount of fine particles mixed with the sand.

A strong wind behaves like a current and moves all the sand it strikes. It produces longitudinal stripes. The same effect is produced by a moderate wind blowing over a hard surface only slightly covered with sand, because eddies cannot excavate and transverse ridges cannot develop.

Winds of intermediate strength produce intermediate forms combining both transverse and longitudinal characteristics. In India the monsoon winds striking the coast produce longitudinal ridges. Farthest inland, where the winds are less intense, transverse ridges prevail. Intermediate types occur between these two.

In a mood of caution, Cotton (44) noted that very long longitudinal ridges in North Africa and Austrialia trend parallel to prevailing winds of moderate strength, while occasional strong winds blow across them.

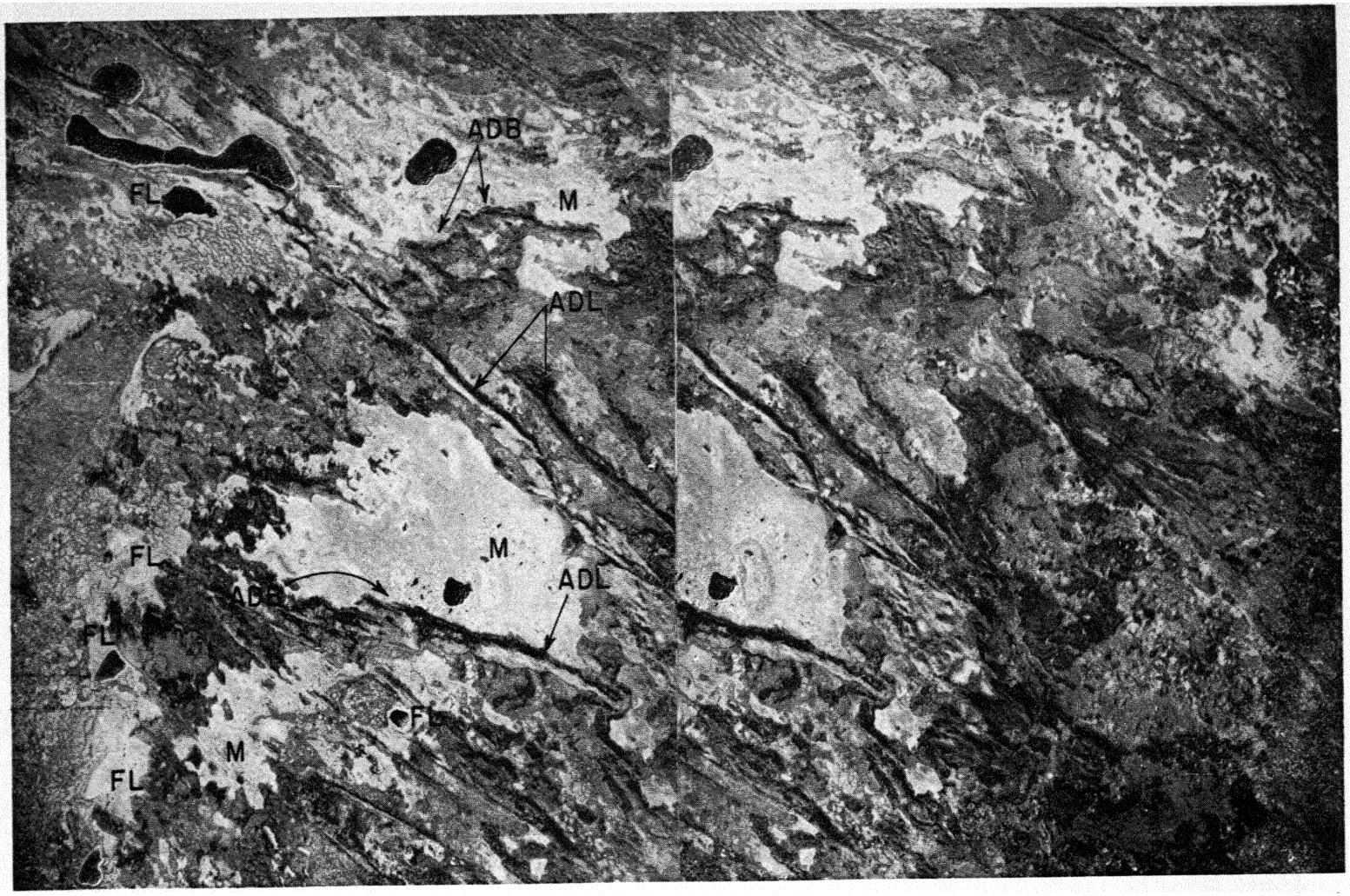


Fig. 14-7. Stereopair. A complex of longitudinal dunes *ADL* and poorly shaped barchanes *ADB en échelon*. The dunes are stabilized by forest vegetation and are surrounded by flatland marsh *M* and bog and swamp (Chap. 15). Filled and filling lakes appear at *FL*. (*Alberta. Alberta Department of Lands and Forests, Technical Division.*)



Fig. 14-8. Once barchane dunes that have been almost completely altered to longitudinal shape, probably by a change in wind characteristics. Wind direction is indicated by W. Originally selected and annotated by the Cornell group (43). (*Washington. U.S. Army.*)

The theory of transverse dune formation by *prevailing* moderate winds, as described by Lobeck, appears logical, although it seems that the word "prevailing" should be emphasized. "Prevailing" implies relatively frequent sustained duration and direction. Such a sustained direction, even if moderate, should probably have a greater effect than occasional strong winds in a counter direction. It is also implied by "prevailing" that shifts in wind direction do occur. If transverse dunes are in the process of formation, is it not possible that counterwinds will tend to advance their work by complementing the sideward eddies of Lobeck? In the process of doing so, they may complicate the topographic expression, but since this is an outstanding characteristic of transverse dunes, it is support rather than contradiction of such a formational hypothesis.

Also of importance to the formation of transverse dunes, in all probability, is the textural gradation of the sand supply. Is it not conceivable that weak winds acting upon very fine sands would produce the same effects as strong winds acting upon medium to coarse sands? This might be an answer to the situation mentioned by Cotton.

Until a better explanation is developed, the general idea of hollows developed into transverse dunes by sideward eddies resulting from winds *having insufficient power to transport all* the source, together with occasional complementary cross winds of variable transporting power, seems a plausible one. Such dunes should be developed, for the most part, on their immediate source of supply.

Similarily, the idea of long streamers of sand, deposited by winds competent to transport all sizes occurring in the source, appeals to the intuition as a reasonable hypothethsis for the formation of longitudinal dunes. The hypothesis should allow, however, for von Engeln's (212) suggestion that barchane dunes can be bisected by blowout erosion, yielding longitudinal dunes.

14-5. Formation of Aeolian Landforms—Barchane Dunes. Barchane dunes are the most interesting of the wind-blown landforms, because of their distinctive and pleasing shape. Lobeck (101) has the following to say of their formation:

> Barchanes show both transverse and longitudinal characteristics. They occur neither where the sheet of wind has the complete mastery over the sand, nor where the drifting sand is too heavy for the carrying power of the wind. They dot the desert plain where the sheet of wind has, for the most part, the mastery of tbe sand, but where it drops its burden at certain

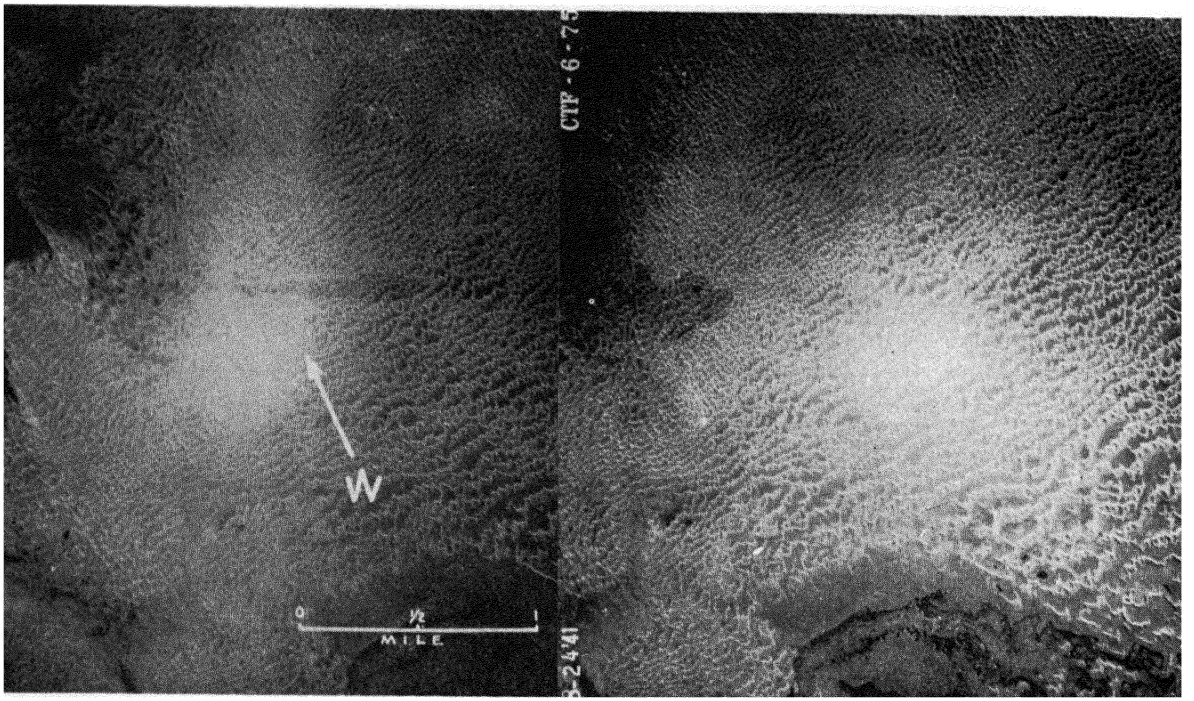


Fig. 14-9. An area covered with transverse chains of irregular, intersecting barchane dunes. These might properly be considered as transverse dunes. The white tones (particularly bright because of the gypsum sands), the uneven slopes, and the abrupt break with the wind-swept flat surface (alluvial lake bed—Chap. 11) are well known. Originally selected and annotated by the Cornell group (43). *(New Mexico. USDA Soil Conservation Service.)*

points. The horns, or cusps, of the barchanes point to leeward, for the lowest parts of the dune travel fastest. A barchane exposed to winds from all quarters gradually changes to a stationary dune.

Von Englen (212) provides an excellent description of barchane formation:

The windward slope is the convex side; the horns point down wind. The barchane is highest in the center; the surface, as well as the outline of the windward slope, is convex. The lee slope tends to be concave because a back eddy of the wind acts to hollow it out. Barchanes are held to be the elementary dune form and are inferred to be the product of a moderate supply of sand and moderate wind velocities. A nucleus starts, builds up to the equilibrium height, then develops the characteristic barchane shape by migration. Grains are moved from the base to the top and dropped on the lee side without being immediately replaced at the starting point. Thus the dune as a whole is shifted piecemeal down the wind. The crescent form develops because, with a uniform force of wind approaching the dune, the sand must be moved over a longer course and to a greater height at the center than at the sides. The particle by particle migration of the dune therefore proceeds more rapidly at the ends, and the characteristic barchane, sickle form results.

Later, von Engeln says that the "barchanes are desert border forms in areas of weak and shifting winds."

It seems that the exact reasons for barchane formation are debatable, or at least not distinguished by conclusive information. The author can add nothing, except that barchanes *do* occur and that von Engeln's description of the manner in which the crescentic shape is produced sounds reasonable.

14-6. Formation of Aeolian Landforms—Coastal Dunes. Coastal dunes occur as fairly steep ridges bordering coastal beaches and extending landward in an irregular manner. These ridges have a predominantly transverse expression on their sea-facing sides. The landward sides of coastal-plain belts contrarily tend to be quite irregular and usually show evidence of longitudinal "duning" counter to the direction of the seaward side of the dunes. These longitudinal expressions are indicative of the usually strong winds that blow in a di-

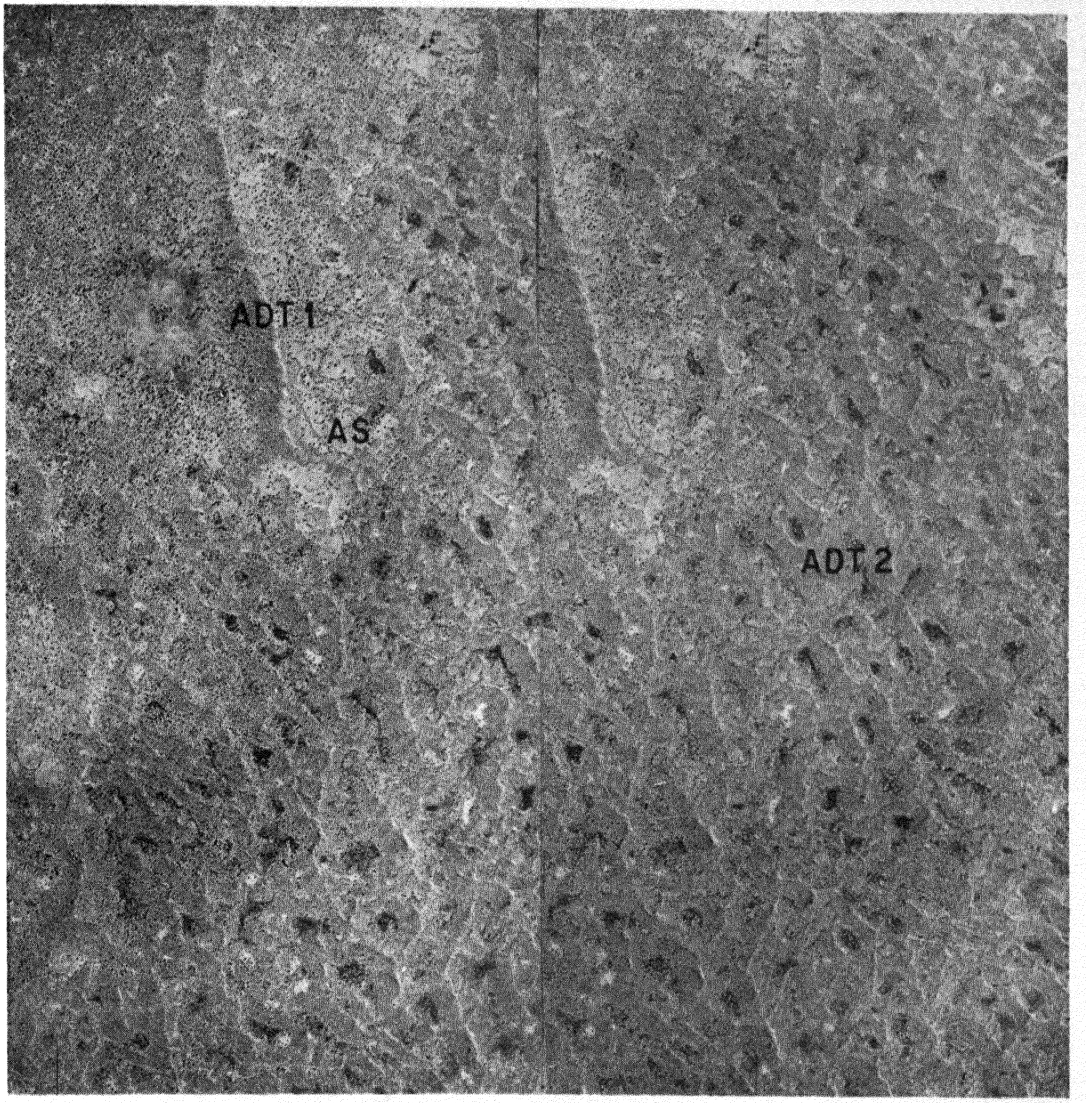


Fig. 14-10. A complex of irregular, detached transverse dunes (*ADT2*) developed partially from thin migrating sand sheets *AS*. Some continuous ridges (*ADT1*) have been formed. Note the different density of vegetation on the sheets and dunes. The abrupt breaks between the flat wind-swept undersurface and the dunes proper are also well shown. (*Middle East. Photographic Survey Corporation.*)

rection counter to that of the seaward transverse belt.

Melton (127) has classified these dunes as "source bordering lee dunes," dependent for their formation upon an unlimited supply of beach sand to the immediate windward. While this may be of predominant importance, other significant factors are those related to diurnal wind inversion and the relatively frequent occurrence (minimums of 1 to 3 yearly?) of high storm waves and tides that carve wave-cut scarps along the dune fronts. The author, while conducting an observational program on beach variations, found that most beaches along both coasts of the United States were subjected to dune scarping with fairly high frequency, at least in a geomorphological sense. Such scarping would tend to aid the creation of the beach-bordering transverse belt.

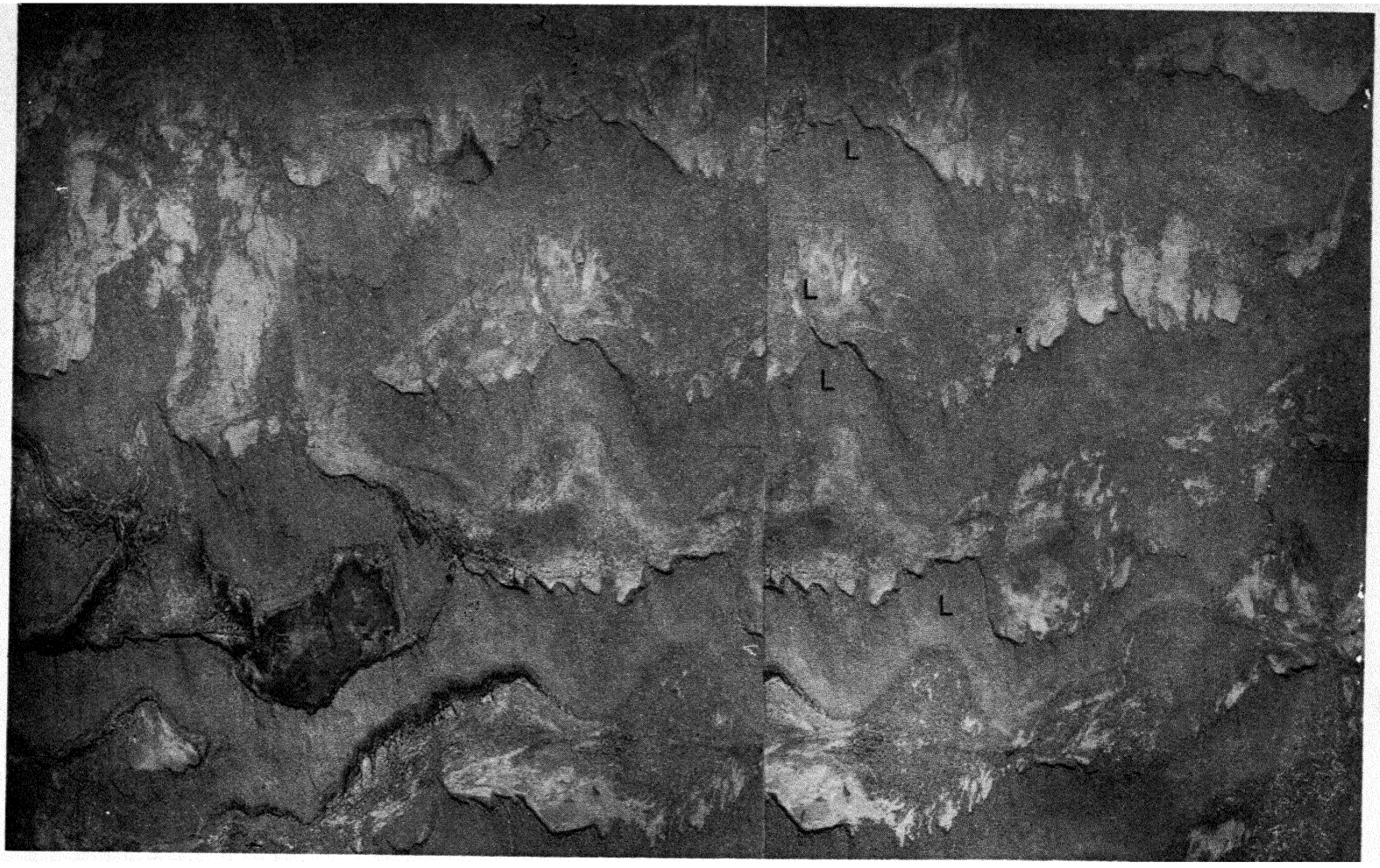


Fig. 14-11. This stereopair shows pronounced transverse duning. The ridges exceed 100 feet in height in places. They are composed of brownish aggregates of silt and clay, which account for their dark tones. The dune ridges are beginning to elongate t and will probably turn into longitudinal dunes. The anomalous rounded surfaces on these dunes are somewhat puzzling, but may be related to wind scouring of semi-cemented sands. Note the characteristic break at the base of the dunes. (*Middle East. Photographic Survey Corporation.*)

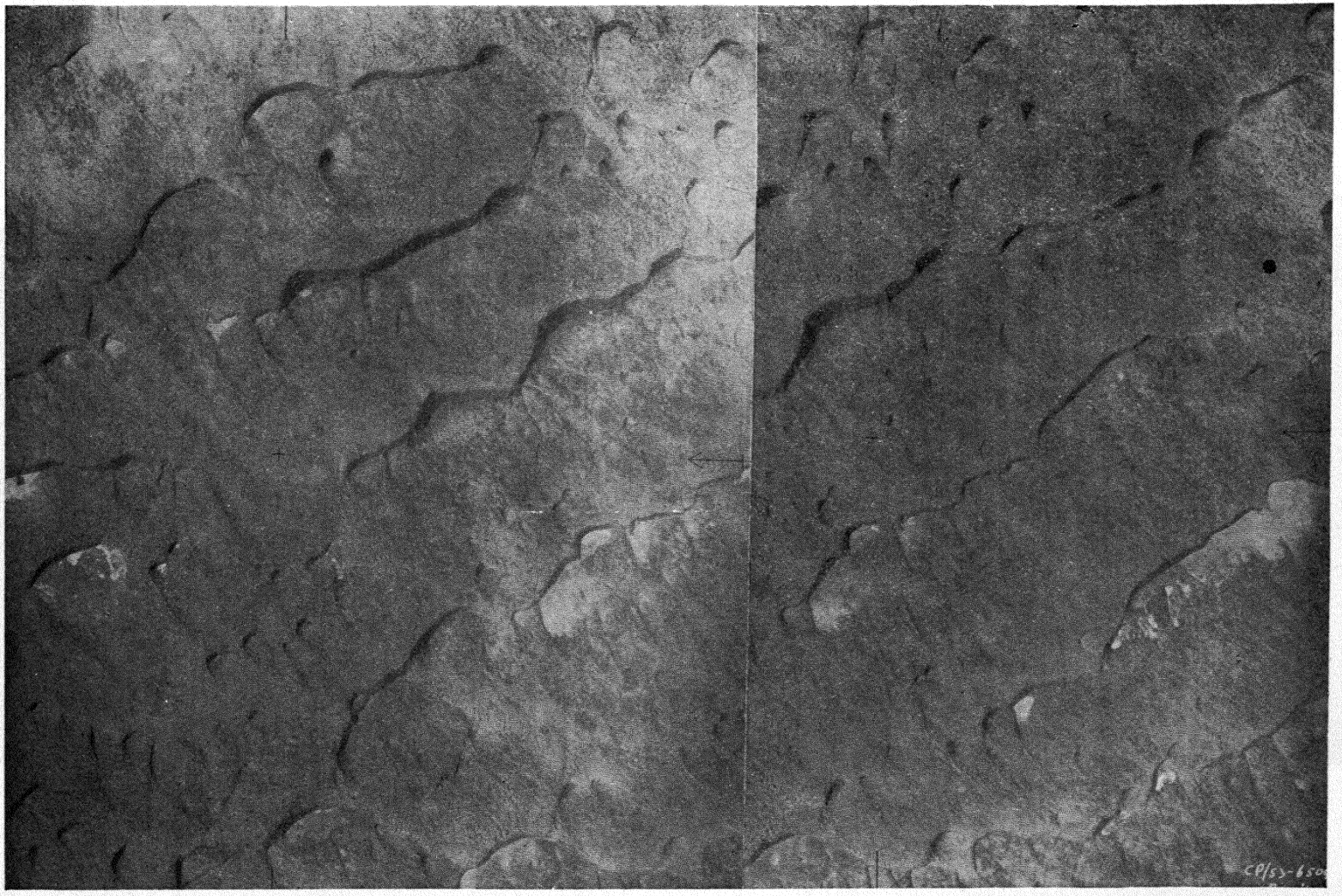


Fig. 14-12. A fine view of transverse dunes that may have developed because of the migration of aeolian materials over barchanes. (*Middle East. Photographic Survey Corporation.*)

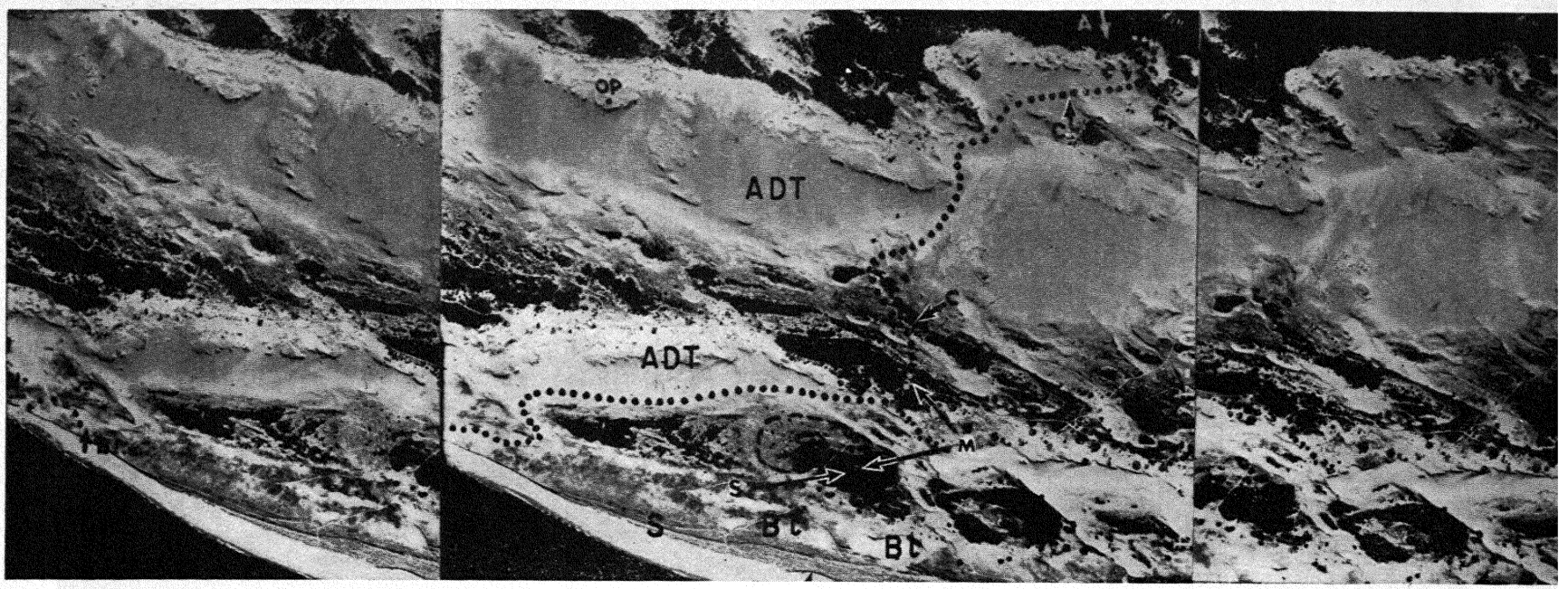


Fig. 14-13. An area of coastal dunes showing the scarp along the beach front(s), a blowout *Bl*, coastal marsh *M*, sand-covered marsh *S* (Chap. 15) and the predominantly transverse dunes *ADT* that are being covered by migrating drift *D* moving perpendicular to the shore line. Very little longitudinal duning is apparent. The dotted line shows best access, and *OP* indicates a high semicemented dune plateau.

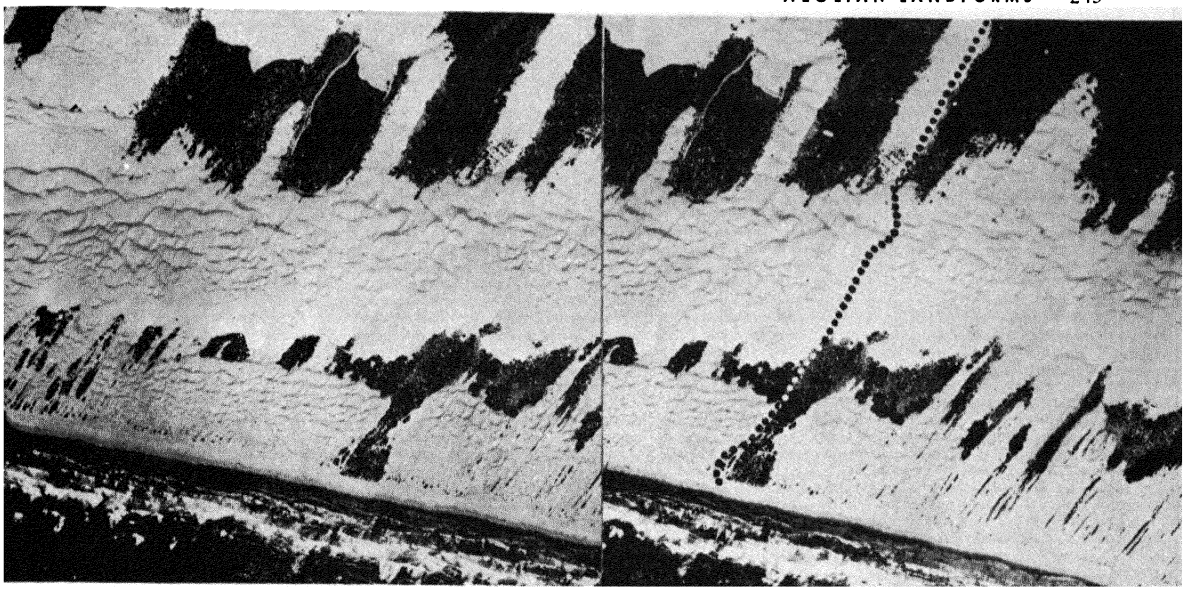


Fig. 14-14. Longitudinal and transverse coastal dunes.

14-7. Formation of Aeolian Landforms—Blowout and Wind-drift Dunes, Dune Complexes. Melton (127) mentions blowout dunes consisting of low crescentic ridges to the *lee* of and derived from blowouts (Sec. 4-24). His "wind-drift dunes" are similar to the blowouts but more elongated, like a hairpin opening *toward* the wind. The important thing about these dunes is their tendency to have "horns" leading *into* the wind instead of away from it as the barchanes do. Certain types of wind-drift–type dunes are termed U-shaped by Gravenor. These are very similar to barchanes (Sec. 14-9).

The desert dune complex is excellently described by Cotton (44):

> The various types of ridges and chaotic assemblages of mounds found among anchored dunes, especially those of a coastal dune belt, are features of a "dune complex," which is diversified also in a well-watered region by the courses of such streams as must cross it to reach the sea, as is the case in the dune complex of western Wellington, New Zealand. Blocked in places by wandering dunes, the smaller of such streams form lakes, shallow but in some cases of considerable extent. These, however, may later become choked with vegetation and converted into swamps. Larger rivers, on the other hand, maintain channels through the dune complex if capable of transporting all the sand tipped into them down the sandfall slopes of encroaching dunes. . . .
>
> When fixed by a cover of vegetation, which eventually holds in place a thin soil, the dune-complex landscape has a surface of small relief but with many steep slopes. These soil mantled slopes become smooth and symmetrical, with a compound (convex-and-concave) profile as blowout and constructional slopes become modified by soil creep.
>
> The dune complex comprises also many undrained hollows, from which water soaks underground, and it is generally quite without organised valley systems of its own, though it may be traversed by the courses of the occasional through-going rivers such as are extended across a coastal foreland. In an inland dune complex, however, the level of ground water may be deep enough to cause all inflowing streams to be swallowed by the sand.

14-8. Formation of Aeolian Landforms—Loessial Plains and Lunettes. In various areas of the world, there occur deep and extensive deposits of predominantly silt-sized materials. These materials are believed by most authorities to have been transported by wind, usually from sources considerably distant. There has been some discussion as to whether the loessial deposits should in reality be considered as products from arid regions, products from denuded glaciofluvial deposits acted upon by down-glacial winds, etc. Actually, the conditions for aeolian action (Sec. 14-1) are those that apply. If proper conditions exist, loessial deposits may be products of wind action on *any* suitable source. In terms of landform, the type of source is immaterial. Only the aeolian origin and loessial nature need be established.

The extensiveness and topography of loessial

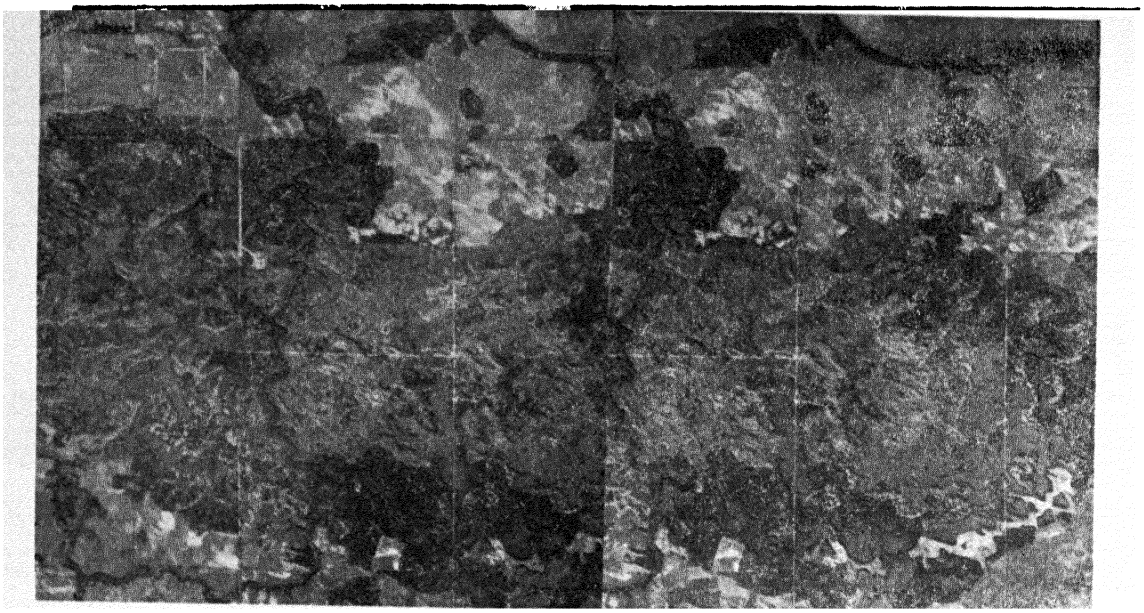


Fig. 14-15. A dune complex. Elemental barchane, longitudinal, and transverse dunes can be discerned, but the general assembly is one of chaotic, steep irregular mounds, ridges, blowouts, etc. Medium-sized streams maintain their courses through the complex. Marshes are frequent. The tones range from light in the cultivated areas (note the sharp tonal boundaries) to light gray where they are stabilized. The small stream, incidentally, shows a fairly young valley along its upper course, but an incipient meander plain along its lower stretch. (*Alberta. Alberta Department of Lands and Forests, Technical Division.*)

plains are characteristic, repetitive, and significant. Consequently, such plains may be considered as unit landforms. Some discussion of loess also appears in Chap. 4.

Another aeolian landform, of a loessial nature, is called a "lunette" and is, apparently, a dust-composed hill built on level surfaces. It occurs in Victoria, Australia, and is described by Cotton (44) as follows:

> These Victorian lunettes are composed of a black loam formed as a result of precipitation from the atmosphere of fine dust most of which must have been brought by strong winds from a great distance. They are closely associated with lakes and occasionally flooded swampy areas, rising just to leeward (eastward) of these and half encircling them. During gales when the air is dust-laden, dust is captured and brought down by spray whipped up from the lakes and thus a deposit accumulates close to the lee margin of the lake. . . .
>
> Lunettes are generally several miles long and average about half a mild broad. Though only 20 to 30 feet high, they are prominent enough to be rather conspicuous features on a plain. They have "regular and smooth contours quite unlike those of sand dunes" (hills). Migration of the shallow lakes has in some cases resulted in the formation of successive parallel lunettes.

14-9. Aerial-photographic Characteristics of Sand Dunes. Sand dunes are among the most distinctive landforms discernible on aerial photographs. Yet, strangely enough, they are also often missed, or incorrectly identified, during the process of interpretation. Possibly this paradox can be explained by saying that, in a manner similar to the well-known eye charts for color recognition, the dunes are distinctive once a line is drawn around them.

Plan and topography are the outstanding characteristics of dune landforms. Barchane dunes have typical crescent-shaped ridges with relatively sharp crests, steep leeward sides, and gentle windward slopes. The "horns" of the crescent are usually more or less oriented and point downwind. The tips of the horns are lower than the central crest. The barchanes may be isolated or may occur in groups and wide expanses of overlapping, imperfect "crescents."

U-shaped dunes resemble barchanes, but their horns point into the wind and the steep slopes lie on the outside of the U.

Longitudinal dunes are characterized by long, low, narrow ridges, tapering downwind both in plan and elevation. They tend to be more or less parallel and oriented in a downwind direction. In many cases, the sides of the ridges have asymmetrical slopes, presumably due to secondary winds. Often they represent the elongated horns of eroded and separated barchanes. In such cases, they may be intermingled with barchanes.

Transverse dunes are fairly complex and variable in form. They usually occur as series of sharp-crested ridges with highly irregular and often scalloped downwind sides, but gently sloping windward sides. In most cases, the dunes resemble, or are synonymous with, closely spaced and overlapping barchanes having poorly developed crescentic forms and variable crest heights. In other and rarer instances, the topographic form is that of even-crested ridges.

Coastal dunes exist in a variety of forms, including transverse, barchane, and longitudinal types, variations, and combinations. In many cases the dunes are quite irregular. In other cases (Sec. 14-6), they have a transverse shape immediately shoreward of the beach, changing to more or less oriented shapes in the belt that extends inland.

Many dunes, particularly when viewed through a stereoscope, exhibit a shape break along the boundary between the dune proper and the often wind-swept plain upon which they occur.

The surface-drainage characteristics of dune landforms are quite simple. Because of high porosity and limited water-collection areas, often supplemented by arid precipitation conditions, no surface drainage appears. Occasionally, washes or even perennial streams carve their way through dune areas. In other cases, streams or ponds may traverse the areas between dune forms. These expressions of surface drainage are not related to the dune forms themselves.

For reasons identical with those mentioned above, sand dunes are not characterized by gully developments.

Tones provide an important clue to the identification of the dune form. Because of their high porosity (and resulting dryness), their absent or



Fig. 14-16. This stereopair illustrates most of the criteria associated with thick loessial plains: the extended undulating topography with even-sided hill slopes parallel to the dominant wind direction; the general wind orientation (lines); the well-integrated, dense, uniform, linearly oriented drainage pattern with characteristic angles of juncture (Chap. 3); the typical featherlike pattern; the gully characteristics G (Chap. 4) and cuts C; the medium-gray, generally uniform tones; and the extensive cultivation. Original selection and annotation by Cornell group (43). (*Nebraska. U.S. Department of Agriculture.*)

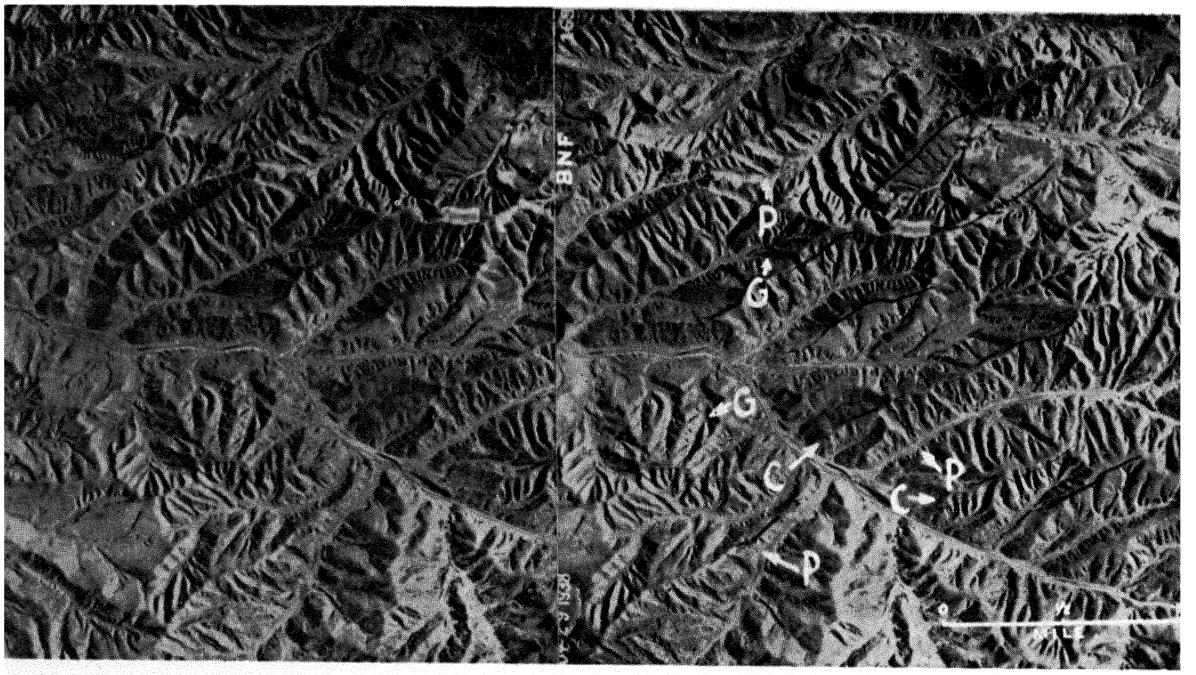


Fig. 14-17. A stereopair showing dissected, thick loessial deposits in a semiarid region. The original topography has been destroyed except for an occasional remnant *R*. However, the remnantal eroded spurs show a dominant orientation (lines), and both sides of the spurs tend to have even slopes. Gully characteristics *G*, buttresses, pinnacles *P*, and faint indications of catsteps *C*, together with uniform tones and lack of visible bedding, throw the weight of evidence in favor of loess. However, this *could* be silty shale, and an interpreter could not be certain of his conclusions without knowledge of the area or selective field check. Original selection and initial annotation by Cornell group (43). (*Nebraska. U.S. Department of Agriculture.*)

sparse vegetative cover (and resulting high light reflection) and the normal light color of the mineral particles composing the dunes, the tones on dunes are almost invariably lighter than those on surrounding areas. In some cases the tones are merely a lighter gray (usually the result of stabilizing vegetative cover). In other cases they are a bright white. In practically all occurrences the boundary between the dune tone and adjoining wetter or darker non-dune areas is sharp, because of the low capillary potential of the dune materials. Many stabilized dunes display gray tones (caused by vegetative cover) interrupted by irregular white patches indicative of barren blowouts (Sec. 4-24).

Vegetation is often completely lacking on dunes. In many cases, however, the dunes have been stabilized by vegetative cover. The cover is that capable of developing in the existing ecological environment characteristic of dunes (low nutrients, dry root zone, strong and persistent winds, prevailing climate, etc.). In general, it may be expected that the vegetation on dunes will be less dense and of poorer development than vegetation developed on adjacent areas.

Dunes generally do not show any productive land usage. In humid areas they are usually left to natural vegetation. Occasionally, they may show misguided attempts at cultivation.

Illustrations of dune landforms appear as Figs. 14-2 to 14-15.

14-10. Aerial-photographic Characteristics of Loessial Plains. Loessial plains are more difficult to identify than dunes, particularly when their occurrence involves a relatively shallow mantle.

Topographically, loessial plains have only a few definite distinguishing characteristics. Because they are wind-deposited, there is a certain tendency to "smooth out" the preexisting relief. Consequently, the plains, if not dissected, may be expected to exhibit a fairly flat to undulating topography having a "soft" appearance. If the plain is

dissected, a surface passing over the summits of the undissected portions may be expected to have a similar shape. Quite frequently, the hills of ridges on undissected plains display a tendency toward parallelism that reflects the prevailing wind direction. This tendency is destroyed in highly dissected areas, the original surface being indicated only by remnantal sharp-crested divides.

One criterion, often of importance, is that of uniform slopes. Because of uniform deposition and composition, the hills tend to weather and erode to fairly uniform slopes on both sides of the wind ridges. This aspect of topography aids in distinguishing loessial hills from, for example, weathered tilted shales.

Catsteps, the products of solifluction, are often present along hillsides (Sec. 4-18).

The surface-drainage pattern and the erosive features of loessial deposits are so closely associated that they may be considered as one. Their joint recognition is of major importance to identification.

The drainage-erosion pattern of thick loessial deposits tends to be intricately treelike, or dendritic, in nature, indicating lack of definite control. To use the terms of Chap. 4, it is highly integrated, very dense, highly uniform, semioriented (in a regional way), with little or no indications of control and angularity. Angles of juncture tend to be only slightly less than 90°. The pattern may be described as "featherlike," because of the wide-bottomed valleys that are developed in the channels of this typical silt material (Chap. 4). The sides of the streamways and gullies tend to be vertical, and the head ends are abrupt (Chap. 4). Pinnacles and semipinnacles are usually present near the head ends of the gullies or as remnantal features in any almost completely dissected areas.

The drainage pattern of thin loessial deposits where drainage has incised the overlying materials to a depth sufficient to encounter those underneath will display characteristics, at depth, which reflect the nature of the subsurface deposits.

The tone characteristics of loessial deposits are of minor significance. The tones tend to range between rather narrow limits of light to medium grays, giving an over-all blended to uniform appearance. There are no bright whites characteristic of the loess itself, although they may occur on exposed underlying materials, adjacent dune areas, etc.

Vegetative cover and land use in loessial areas are only of occasional importance. Because of their medium grain size, flat to undulating topography, good tilth and drainability, usual calcium content, etc., they are generally farmed intensively. If, because of dissection, remoteness, adverse climate, or inaccessibility, they are not farmed, natural vegetative cover may be expected to be fairly uniform.

Illustrations of loessial deposits appear as Figs. 14-16 and 14-17.

15 ORGANIC-MINERAL COMPLEXES

15-1. General Discussion of Organic-Mineral Complexes. Everyone is familiar with the terms "swamp" and "marsh," as well as their many local, regional, and geological equivalents or variations, e.g., "bog," "muck," "muskeg," "tidal marsh," "mangrove swamp," "quaking bog," "tidal flat," "peat," "meadow," etc.

All these terms describe organic-mineral complexes, i.e., *variable accumulations* (15 to 99 per cent) *of organic matter, in various stages of decay, mixed with greater or lesser amounts of mineral soil* (1 to 85 per cent), *all components having their own origins or combinations of origins.* Pedologically, these accumulations would be considered as climatogenically subdued soil types (Secs. 7-9 and 2-8) and would be classified as peat (50 per cent or more organic) and muck (20 to 50 per cent organic) "soils," meadow podzols, peat podzols, and glei soils, depending upon their profile and terrain situation. In this book such accumulations are called organic-mineral complexes [1] and are considered from the standpoint of their geomorphological and terrain environment. In Sec. 2-21, it was shown that their formational chain of origin ranged between simple and complex.

In Sec. 2-8, processes of humification and mineralization under both aerobic and anaerobic conditions were discussed. It was shown that any organic or humus layer acts as a source of chemical reagents for the pedological attack of mineral matter. Further, it was stated that this attack proceeds, with variations, under both aerobic and anaerobic conditions.

The organic-mineral complexes discussed herein may all be considered to have been created *partially through the climatically favored processes of humification, mineralization, and pedological attack, under predominantly anaerobic conditions as caused by topographic or subsurface conditions, and partially through the normal geomorphological deposition of sediments.*

A predominance of anaerobic conditions implies that the water table is high during a *greater* part of the year and that the organic-mineral complex is submerged or nearly submerged during *some* part of the year, either for a single length of time, or periodically on a daily, weekly, etc., basis. These anaerobic conditions may be related primarily to topographic situation, such as low positions with respect to local ground-water or sea-water levels; depressed positions receiving comparatively great amounts of surface and subsurface runoff; flat or depressed positions from which surface drainage of normal rainfall and upstream runoff is impeded; and relatively high positions that lie in the path of ground-water effluent. They may be related also to underlying "impervious" layers (previously desiccated layers, cemented layers, and other hardpans or claypans, permafrost, climafrost strata, clay, impervious fill, bedrock, etc.) or both.

Favorable climate implies a sufficient supply of plant remains for the operation of the organic processes. If the climate is too cool (near glaciers and in the far north) or too arid (in the deserts), the growth of plants is inhibited and the organic processes are slowed because of adverse moisture and temperature conditions.

The nature of specific organic-mineral complexes (specific swamps, bogs, marshes, sea-bottom zones, etc.) has received much attention from botanists, ecologists, and geologists. This is attested by many papers in the literature. However, with exceptions, most of the treatments have been concerned largely with descriptions and discussions of the biotic types, colonies, and sequences. They

[1] None of these should be considered in the same class with the upper layers of the podzol (A_0, A_1, A_2) or chernozem soils, which also have high percentages of organic matter (5 to 15 per cent for chernozems and up to 90 per cent for the A_0, that is, humus, layer of the forest podzols).

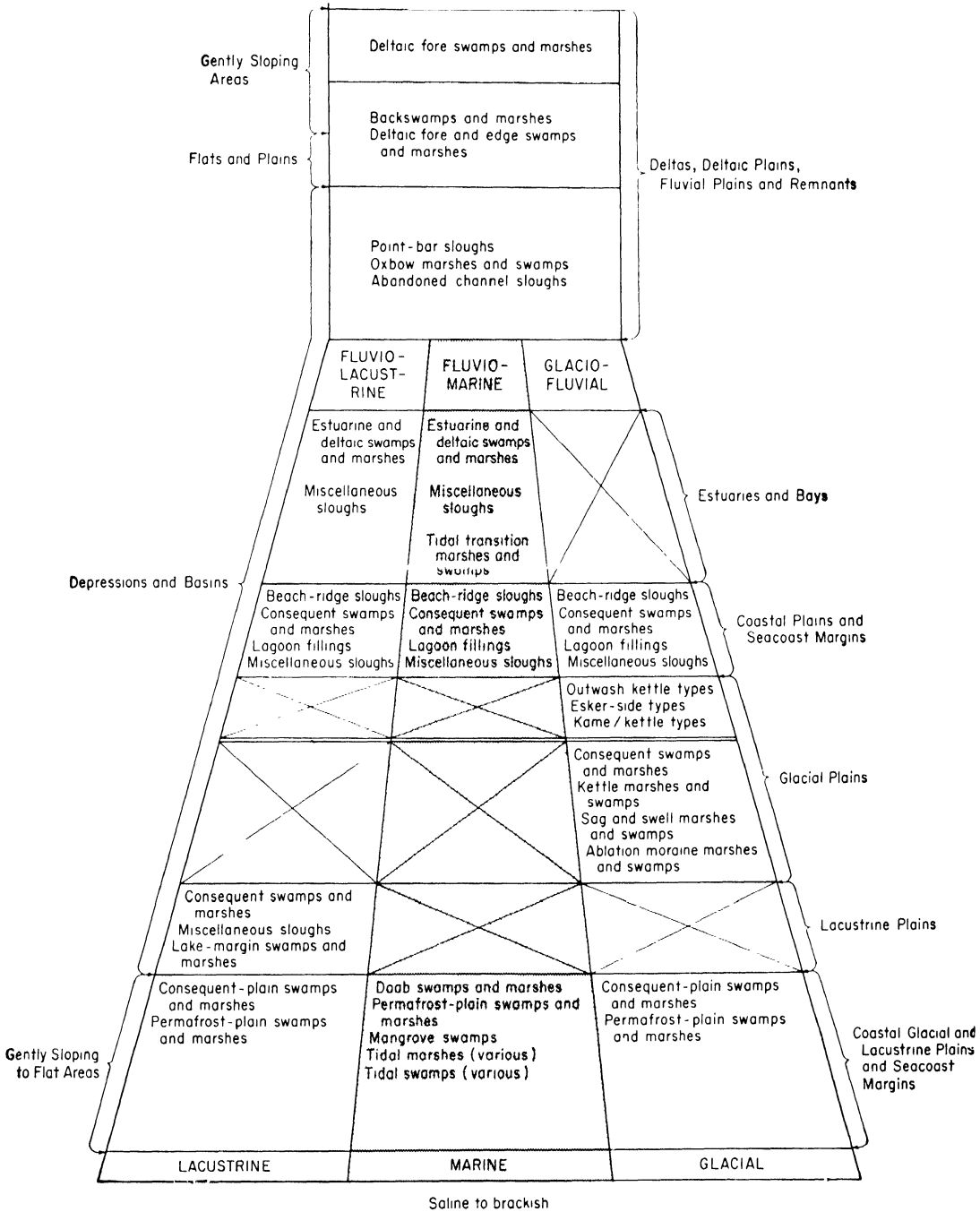


Fig. 15-1. A compartmentalization of organic-mineral complexes.



Fig. 15-2. This oblique, taken by the author from a Navy blimp, shows views of two lakes being invaded by organic mats. The lake in the foreground is being invaded around its entire periphery and will soon be completely covered. It may now be classified as a floating, lake-bordering marsh. From this it will become a "quaking bog," a bog, and finally a swamp. Later figures in this chapter show its aerial-photographic appearance. The lake in the background is partially covered with floating marsh that is proceeding mainly from one side. (*New Jersey. U.S. Navy.*)

have been only slightly concerned with the interaction and interrelation between the formation and *in situ* characteristics (depths, proportions, supporting capacities, reactions, compositions, agricultural potentials, etc.) of the organic-mineral complex and the geomorphic processes, nonorganic sedimentation, and water regimen which act or acted upon them.

Few have attempted an organized discourse on the detailed formation of organic deposits as a whole. Such a study should give attention, both qualitative and quantitative, to the relative place of the various factors affecting formation and accumulation and a classification of all deposits on the basis of results of study. Twenhofel (209) has probably gone as far as anyone in this direction, but his efforts have been only preliminary. In the preface to his entire book on sedimentation he wrote, "There is so much that is unknown that one should be humble. Only the margins of the unexplored domain have been invaded."

In view of the above, and also because there is neither room nor purpose, this chapter cannot include a detailed survey and discussion of organic-mineral complexes. Rather, it includes a general discussion of some of the more important complexes. This discussion is based largely upon Twenhofel's remarks, together with the author's experience and studies. Information on certain special aspects has been derived from a few other sources, notably Radforth (151, 152), Joffe (85), and the Cornell group (13, 14, 43).

15-2. Classification of Organic-complex Deposits. Organic deposits are classified best on some basis other than landform. Unlike the *unit landforms* (Sec. 2-27) associated with deposits of different origin, all organic deposits have variable and generally nonsignificant shapes as well as general topography that is *alike*, even though the nature and formational history of the deposits are *different*. In some cases, the visible general topography resembles that of deposits having completely different origins and no organic content at all.

As examples of the above statements, consider a tidal marsh, a lake marsh, a muck pocket, a

fluvial-plain backswamp, and a treed swamp in an area of residual soils. Common experience informs us that the topography of each of these organic deposits will be alike, i.e., generally flat. Yet basic geomorphological knowledge will inform us that each of these deposits must have been formed by one, or a combination of, geomorphic processes of different origin; that they were formed in association with waters of varying general depth, agitation, length, and frequency of inundation and degree of salinity or other chemical saturation; and that they may have been formed under the influence of different climatic factors.

As a result of all these differences, it may be reasonably expected that the biotic-growth, humification, etc., processes, as well as the depth, stratification, and characteristics of the organic-mineral layers must be different and, in all probability, reflective of the other factors that were active during their formation.

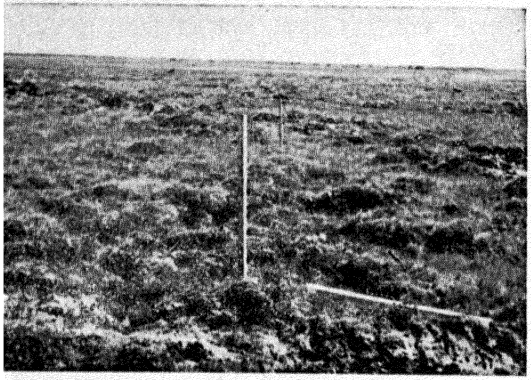
Consider also that each of these organic deposits has a surficial expression similar to that of a fluvial terrace, an emerged lacustrine deposit, certain areas of certain types of fluvial plains, or portions of a newly emerged coastal plain. Yet a fluvial terrace also has shape and a third dimension. A lacustrine deposit, while it has no particular shape, usually has other features associated with it. A fluvial plain as a whole, including its backswamps, has shape and subsidiary features.



Fig. 15-3. Rock-basin muskeg *M*. The lines are stringers of sphagnum moss. See also Fig. 13-11. (*Quebec, Alberta, Ontario. Photographic Survey Corporation.*)

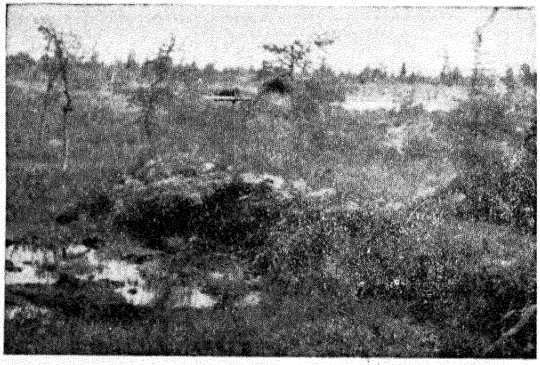


(a)



(b)

Fig. 15-4. These four photographs show microtopographic features of organic terrain. Included are (a) the edge of a peat plateau, (b) a mound, (c) a ridge, and (d) abrupt pond margins. (*Canada. Norman W. Radforth.*)



(c)



(d)



Fig. 15-5. Stereopair of a lake-type deposit, showing the central floating organic mat *FO* and the lake margin deposits, consisting of mineral material mixed with, and overlying, organic material *M/O*. Two small bird's-foot deltas *BF* are visible, as are a number of completely and partially filled lakes *FL*. Drawn circles indicate ground control. (*Alberta. Alberta Department of Lands and Forests, Technical Division.*)

A coastal plain has neither shape nor special features but borders a water body and is relatively elevated. Organic deposits do not have as much landform as any of these unit landforms, except possibly lacustrine deposits, with which they are often mixed and confused. To repeat, the chief reason for this is that they have no typical *shape* [2] or *special topographic expressions* (except on an exceedingly small scale).

Organic deposits should be classified on the basis of their environment, i.e., the processes, climate, vegetative cover, water conditions, and terrain positions that have affected their formation.

In terms of water conditions, all organic-complex deposits have one thing in common: they were

[2] With a few exceptions, e.g., sloughs.



Fig. 15-6. This view illustrates the aerial-photographic pattern exhibited by some of the immense flatland marshes, bogs, and swamps of Alberta. These are developed on glacial till plains. Note the complicated tonal patterns, frequent "furzy" textures, numerous ponds, lack of surface drainage, and accumulations of dunes *AD*. Incidentally, except for the forested (black) areas, this entire photograph is covered with organic complex, including some typical irregular to circular areas *L*, indicating the last stages in organic filling. (*Alberta. Alberta Department of Lands and Forests, Technical Division.*)

formed in a *transitional zone* between land and water, the water dominating to the extent that an organic deposit of a nonremnantal type may be considered synonymous with high-water-table conditions of some kind. Beyond this similarity, water conditions imply differences related to variations in anaerobism and content of dissolved salts. Broadly, the variations in anaerobism may be listed as completely anaerobic (submergent for 100 per cent of time), incompletely but regularly varied anaerobic (various types of fluctations in submergence including those of a daily—tidal—and seasonal nature), and incompletely but erratically varied anaerobic (various fluctuations caused

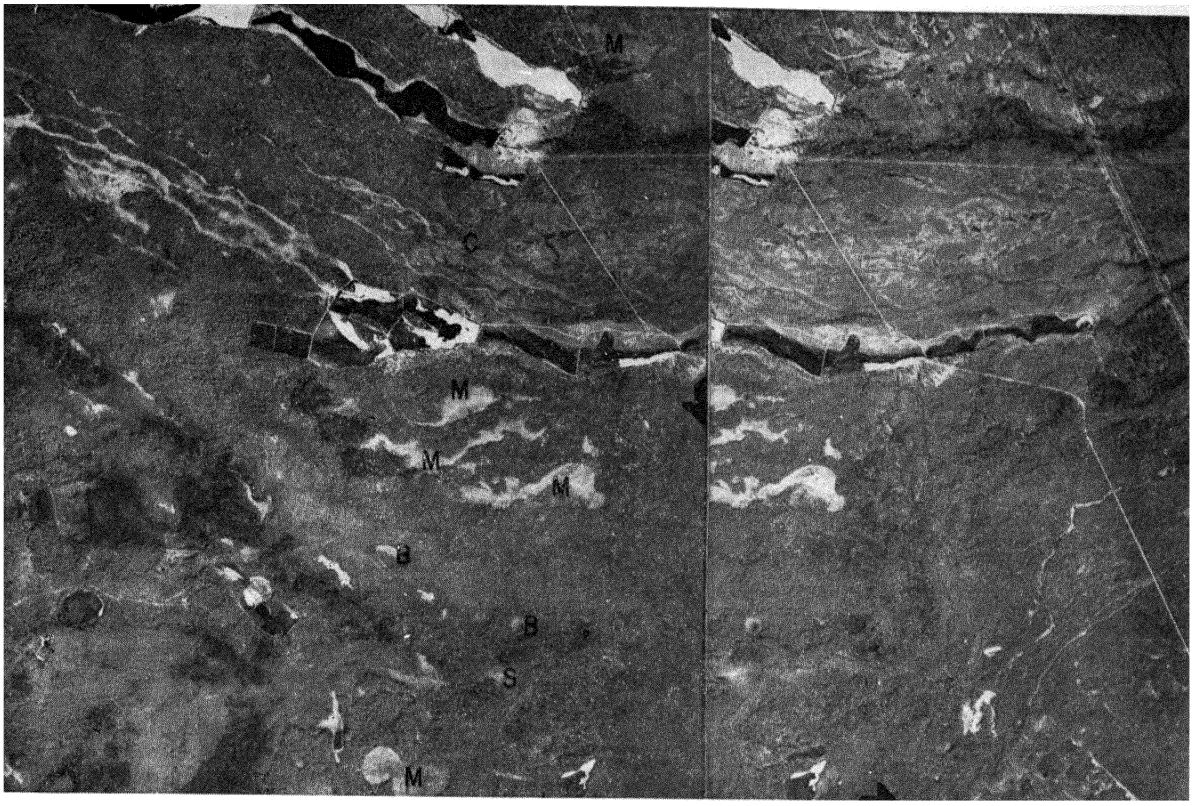


Fig. 15-7. Flatland marsh and swamps in the doab area (Chap. 11) of a young coastal plain. The marshy and bog areas *M* and *B* are easily distinguishable. These are surrounded by sands (forested, slightly elevated, light tones) through which a pattern of marshy, anastomotic low-gradient drainageways *C* carve their way, probably on top of a hardpan or claypan (Chap. 4). The roads in this area are constructed on fill. This particular photograph was taken in winter (ice in ponds). In spring, this area is not very dry. (*New Jersey. Aero Service Corporation.*)

by irregular flood levels). None of these, of course, consider the relative levels and durations of the water table during "nonanaerobic" periods. The variations in saline content, based solely upon the alkalines, sodium particularly, may be listed as fresh, brackish, and saline.

In terms of terrain position, the remarks of the fourth paragraph of Sec. 15-1 apply. To these remarks must be added considerations of position in relation to sedimentation by materials and waters of other origins. This latter is closely tied to the process factor of environment, i.e., those geomorphic processes that are actually effective in contributing to the formation of the organic-mineral complex. These include various depositional processes of fluvial, marine, lacustrine, fluviomarine, fluviolacustrine, glaciofluvial, and glacial origin.

In terms of vegetative cover, a broad variety of types, heights, colonies, and sequences, dependent partly upon climate, may be noted. Initially, at least, it would seem best to generalize these varieties under three headings based upon height and general type of growth. These are areas of low growth such as aquatic plants, grass, mosses, etc., called "marshes"; areas of medium growth such as Labrador tea, huckleberry, tamarack, and other shrubs or low trees, etc., called "bogs"; and areas of high growth such as tamarack, cedar, ash, cypress, birch, mangrove, alder, black spruce, etc., called "swamps."

In terms of climate, the remarks of the second and fifth paragraphs of Sec. 15-1 apply, as well as do further considerations of temperature-moisture regime and their effects upon biotic types and rates of accumulation.

With such a variety of important factors, it is probable that any rigorous classification would

involve an imaginary figure with nine or more axes. For purposes of this book, essentially geomorphic in approach, a much simpler compartmentalization has been adopted. This compartmentalization emphasizes the two interrelated factors of major extraneous geomorphic process and physiographic position of the organic-mineral complex. The scheme appears as Fig. 15-1. In the classification some local and colloquial names are used where they seem to have the sanction of long or widespread usage or appear to be advantageous as special nomenclature.

It must be emphasized that while most organic deposits lack unit landform, they do not lack the other elements of the aerial-photographic pattern, such as drainage features, tonal pattern, vegetative features, etc. The arrangements of these various elements in a complete pattern serves as a means of identifying and differentiating between organic deposits of various types.

15-3. Formation of Marshes and Swamps in Lakes, Basins, and Depressions. The greatest number of marshes and swamps, and those with which we are best acquainted, are formed in lakes, basins, and depressions. They are associated with a variety of geomorphic origins and processes, as well as with bedrock areas and regions of residual soils. They include accumulations of point-bar and beach-ridge sloughs, oxbow lakes, abandoned channel deposits, the entire range of consequent ice block, ablation, sag-and-swell moraine, glaciofluvial and lake margin swamps and marshes, rock-basin muskeg deposits, seacoast and crustal lake margin deposits, evaporite lake deposits, etc. They are also associated with almost every type of environment, in almost every variation and combination (Sec. 15-4).

All these organic-mineral complexes except those associated with evaporite (Sec. 11-16) and seacoast lakes come into being under the influence of fresh water, are subjected to no tidal action, and have little or no wave and current action.

Considering the lake margin deposits as a type (lacustrine environment), Twenhofel (209) describes their formation as follows:

> Plants responsible for the accumulation of the organic materials are chara, sphagnum, canes, reeds, grasses, sedges, rushes, arrowleaf, and water lilies. Each type of plant is adapted to some depth of water, and they succeed each other from the shore outward. Some plants, as sphagnum, float on the surface; others, as the pond lilies and chara, are rooted in the bottom. Floating plants form mats that live above and die below. These catch sediments and in course of time may form a thick cover. Beneath the mat there is water or black sludge. The mat may move with worm-like motion when disturbed and is then termed a "quaking bog." In time it may support large plants and ultimately trees. These destroy the plants to which the mat originally was due. The basin in time becomes completely filled with semidecayed organic matter. [Figure 15-2 shows a small lake invaded by plants.]
>
> As vegetation is advancing into a lake from the shores, the central part of the lake remains open and to some degree agitated. Bacterial action continues in these central waters, as agitation permits entrance of oxygen and prevents extreme toxicity, and bordering vegetation limits entrance of inorganic sediments. The organic deposits beneath this central part consist of waxes, fats, gums, and lignin, and there are frequently many tests of diatoms, producing an organic deposit quite different from that of toxic waters. . . .
>
> Peat is a common sediment about the margins of many lakes, and central parts of lake basins not receiving much clastic sediment may become filled with black muds rich in organic matter (Rickett). Hard-water lakes do not commonly contain such deposits in very pure form, but small soft-water lakes may contain a great deal. Woodland lakes of northern Wisconsin (Twenhofel, McKelvey, Carter, and Nelson) contain large volumes of organic sediments of plant origin. These are deposited beyond the shallow bottoms of the shore zone and consist largely of a pale greenish-yellow gel in which are fragments of plants, diatoms, sponge spicules, and inorganic matter, the proportions varying considerably from place to place. Deposits of this character are nearly 16 meters (52 ft.) thick in Allequash Lake in northern Wisconsin. The water content is about 90 per cent, and there is little variation no matter what the depth. After drying, the organic sediments shrink to a very small percentage of the original volume and become black, tough, and rubbery. The dried sediment ignites in an explosive manner. The 16 meters of thickness of these organic sediments in Allequash Lake would make not more than 1.5 meters of solid sediments. Such fine organic sediments of lakes have been termed sapropel . . .

The formation of organic deposits in random depressions, basins, and hollows—the consequent marshes and swamps—may and usually does take place without any effect due to open waters. Moisture-loving plants and trees live, grow, and die, depositing their annual residues, which undergo humification under subaerial or anaerobic conditions, depending upon whether the high water table occurs seasonally, daily, yearly, or constantly.



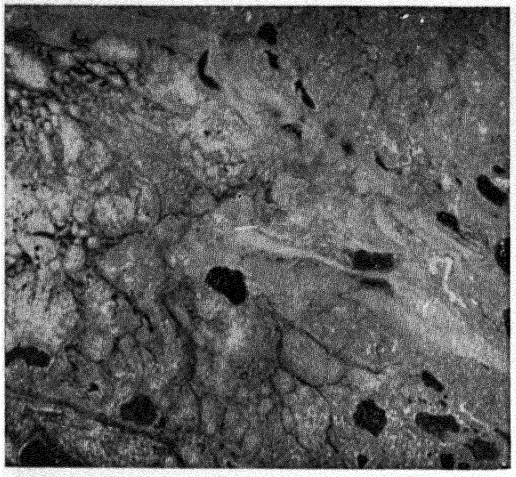
Fig. 15-8. A fairly large flatland marsh-bog complex *M* surrounding hummocks of ablation till, and aeolian deposits (forested), including some barchane types *AD* (Chap. 14). Some lake margin "quaking bogs" *LM* are also visible. This organic complex is relatively high in two directions, draining to the lower left and toward the upper right through a transition *T*. Ablation till *GM* encloses the organic area with its typical knobby topography. Some filled lakes are indicated by *OA*. (*Alberta. Alberta Department of Lands and Forests, Technical Division.*)

These humified products are also subject to the deposition of certain mineral sediments having fluvial origin.

15-4. Formation of Fresh-water Organic-Mineral Complexes in Miscellaneous Special Depressed Environments. Organic-mineral deposits accumulated in depressions include many special types that are affected by fluvial geomorphic processes to a greater extent than are other depression occurrences.

Accumulations in the point-bar swales, oxbows, abandoned channels, and backswamp areas of fluvial floodplains and deltas are much more frequently and significantly affected by fluvial action than are accumulations in bedrock hollows, consequent depressions, kettles, etc.

Fluvial floodwaters often inundate otherwise quiet marshes and swamps in floodplains and deltas. In doing so, they deposit considerably more mineral sediments composed of clay, silt, and sand sizes than would be normal for other types of depression occurrences. At the same time, they tend to wash out toxic waters, existent anaerobic organisms, and organic accumulations, replacing them with new waters and river organisms. The net results of this action are an interstratification of organic and mineral materials, with the mineral component existing in thicker, more frequent, and more continuous strata than in other depression-



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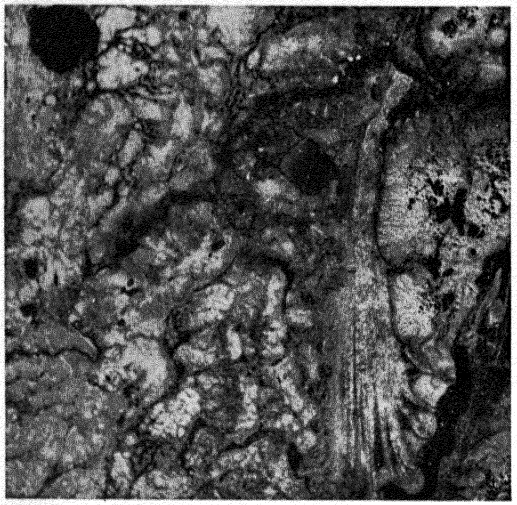

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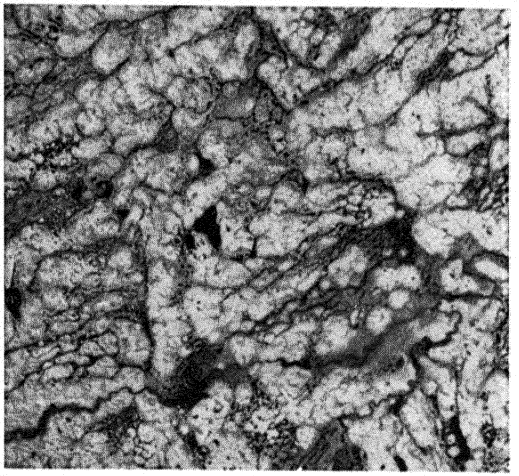

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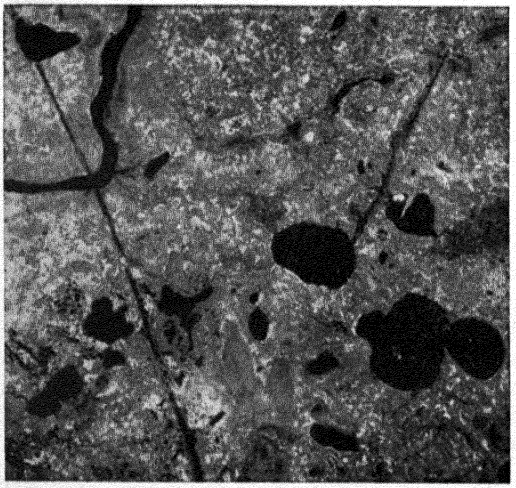


(c)

Fig. 15-9. These photographs, used to illustrate Radforth's article (151) and kindly supplied by him, show certain air forms that predominate in aerial photographs at a scale of 1:60,000. Radforth names the patterns as follows: (*a*), dermatoid, (*b*) stipploid, (c) terrazzoid, (*d*) reticuloid, and (e) marbloid. As Radforth said, "recognition of them, their relative frequency and distribution on the air-photo records, provides the first step toward an understanding of the actual physical nature of the muskeg for which each pattern prescribes." (*Northern Canada. N. W. Radforth.*)

type swamps; a more frequent occurrence of desiccated layers; and different sequences and types of organic growth, death, and pond filling.

15-5. Formation of Organic Deposits Associated with Flat to Gently Sloping Land. Extensive organic deposits often form on flat to gently sloping land. This statement often leads to some disbelief, particularly regarding formation on slopes. Yet organic complexes of the flat to gently sloping types cover large areas in the younger geomorphic regions of the world, e.g., the doab regions of coastal plains, emerging coastal plains, glacial plains, lacustrine plains, etc., while the sloping muskeg of Quebec and widespread organic deposits of northcentral Canada are well known. Twenhofel (209) says the following of flat to gently sloping deposits:

> A swamp on a level or nearly level surface presupposes an initial high water table. A fallen and semidecayed vegetation serves as a blotter or sponge to raise the table. Such a swamp may raise its surface above surrounding levels and spread laterally. The shape would become a low dome, which under conditions of great rainfall may "burst" and spread the black organic matter over parts of the surroundings. These "bog bursts" are known to have produced streams of black soupy materials as much as 30 meters wide and more than 1 meter deep (Barkley).
>
> Plants growing on flat-surface swamps consist of mosses, ferns, sedges, grasses, horsetail rushes, and various other plants. The tundra of subpolar regions is a flat-area swamp, with sphagnum moss the chief plant. Most swamps on flat surfaces have pools of more or less brown water scattered around in irregular distribution. The water in these pools may be extremely toxic to plants and animals.

Radforth (151, 152) mentions and illustrates what he calls "peat plateaus," and the extensive interfluve swamps of the Atlantic Coastal Plain—many of them formed on flat to slightly convex surfaces—have been noted by various scientists.

15-6. Formation of Tidal Marsh and Swamp. Tidal marshes and swamps cover large areas along the present margins of most emergent (subaerially exposed) and emerging (shoaling and soon to be exposed) coastal plains and river plains of marine origin. They also occur along the present borders of any other landform or rock type if environmental conditions are satisfactory. These conditions include:

1. Suitable shoaling conditions (subaqueous "bottom," generally nonorganic, has a slope that probably ranges between 0.1 and 5.0 per cent)
2. Suitable tidal fluctuations (daily tidal fluctuations cover and uncover shoal areas to variable but generally shallow depths)
3. Suitable protection from wave and current action
4. Some saline waters

Suitable shoaling conditions may be created by the emergence of coastal or marine river sediments or any other gently sloping landform, e.g., a delta; the submergence by the seas of flat terrain of any type; the fluvio-marine-lacustrine filling and reworking of an area bounded by wave- and current-made features, e.g., spits, bars, barrier beaches.

Suitable tidal fluctuations exist along most of the sea margins of the world.

Suitable protection from wave action is rapidly provided by the forms resulting from shore processes. These forms absorb the shock of waves having long fetch and height, even out tidal variations within the protected areas, and break up wind action, thus inhibiting wave reformation.

Saline waters may be assumed to be present if tidal fluctuations are present (neglecting minuscular lake variations). However, tidal marshes, because of their low position and their probable receipt of much fluvial flow, often display a transition from saline waters to fresh waters as high lands are approached.

The first stage in the formation of tidal-marsh deposits is the emergence or shoaling of subaqueous nonorganic sediments, or alternatively, the deposition of fluviomarine and marine nonorganic sediments beneath existing waters. These sediments, in the author's experience, may be almost anything, but seem to follow the usual laws of velocity transport. So long as protection is sufficient for these areas, aquatic weeds and grasses begin to grow on the bottom, going through their cycles of birth, life, death, and decomposition under anaerobic conditions. In the process of so doing, they receive, absorb, or intercept fine-grained mineral sediments of fluviomarine origin, which become mingled with their own remains. They also receive the remains of animate aquatic organisms and add them to their gradually accumulating basal layer. Ultimately, the accumulation is built to water level and, under the influence of tidal action, to a level above it (but not more than 1 to 4 feet). Of course, these later stages support different plant growths, as do the brackish and

fresh-water areas toward dry land. The end result of these varied but continuous processes is an accumulation having great organic and nonorganic variation both vertically and horizontally,[3] as well as a complex air-photo pattern.

It is possible to have the tidal marsh change to a coastal marsh or swamp as the inward areas are approached and fresh water becomes more dominant.

It is also possible to have marine swamps composed of trees that require root inundation with saline waters (mangroves). Mangrove swamps, by virtue of the accumulation of decay products, eventually prevent their own growth. They then change into "normal" tidal marshes (Chap. 10).

15-7. Formation of Tidal Flats. Tidal flats are, in the main, nonorganic. Their inclusion in this chapter is one of convenience.

It might be said that tidal flats are tidal marshes in the making. In Sec. 15-6, it was stated that the first stage in the formation of tidal-marsh deposits was the emergence or shoaling of subaqueous *non*organic sediments, or alternatively, the deposition of marine or fluviomarine nonorganic sediments beneath existing shallow waters. Tidal flats may be considered as this first stage.

Tidal flats may be divided into "mud flats" and "sand flats." They are essentially fluviomarine accumulations in shoal areas having or developing *some* protection from strong wave and current action and are periodically covered and uncovered by tidal waters.

Tidal mud flats are often completely devoid of vegetation. In other cases, their organic cover is scattered and/or sparse and their humus layer is thin (less than 3 inches?).

In essence, they may be considered as areas of mineral soils.

Tidal sand flats are practically always devoid of vegetation. This is the combined result of a coarse, inactive soil fraction, relatively strong current or wave action (to be competent for the transportation of coarse sediments), and generally shifting channels with associated deposition and erosion that tends to provide a poor environment for stable organic development. Tidal sand flats are relatively rare, being largely confined to areas near the sea mouths of heavily loaded streams and rivers from such mouths, in coastal indentations, behind points, etc. Tidal sand flats may be considered as areas of mineral soil. Figure 15-12*b* shows, contrarily, part of an immense area of tidal flats.

15-8. Aerial-photographic Characteristics of Organic-Mineral Complexes Formed in Fresh-water Lakes, Depressions, and Basins. The dominant photo characteristics of these deposits are their depressed position (obviously) and their flat surface.

Sizes and shapes vary. The deposits may cover many square miles or be less than a few hundred square feet in extent. Shapes may be virtually of any kind. Consequent marshes and swamps have shapes that are conditioned by the topography of the enclosing materials. Sag-and-swell marshes and swamps, kettle muck pockets, muskeg areas, and lake-bordering swamps may also have any shape, although the kettle muck pockets tend to develop smooth subcircular shapes because the melting ice tends to assume a mass having minimum surface area (Chaps. 12 and 13). Certain types of depression occurrences have shapes that indicate their geomorphic history (Sec. 15-4 and figures in Chaps. 9, 10, and 11).

The "drainage" pattern also varies. Most depression swamps are completely devoid of visible drainage channels. The occasional exception occurs if the depression has an outlet; or drainage-flow channels may be visible around the higher, outer edges.

Erosion features are, of course, completely absent.

Gray-tone patterns are an exceptionally interesting characteristic of depressed organic occurrences. At the same time, they are a variable one. In many cases, the grays are almost even-toned, but in an equal number of cases, they display zonation or "scrambling." In the majority of cases, tones are darker than in the enclosing materials, but frequently purely organic deposits are quite light, probably because of different vegetative covers and depths of water (Sec. 15-10). In some cases, the tones are very dark. In other cases they

[3] A generalized section, based upon the author's experience in humid climates, would probably show a thick (6- by 12-inch) tough mat of partially decayed organic remains having the capability of supporting a man as well as other light unit loads. Beneath this mat there would be from 3 to 8 or 9 feet of greasy, black, indistinguishably intermixed organic humus, clay, and silt heavily charged with water and having such little supporting capacity that a posthole auger could be pushed through it with little trouble. Beneath this layer would be a layer having increasing amounts of mineral content until clean bottom was reached. The entire thickness of organic layer, under normal conditions, would probably not exceed 15 feet. Under conditions of gradual submergence, greater depths (exceeding 50 to 100 feet) might be found, and under conditions of isostatic and geomorphic fluctuation, organic layers might be interspersed with beach sands, gravels, etc.

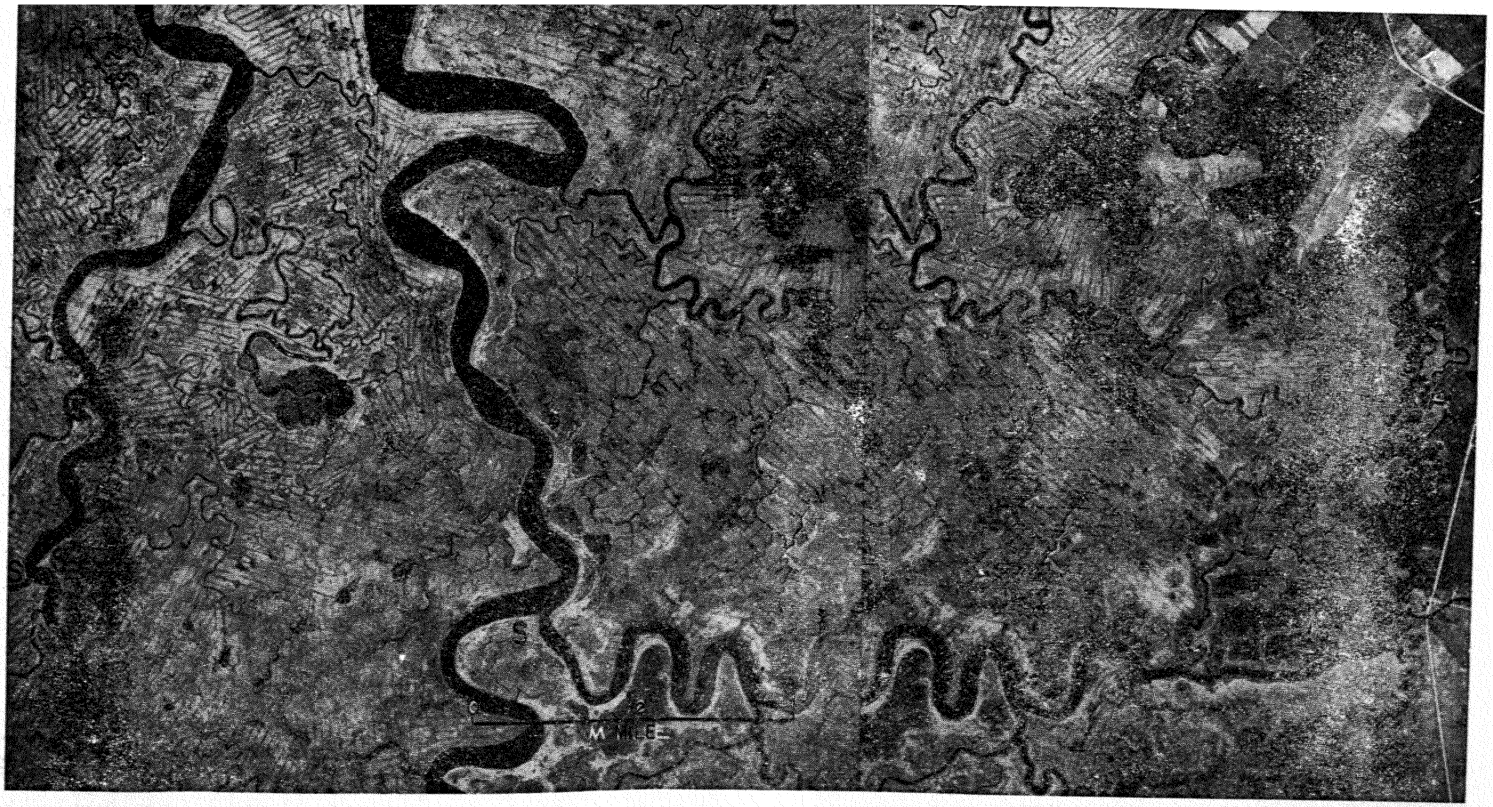
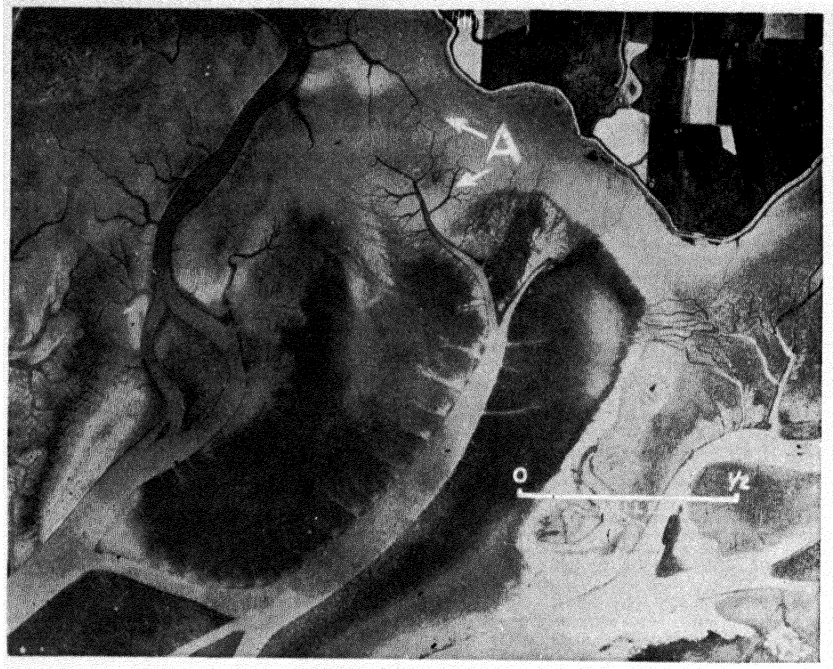


Fig. 15-10. This fine stereopair of a tidal-marsh area shows many of the typical characteristics associated with such areas. These include the "irregularly uniform" thickness of the tidal inlets with anomalous constrictions at the bends, absence of point bars at meanders and oxbows O, sharp cornered intersections S, islands I, extremely complex tonal patterns, etc. The straight lines indicate unsuccessful attempts at drainage and mosquito control. (*New Jersey. Aero Service Corporation.*)



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(b)

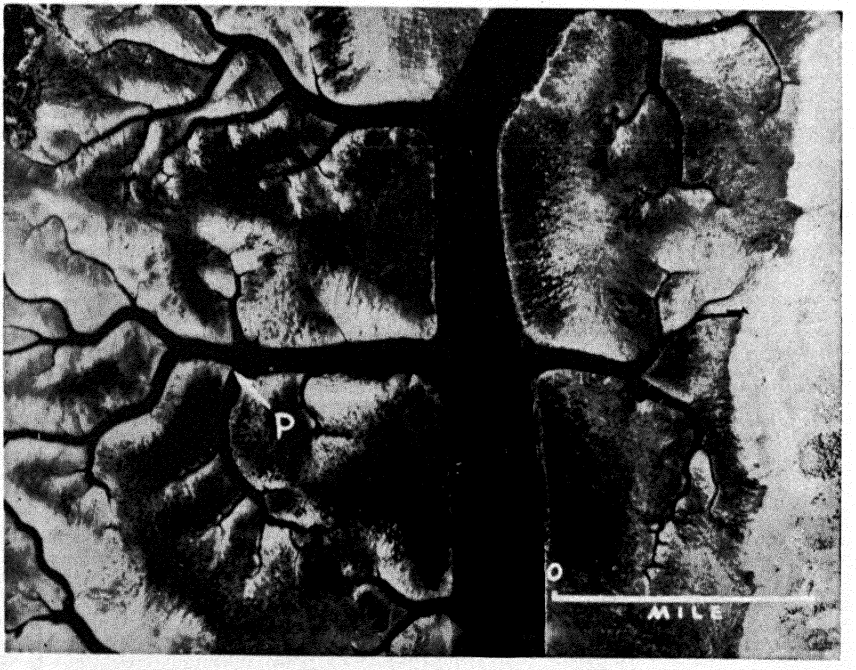

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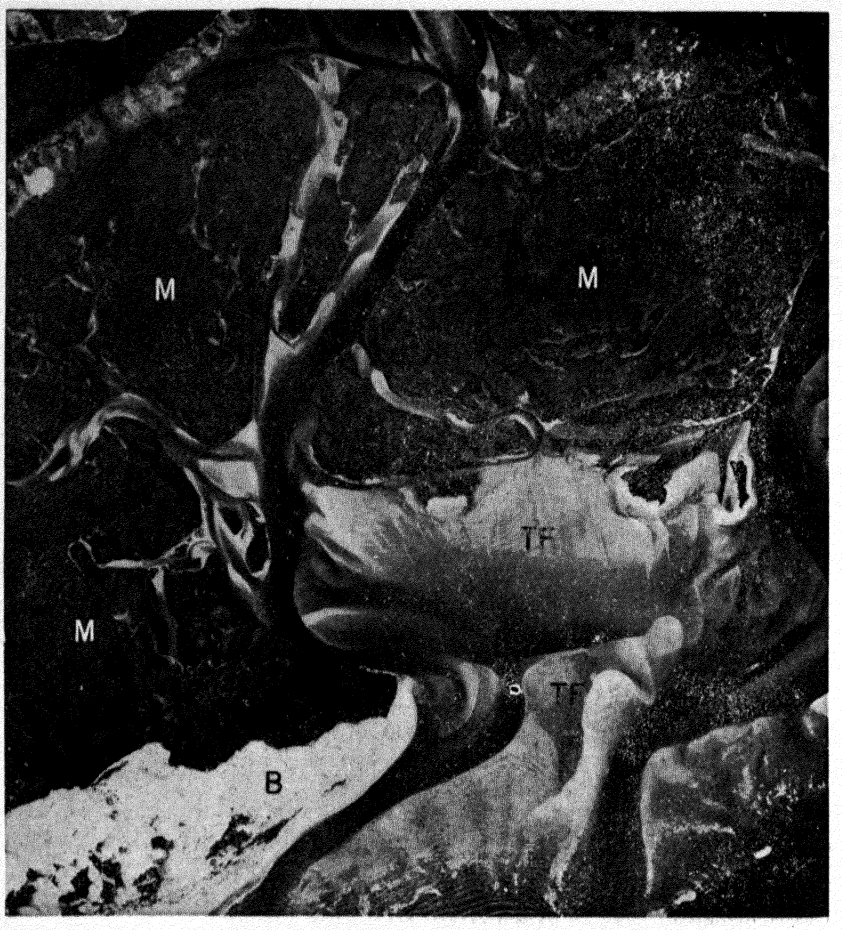
Fig. 15-11. Several single views of tidal flats, showing many characteristic features. Tidal flats developed in fine-grained materials are shown in (*a*) and (*b*). The tonal changes indicate low, young vegetation. Note the hairlike channels at *A* and the sharp break at *P*. Granular tidal flats with their typical runoff swales are shown in (*c*), and a broad expanse of limy sands and muds that are periodically inundated by tides is shown in (*d*).



(c)



(d)



(a)



(b)

Fig. 15-12. A fine view of granular tidal flats *TF*, tidal marsh *M*, and coastal beaches *B*. A low oblique of fine sandy flats with their runoff channels visible in the background is shown in (*b*). The running figure is a somewhat annoyed polar bear. [(*b*) *D. R. Lueder.*]

are quite a light gray. An important aspect of tonal qualities is the frequent impression that they have a "furzelike," or velvety, texture.

Vegetative cover is an identifying criterion for organic deposits. If the deposit is a swamp, it will have tree and brush cover by definition. If marsh, it will have grass cover with the textures and tonal patterns mentioned above. The so-called "quaking-bog" condition may often be identified, if it is in process, by the fact that it surrounds open water having an oval shape.

Depressed organic deposits are seldom typified by land-use patterns; rather, the lack is characteristic. However, they are occasionally developed for truck farms and frequently show evidence of attempts at drainage and mosquito control. In certain areas of the world they have been exploited for peat.

Occasional special features of depressed organic occurrences in the northern latitudes are polygonal developments (Secs. 4-25 and 18-32), mounds, and other thermal mass-wastage features (Chap. 4).

Figures 15-2, 15-3, and 15-5 illustrate the aerial perspective of depressed organic occurrences. Illustrations in Chaps. 9 to 14 and 16 show other occurrences.

15-9. Aerial-photographic Characteristics of Organic-Mineral Complexes Formed over Flat to Gently Sloping Land. For sheer extent and geographical significance, these deposits are the most important of all. They extend across northcentral Canada from Quebec to British Columbia (including the "tundra"); across Siberia, Russia, Finland; across the Everglades, Okefenokee, and large parts of the Atlantic Coastal Plain in the United States; over substantial areas in central and eastern South America, Africa, and certain parts of southeastern Asia.

These organic-mineral complexes are characterized by wide expanses of predominantly flat land that nevertheless display actual and seeming relief features of the fourth order. Shapes and position with respect to surroundings are rarely significant, though occasional broad depressed phases do occur.

The actual relief features may consist of hummocks and mounds, ridges, rocks, and boulders, peat plateaus, pond margins (both sloping and abrupt) and ponds (Fig. 15-4), and thermal features such as polygons, pingos, etc. (Sec. 4-25). The seeming relief features usually reflect differences in the height of low- to medium-growing vegetation. Since these differences are often coincident with channels and zones of varying water depth and sluggish velocity, they may be quite annoying and even confusing.

Practically all organic-mineral complexes developed in flat to gently sloping areas display some type of surface-drainage pattern. This may consist of visible stream channels or vegetated zones of differential water velocity and/or depth. Practically all shapes of streams occur, but those having linear or geometric characteristics may be expected to reflect underlying conditions rather than organic accumulation. Stream patterns are predominantly constructional in nature (densely to widely anastomose or braided), but other random, poorly integrated, nonuniform, unoriented nonangular patterns occur (Chap. 3).

Erosion features (except those of a thermal mass-wastage nature) do not occur.

Gray tones, like those for depressed organic accumulations, are exceptionally variable in range and pattern.

Vegetation is also variable. However, it generally covers the entire expanse of the organic material and frequently is arranged in zones or patterns that probably reflect variations in the depth, consolidation, fibrosity, etc., of the organic and mineral accumulation, as well as difference of water depth and velocity.

Figures 15-6 to 15-8 illustrate several manifestations of flatland swamp occurrence.

Radforth (151) has recently spent considerable time and effort investigating the photo patterns of various flatland organic deposits in the northcentral areas of Canada and has begun to develop both a classification of patterns and an analysis of them with respect to the practical characteristics (access, bearing capacity, drainability, climafrost, etc.) associated with them. At the moment, Radforth's small-scale patterns (smaller than 1:20,000 and up to 1:60,000) (Fig. 15-9) have not been evaluated. However, they have provided a start. His large-scale indications and patterns (1:300 to 1:1,000) have received more field verification and study and show real promise and applicability as indicators of terrain conditions. Without doubt, these early steps will lead to an ever-increasing knowledge of organic-mineral complexes.

Additional photographs of flatland marsh and swamp appear throughout this book, particularly in Chaps. 11 and 14.

15-10. Aerial-photographic Characteristics of Tidal Marshes and Flats. Tidal marshes and flats usually exhibit striking air-photo patterns, yet these patterns are based almost completely upon location, drainage pattern, and tonal pattern. Topography is flat, shape insignificant, erosion absent, and vegetation indiscernible or of no moment.

Tidal marshes are invariably in contact, at one point or another, with a body of water that presumably is capable of experiencing tidal variations. The body of water may be the sea, a lagoon, an estuary, a river mouth, or a river. Mainland boundaries are, of course, always higher and may be formed of any material. Tidal flats have a *penchant* for occurring near—and downcurrent from—river mouths, particularly if headlands, spits, and bars protect such areas.

The "drainage" pattern of a tidal marsh area is very striking and unmistakable. In reality, it *appears* to be the result of alternate tidal forcing and draining, rather than a true surficial drainage pattern. The channels are wide (particularly at their foot ends) compared to their length and may either taper or remain semiuniform throughout their course. They are characterized by numerous, unrelated sharp bends and "meanders." Two or more channel systems *may intersect*, creating irregular islands. Junctures between channels tend to be right-angled and are generally characterized by one sharp point.

The drainage pattern of tidal flats may be more of a true runoff pattern than that of the tidal marsh. Vegetation, and consequently its constricting effect upon tidal pressure, has not become established. The tidal-flat pattern therefore seems to have some reasonable shape. In fine-grained flats, it is semi-treelike, usually with fine channels. In coarse deposits it tends to consist of subparallel, broad, ill-defined runoff troughs.

The color patterns of tidal marshes vary, but are *usually* nonuniform to mottled to erratic, with a moderate to high range of tonal values. The author has found, by considerable field work, that these tones do not reflect any of the factors discussed in Chap. 5 except *surface texture*. In the particular case of tidal marshes, the texture is a function of very small differences in type and height of vegetation combined with minor differences in the height of water (see Chap. 22 for possible ecological significance).

The color patterns of tidal flats tend to be zonal to uniform, reflecting primarily their texture and moisture content. Where they tend to become variable or erratic, vegetative accumulations should be suspected.

Most tidal marshes grade into fresh-water marshes and swamps as dry land is approached.

Figures 15-10 to 15-12*b* illustrate various appearances of tidal marsh and flat.

16 ROCK TYPES

16-1. General Discussion. In Chap. 2, primary geologic origins were discussed. It was there stated that all rocks could be described as having an igneous, sedimentary, or metamorphic origin. It was further stated that each of these origins covered a *broad variety of rock types* having generally typical, but specifically different, modes of occurrence, genesis, types of source, physicochemical environment during solidification, alteration, or deposition and physicochemical-mineralogical nature after solidification.

This chapter goes further into the matter of rock types. It demonstrates how rock classifications, based upon petrology and petrography (Sec. 7-4), inherently support the suggestion that aerial-photographic techniques can be used to aid petrologic-petrographic surveys. It attempts to illustrate and discuss the photo patterns of some rock types as there is knowledge of them at present. It also discusses some miscellaneous aspects of rock identification.

Only a little work has been done on the true photo patterns of specific rock types. Because of this, the illustrations and discussion of the photo patterns exhibited by various rocks are brief, general, and tentative or suggestive, rather than final or authoritative. They should be examined with particular interest and discrimination. This should lead to an appreciation of the amount of work that must be done before true rock photo patterns may be systematized, even in a general way.

16-2. Rock Classification. Geologists, petrologists, and petrographers have, since the early beginnings of earth science, been gradually evolving an acceptable system for the complete, accurate, and universal classification of rock types that will be suitable in both field and laboratory.

Although much progress has been made, it is safe to say that, at the moment, no such system is universally accepted. This situation, the correction of which would seem to be a major preoccupation of the world's geologists, has real and valid causes.

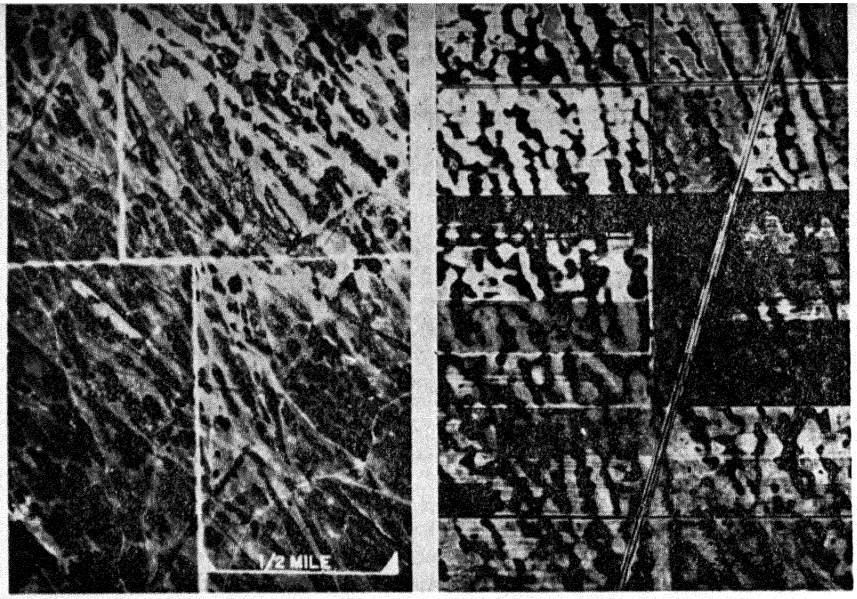
The first cause is related to the variety of factors that must be considered in any rock classification covering the thousands and thousands of rocks making up the earth's crust.

The second cause is related to the fact that field petrological classification takes great note of occurrence, is completed rapidly, and uses simple methods and inexpensive equipment, while laboratory petrographical classification ignores occurrence, is completed slowly, and uses painstaking methods and expensive equipment. As Grout (71) says:

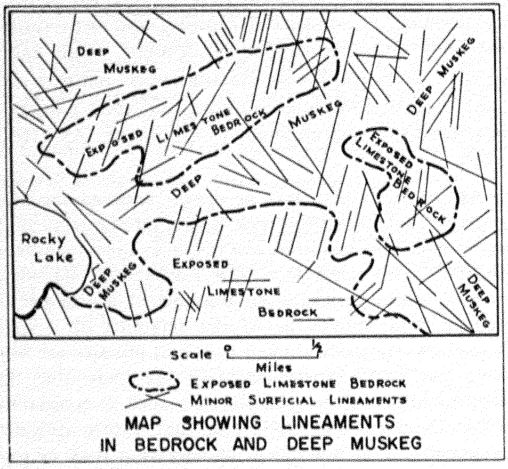
> Again, a contrast may be drawn between the field geologist, who classifies rock bodies emphasizing their occurrence and relations, and the laboratory man, who classifies hand specimens. The Rosenbusch classification of igneous rocks is an example of a scheme requiring field knowledge of the relations of a rock before classification, though in actual practice all who have had much experience in its use know that the determination of the relations of a rock is commonly left to the unreliable supposition that texture indicates occurrence. This practice of classifying a rock by one scheme when field information is available and by another scheme, using the same names, when only laboratory data are available is not to be recommended. The truth is that most petrographers who name rocks according to the geologic or field basis are using, unconsciously perhaps, two or more classifications.

The third cause is related to a lack of reliable, detailed, and widespread enough information on rock types, both in the form of laboratory data on samples and field data on physical, petrological, environmental, or historical occurrence.

Because of the lack of a system, however justified, much confusion has been caused within the geological field in general and geological mapping in particular. Controversies have been constantly in progress regarding alleged mismapping, misclassification, and misinterpretation. These controversies, while revealing many problems, have had


1/2 MILE

(a)


Deep Muskeg
Exposed Limestone Bedrock
Muskeg
Deep Muskeg
Exposed Limestone Bedrock
Deep
Rocky Lake
Deep Muskeg
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Scale
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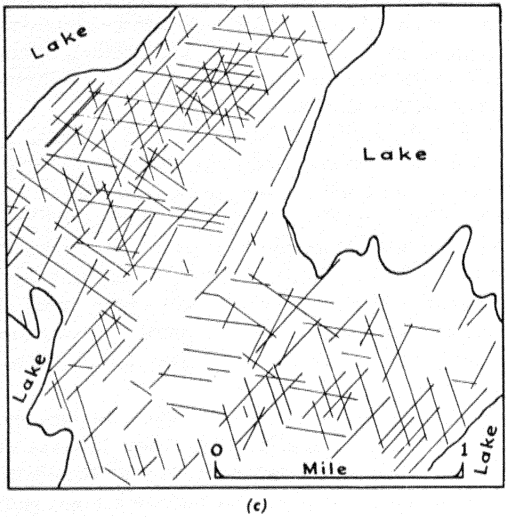
Minor Surficial Lineaments
MAP SHOWING LINEAMENTS IN BEDROCK AND DEEP MUSKEG

(b)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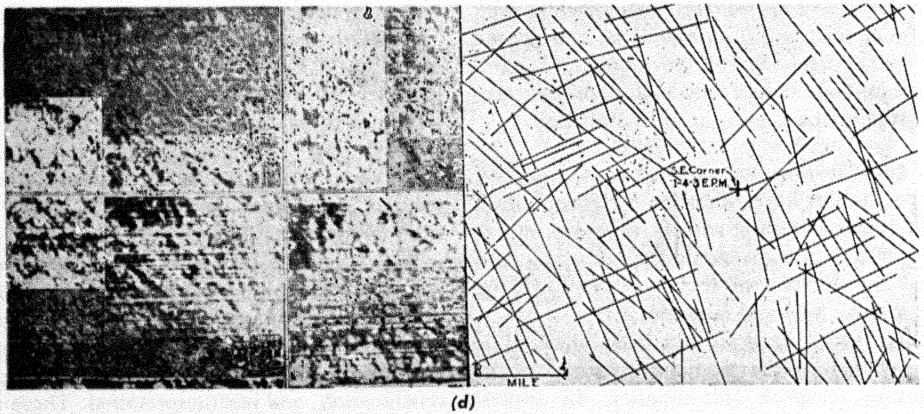
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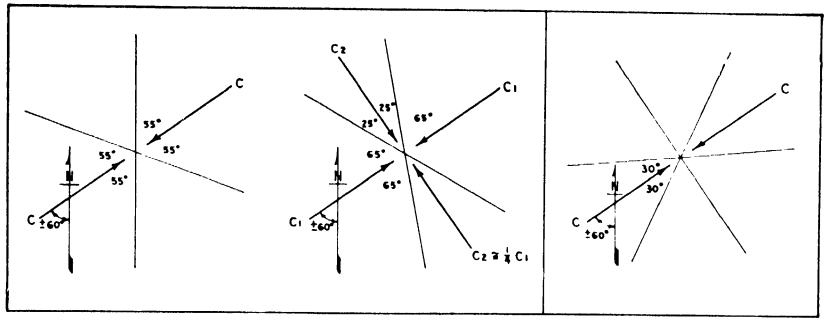

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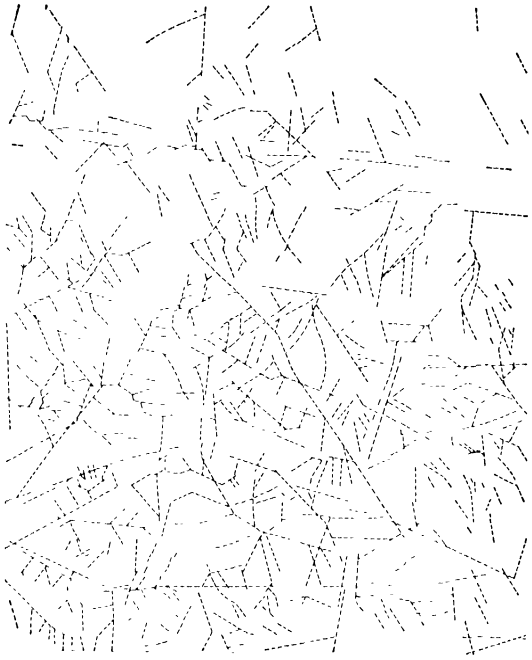


(f)

Fig. 16-1. Several aspects of fracture patterns are illustrated. (*a*) *Left:* Intersecting lineaments on a shallow mantle of wave-eroded glacial till overlying horizontally disposed Paleozoic limestone and dolomite rocks. In places the bedrock outcrops. *Right:* Similar in pattern, the lineaments occur on 50 feet of highly plastic glacial-lake clay overlying till; the depth to Paleozoic bedrock is about 200 feet. Although 100 miles apart, both photos show the floor of old glacial Lake Agassiz: the left photo shows the wave-eroded portion; the right, an area of deep glacial lake deposition. (*b*) A tracing made from an aerial photograph showing an area north of Namew Lake, Saskatchewan. Individual lineaments can be traced across locally exposed Paleozoic bedrock plateaus, down surrounding steep escarpments on which several beach ridges are superimposed, thence into deep muskeg. (*c*) Lineaments (probably joints) on exposed limestone outcrop, vicinity of Cedar Lake, Manitoba. This fracture pattern was traced from contact air photos. (*d*) The air-photo pattern and the map produced from it closely resemble fracture patterns developed in a sheet of floating sea ice by oscillation of the ocean surface. (*e*) *Left:* Preferred direction of flow lines in the rigid crust for unilateral compression C (calculated for the glacial Lake Agassiz region, south of Winnipeg, Manitoba). In western Canada, linear elements in the drainage and conjugate sets of dominant surficial lineaments very commonly intersect at or near 110°. *Center:* Similar diagram to left but for the condition where a small compressive force C_2 (about one-fourth that of C_1) acts perpendicular to C_1. For C_2 roughly equal to $1/5C_1$, the enclosing angles around C_1 would be about 60°. *Right:* Diagram showing the directions of multiple-conjugate-plane parallel vertical fractures for the condition of elastic failure of near-surface rocks, following Mohr's theory. Assuming an angle of internal friction of 30°, the angles between C and the enclosing vertical fractures are 45° (30/2), or 30°. Fractures dipping under 30° with the surface may also arise perpendicular to C. (*All diagrams after P. P. Bijlaard.*) Whether there is a single break or a multiplicity of breaks depends on certain physical properties, particularly the abundance of weak points at which failure might occur (28). [(*a to e*) *J. D. Mollard.*] (*f*) This figure shows the amazing number of linears (Sec. 19-9*a*) mapped by means of aerial-photographic interpretation. The area covers one 7.5-minute USGS quadrangle (approximately 60 square miles). Note the intriguing and varied patterns of persistence and secondary fracturing, as well as the semicircular pattern near the bottom that outlines a circular rock structure even farther down. Analysis of a pattern such as this would be a challenge to the theories of stress analysis of, for example, thin shells. (*United States. Geotechnics and Resources, Incorporated.*)

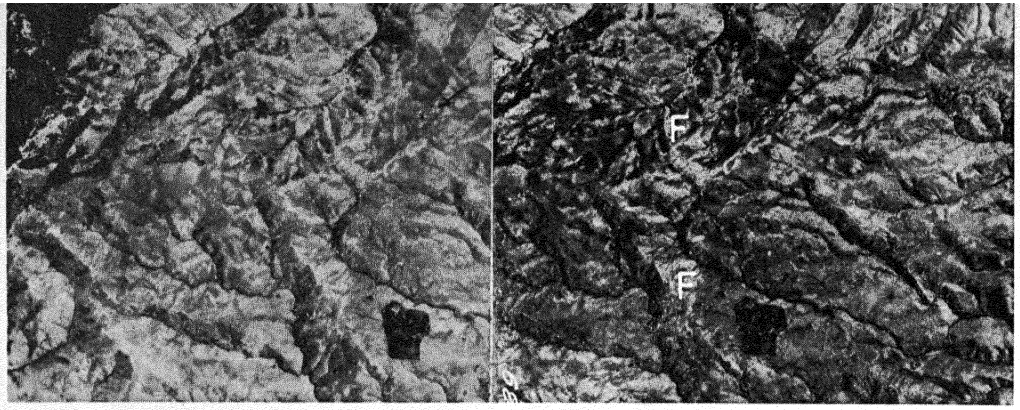


Fig. 16-2

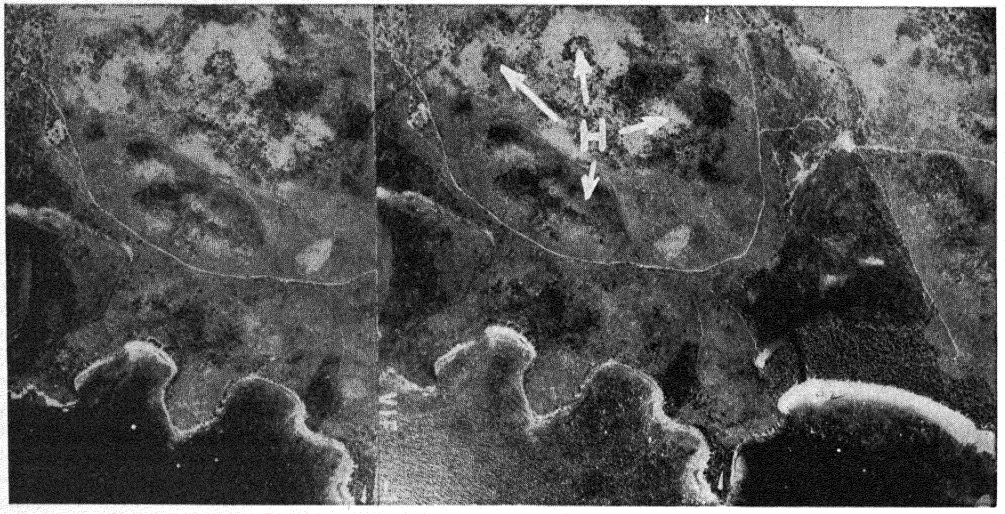


Fig. 16-3

Figs. 16-2 and 16-3. Two stereopairs show some features characteristic of granitic rocks. Note the generally light tones, the tendency to assume a large-scale dome shape characterized by numerous smaller convex slopes and hills *H*, the fracture lines *F* (subdued in Fig. 16-2), and the generally smooth surficial texture. The figures were originally chosen and annotated by the Cornell group (43). Figures 19-6, 19-8, 19-14, 19-16, and 19-17 also illustrate various aspects of granitic rocks. (*Idaho, Puerto Rico. U.S. Department of Agriculture.*)

the net effect of slowing the evolution of a universal classification system. Meanwhile, mapping has gone on, at an ever-increasing rate, and since no one classification has been accepted, many are used. The result is a compounded condition of the initial confusion.

Regardless of these general and unfortunate trends, petrological-petrographical classification *has* progressed, or at least changed. Certain methods have had, and still enjoy, wide acceptance. To evaluate the use of aerial-photographic techniques for the delineation of rock types, it is certainly necessary for the reader to have some familiarity with these major systems. Recommended in this regard are the works of Kemp (92), Shand (165), Mohr (131), and Grout (71).

16-3. Significant Points of Agreement and Disagreement among Various Systems (Igneous Only). Significant points of agreement can be noted among various systems of igneous rock classification, irrespective of their individualities, basic approaches, etc.

For every system, *mineralogical composition* is a *primary* element of differentiation.

For every system, the *major* minerals used in differentiation include *quartz*, the saturated minerals—*feldspars, pyroxenes, amphiboles, micas,*

etc.—and the unsaturated minerals—*feldspathoids, olivine.*

For every system, the *color*—or at least the proportion of colored minerals—is considered important.

For almost every system, *mineralogical texture* is considered important. It might be mentioned that Shand's system of crystallization is much simpler and broader than that of Kemp, consisting of two classes rather than six, while Mohr's consideration is transitional and related to genesis.

Every system includes some attention to the *relative amounts of the various feldspars.* Some use a simple majority between orthoclase and plagioclase (andesine, labradorite, bytownite). Some place quantitative limitations on the amounts of silicic (orthoclase, albite), medium (andesine), and basic (labradorite, bytownite) feldspars. Shand objects, quite reasonably, to the inclusion of the orthoclase-plagioclase comparison. He says (165), "But since 'orthoclase' or 'alkali-feldspar' (acidic) includes varieties that are rich in soda, and 'plagioclase' means anything from pure soda-feldspar to pure lime-feldspar, the practice referred to is not good chemistry; and since soda appears in both terms of the ratio, it is not even good arithmetic." Shand therefore differentiates upon the basis of pure components, $KAlSi_3O_8$ (orthoclase), $NaAlSi_3O_8$ (albite), and $CaAl_2Si_2O_8$ (anorthite) (Sec. 16-5). Mohr's system simply uses the relative proportions of silicic acid and their implied associations with the various feldspars. None of these differentiations, with the possible exceptions of Kemp's, are easily distinguishable without a microscope.

Beyond these points, the systems diverge to a certain degree. Shand places considerable emphasis on the ratios between the molecular proportions of alumina and those of soda, potash, and lime. These proportions cannot be seen visually in hand specimens, but then Shand's system is not intended for such use. None of the other systems include any consideration of this factor, except in a broad and approximate way via the above-mentioned orthoclase-plagioclase comparisons. Such comparisons, with the possible exception of Kemp's, are also usually difficult to make in the field.

Some systems neglect mode of occurrence completely. While this may have some justification from a petrographical standpoint, it has little from the practical standpoint of mapping rocks *in situ.* Other systems pay some attention to mode of occurrence, or at least genesis, and it seems apparent that a classification which accepts the generality that certain types of rocks, textures, etc., *tend* to occur in connection with certain forms and at usually different depths, is certainly not on the wrong path. In this respect the quotation in Sec. 16-5 is of interest.

Mohr's system pays some attention to the mass

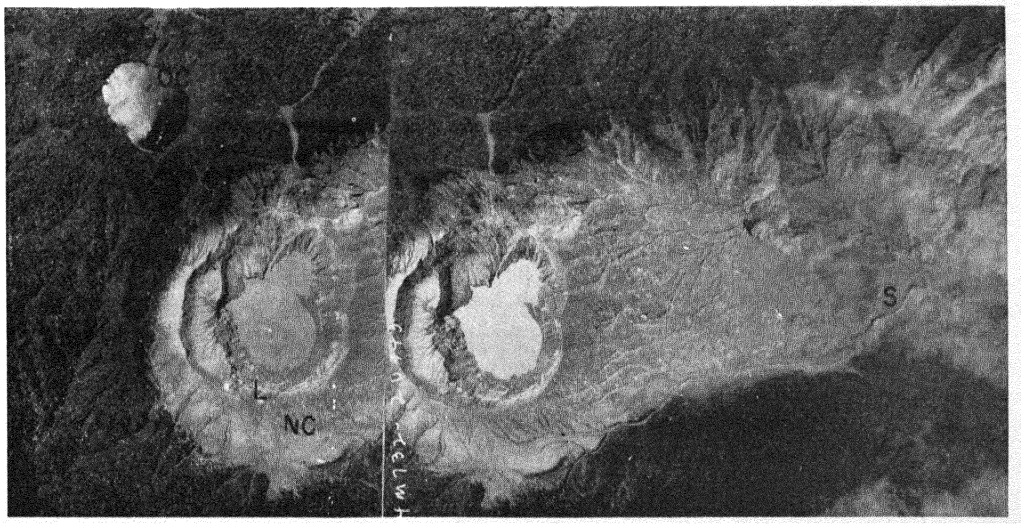


Fig. 16-4. A stereopair showing a volcanic cone. This shows an old crater OC and a new crater NC formed at lower elevation. Note also the jagged strata that appear in the crater and the flow drainage pattern, which is beginning to assume a sicklelike shape S. This particular flow is light in tone.

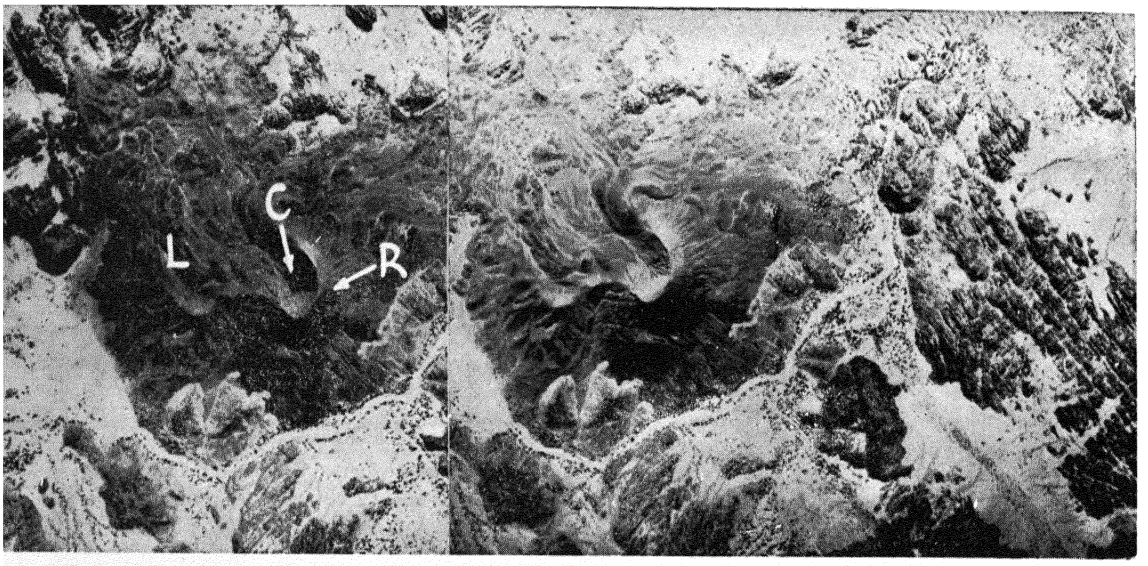


Fig. 16-5. A stereopair showing a volcanic cone. This shows a crater C and small flow L of very basic dark-colored lavas, surrounded by rock outcrops of basic rock. Note the radial drainage R. (*Africa. U.S. Army.*)

textural nature, or density, of the rocks by showing a transition from the pulverized (and reaggregated by cementation, presumably) state to the solid state. None of the other systems give consideration to this factor, which has significance to interpretation.

16-4. Possible Value of Aerial-photographic Interpretation to Petrologic-Petrographic Survey. Some years ago (1953) the author presented a research proposal to investigate the use of aerial-photographic techniques in surficial petrologic-petrographic mapping. The initial research subjects included:

1. The differentiation of broad petrologic-petrographic rock types by means of aerial-photographic interpretation
2. Investigation of the relative values of different photographic scales in petrologic studies
3. Investigation of the value of filters and color photography in such studies

In support of the feasibility of research for these purposes the following brief comments were offered:

1. Rocks, particularly those of igneous and metamorphic origin, show a great variety of characteristics within one class or one occurrence. These rocks are differentiated by petrologists and petrographers on the basis of mineralogical composition, physical characteristics (texture, color), and occurrence. This differentiation is done by field and laboratory methods. Yet, there is much justification for broad separation of rock types by means of aerial survey. Because of variations in dominant mineral and physical composition, rocks may be expected to have different responses to weathering that will be reflected by differences in landform, detailed surficial texture, drainage pattern, fracture and weathering patterns, erosion details, weathering colors, vegetative types, etc. . . . Further, rocks are generally light- or dark-toned; often have typical ranges of colors; and occur in typical manners. It is believed that adequate research based upon the air-photo examination of numerous deposits would do much to aid in the differentiation and identification of many major rock types.

2. Research on scales is badly needed. No one has yet made a thorough study relating the information to be gleaned from the aerial photographs in various climatic regions, and at various seasons, with the scale of the photographs.

3. Filters may provide a promising field for determining rock types. In addition to standard filters, filters utilizing actual mineral pigments can be constructed. It may be possible, therefore, to look for given indicator plants, rock types, indicator and mineralization colors by examining color photographs and negatives through filters that will emphasize the particular plant or rock colors desired. This technique might be of particular value in arid and heavily forested areas. Color photography, by itself, has re-

ceived only a little attention in geological reconnaissance. Its use in detecting and examining outcrops, gossans, and alteration halos would appear to be of tremendous value.

The actual and implied content of this research proposal seems as applicable today as it did when submitted. The proposal may be rephrased as a hypothesis: Inasmuch *as different rock types are composed of different mineral mixtures having different typical surficial textures, chemical composition, crystallization types, specific surfaces, intercrystalline bonds, and intercrystalline qualitative and quantitative reactions to the agents of weathering;* and inasmuch as *these differences in rock types also tend to be related to depth of genesis and mode of occurrence;* then *massive assemblages of such rock types, i.e., rock bodies, having dominant types of mineral mixture, should have typical mass reactions to the agents of weathering and typical mass appearances in terms of form, structure, drainage, tone, erosion, etc., which should be broadly discernible and separable on aerial photographs.*

Of course, the above hypothesis is intended to be general and admits of numerous specific exceptions. Nevertheless, there is considerable justification for the hypothesis as a whole. The following sections discuss this.

16-5. The Weathering of Rocks. One key point of the preceding hypothesis has to do with variations in the weatherability of various minerals and mineral mixtures, i.e., rocks. Fortunately, there is a reasonable amount that can be said about differential weathering. To begin with, geologists and geomorphologists have long recognized the existence of rocks having superior and inferior resistance to weathering. They have expressed this in terms of rock hardness, competence, density, etc., as well as practical terrain effects related to ridge forming, waterfall sites, mountain "parks," etc.

Secondly, the concept of differential rock weathering is soundly embedded in personal experience and observation, while the concept of differential mineral weathering appeals to both logic and intuition.

Thirdly, there is the comment of many earth

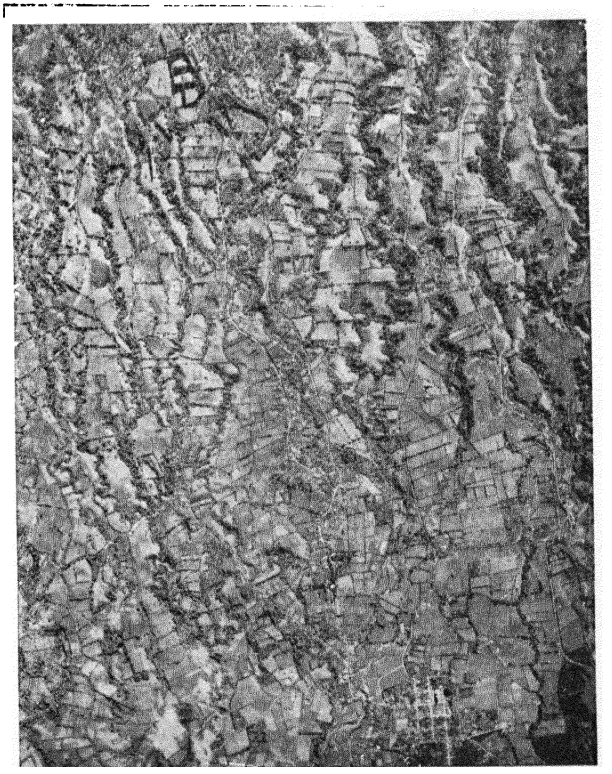


Fig. 16-6. This single picture shows the soft, residually weathered textures, uniform gray tones, intensive cultivation, fairly accordant surface, and typical parallel *constructional* drainage pattern typical of a lava flow. (*Central America.*)

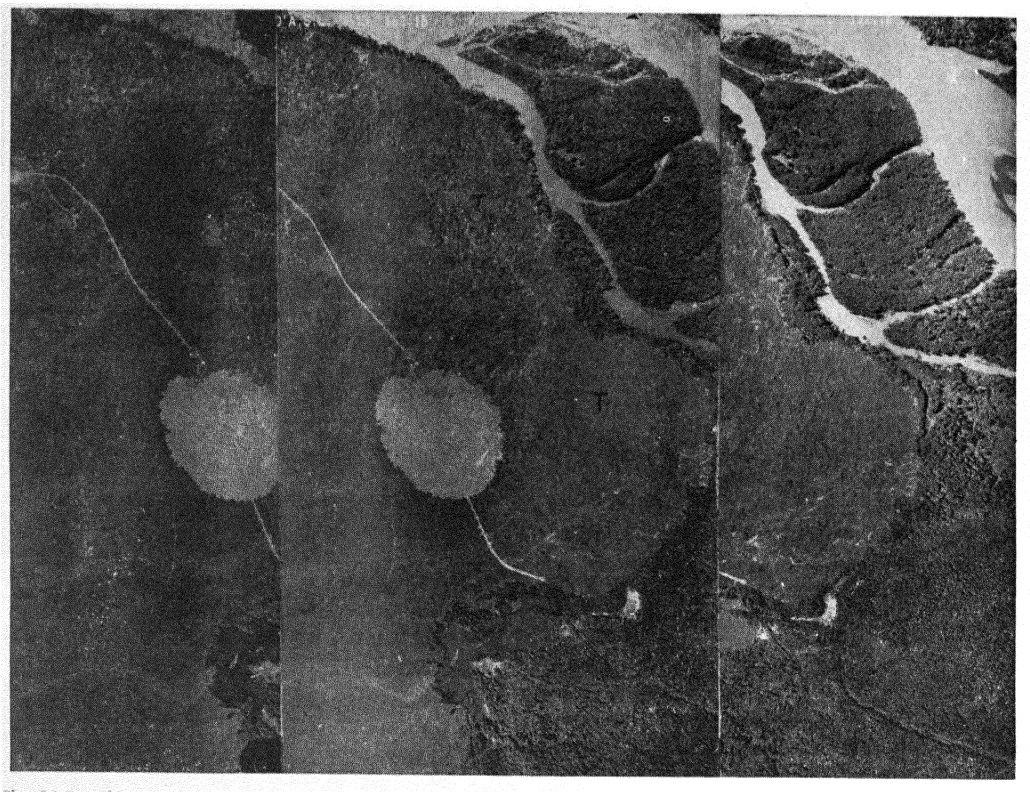


Fig. 16-7. This stereo picture shows a fine example of an effusive flow. Note the low terminus with its blocky, vesicular texture *T*. Behind this are the more viscous phases of deposition with well-developed flow-line patterns. The flow is covered with low scrub except in the center where a small fire has removed it. (*British Columbia. Photographic Survey Corporation.*)

scientists such as Rankama and Sahama (152*a*), Joffe (85), Jenny (84), Merrill (127*a*), Mohr (131), and others. Of all these, Mohr's comments are most pertinent to the subject of this chapter.

Mohr, in preparing his classification of rocks (Sec. 16-6), had a definite objective in mind, namely, that of providing a reasonable basis for the study of tropical soils. Because many tropical soils are the residual products of deep and intense weathering, Mohr had to pay considerable attention to the "weatherability" of various rocks so that he could properly evaluate the pedological effects of parent material as opposed to age of parent material, length of weathering, topographic position, and importance of biotic factors (Sec. 7-9).

Mohr's initial comments on rock weathering deserve the attention, if not of all earth scientists, at least of interpreters.

Now this [aforementioned (Sec. 16-3) mineralogical] difference also stands out clearly in the *weatherability of the minerals.* Quartz practically does not weather at all. Potassium feldspar weathers with much more difficulty than the calcium-sodium feldspar; the latter weathers more rapidly, if the calcium/sodium ratio is high. In the series of dark minerals: mica, hornblende, augite, hypersthene, and olivine the weatherability increases from the first to the last mineral. Dark iron-rich glass weathers much faster than colorless glass. In short—practically all the *mineral components of the rocks poor in silicic acid weather faster than those of the rocks rich in silicic acid.*

This will be seen to have many consequences in soil formation. For example, we know that the rapidly weathering rocks will give rise in a relatively short time to a soil upon which vegetation can develop, which, in turn, has a great influence upon the further course of weathering. Under tropical rains the weathering precedes the erosion and the chemical leaching out. On the other hand with rocks which

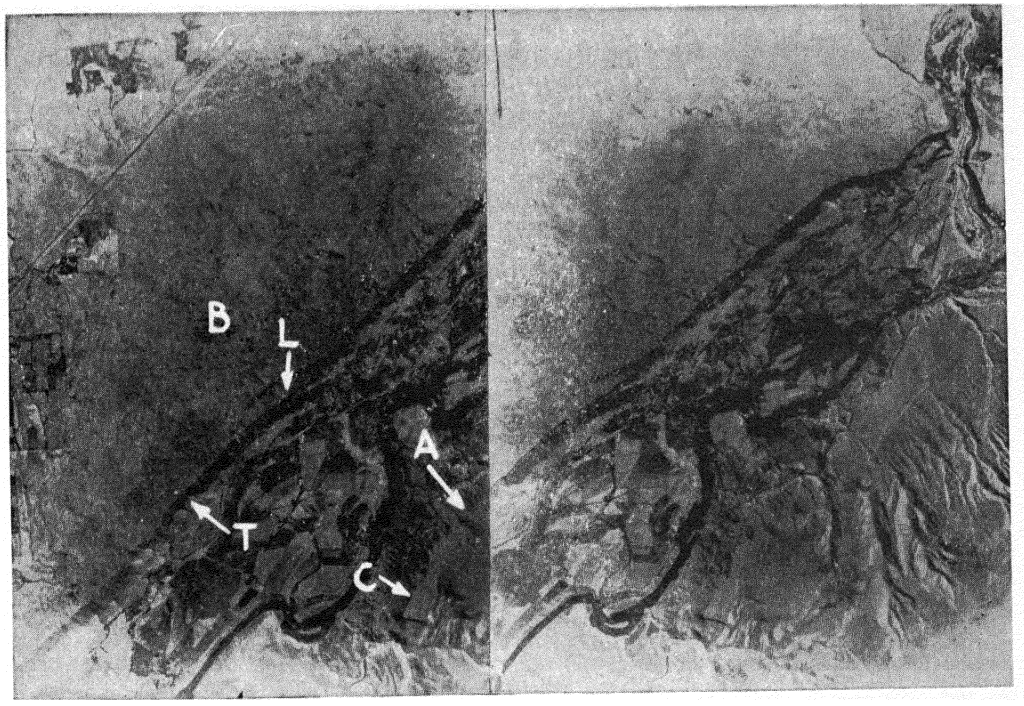


Fig. 16-8. Another example of an effusive flow. Note the edge and surface of an extensive basaltic flow *B*. Very close inspection reveals evidence of columnar structure along the scarp. The bottom of the cliff is characterized by appreciable quantities of talus *T*, while a land slippage of considerable magnitude is occurring at *L*. Note the dark basaltic tones, generally flat surface, vesicular texture, and lack of drainage of the lava surface. A remnant of flow *C* remains on the other side of the river, which is mostly composed of alluvial deposits *A*. (*Idaho. U.S. Department of Agriculture*.)

weather with difficulty, the chances are great that weathering and soil formation cannot keep up with the loss of soil through erosion and the impoverishment of the soil through leaching out, so that entirely different and less favorable conditions for vegetation must prevail. More about this later on.

At another place he said:

It is a well-known phenomenon that, whether simply in a solvent, or in a liquid which chemically attacks the molecules of the crystals, the solution of crystals takes place more slowly and with greater difficulty if the crystals are large, homogeneous and pure, than when they are small, impure and full of inclusions. One can also say that the speed of solution or attack by the solvent is proportional to the contact surface, hence when one wants to quickly dissolve crystals, he grinds them fine in a mortar, and if one brings into contact with the solvent the same material as that of which the crystals are formed, but in the colloid state, the solution takes place still more rapidly.

If we apply this theory to the rocks referred to, then the *weathering* which is caused by the water which circulates in contact with the rocks, must more quickly attack, first, the finely divided rocks—i.e., the blown-out ash, the sand and the porous pumice stone—than the hard and compact rocks; and second, more quickly attack the amorphous colloidal glass-containing volcanic rocks than the deepseated rocks consisting of massive, hard, homogeneous crystals.

Consequently, a genetic classification of the rocks according to the depth and the method of their formation gives at the same time a classification according to their weatherability. This is of great significance in soil formation.

Next he touched generally upon the weathering of minerals:

Whenever chemical weathering affects the minerals present, then it may be said that:

1. Each mineral begins to weather in its own way, independent of surrounding minerals, but depending upon the liquid surrounding this mineral: and
2. The constituents, either atoms or groups of

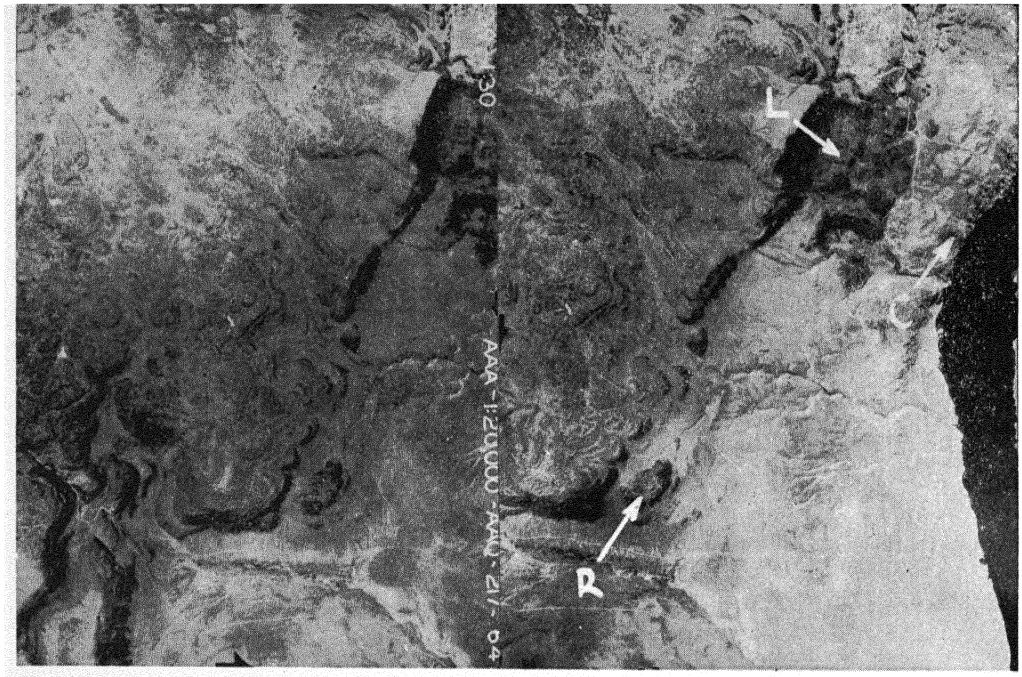


Fig. 16-9. This example of an effusive flow shows the partially eroded edge of a lava flow with an outlier *R*, land slippage *L*, and the beginnings of pear-shaped tongue weathering that is related to the shape of the boundary when the flow solidified. Note the rough stratification along the edges. The white "pimples" are aeolian materials accumulated in old blister scars. Figures 16-8 and 16-9 originally selected and annotated by T. Liang. (*Washington. U.S. Department of Agriculture.*)

atoms, once set free, then behave according to their chemical nature, and independent of the mineral from which they have been liberated. It is therefore obvious, that in a consideration of the weathering processes, one must pay attention not alone to the chemical elements, but at the same time to the mineral form in which these elements are exposed to weathering.

Finally, and delightfully, his remarks become specifically pertinent to the hypothesis of Sec. 16-4:

There are two paths open for the study of those exogenous weathering phenomena.

The first would consider the rocks *as a whole,* follow their total changes, and in conclusion would study the *kinds of soil as a whole* which originate from those rocks. In commencing a study along this line one would restrict himself to a more or less minute description of what could be observed; in a later stage one would proceed to all sorts of analyses and so arrive at more amplified conclusions. In the past, and still today, for many, this is the only useful path.

The second path proceeds from the idea that rocks are complexes of *minerals,* that these minerals, which upon weathering under the action of the weathering influences, *behave differently,* so that one has to *consider the minerals first separately,* and then go into the changes which each can undergo by itself. Also the intermediate and end products which they will give in the course of their weathering must be considered, so that it will be possible to draw an adequate picture of how the rocks weather, as well as how the soil is formed.

It may be doubted whether it is possible to choose between these two paths, that is to say, whether the one path excludes the other. More likely it should be considered that each one supplements the other, and that either one will throw some light upon the other. This is especially necessary, since *a priori* the second path promises more insight into what goes on in weathering and soil formation, but on the other hand for the second path a presupposition is made which is superfluous for the first. This supposition is that with reference to the weathering forces the minerals of a rock behave independently of each other; that each one goes its own way, provided that the environment in so far as it takes part in the weathering, remains but the same. In an absolute sense this

theoretically established premise will occur very seldom; it is only intended to express that one mineral will not influence the other *directly,* for example, in its reacting with water or air. Practically, however, this comes down to indirect influences via an environment such as water, where the diverse minerals react with it, and owing to this the surroundings are changed, as in a definite solution. This new environment can now be changed through the influence of mineral A in such a manner that it becomes different in its reacting with mineral B [and] thus an *indirect influence* of the weathering of one mineral upon another is easily imagined. But with the knowledge of physical chemistry and of colloid chemistry those mutual influences can, to a great extent, be reduced to known laws; these facilitate the construction of the composite weathering picture and place it on a known and firm foundation.

It stands to reason, and can therefore be demonstrated in the process of development of a number of sciences, that in comparison with the first, the second path wins in importance and interest. Haven't people always done that whenever it was possible, splitting a very involved and complex problem into a number of questions of simpler nature? As a rule they have even done this in spite of the fact that they might anticipate that in so doing the amount of work involved would really be more. However, in passing final judgment upon the results of such a partial investigation as here intended, we must never lose sight of the fact that even though the individual parts are placed together these do not necessarily give the whole picture. Just as a human being is still something more than the complex of the morphological, physiological, and chemical subordinate parts and characteristics which can be observed; just as even an atom is probably something more than merely a crowd of mutually related protons and electrons; in just the same way also the "living soil," considered in a broad way, is still something more than a complex of constituents, whose characteristics and behavior one can, to a certain degree, study and determine. This inspires one to caution and modesty, but should not encourage despair and inaction!

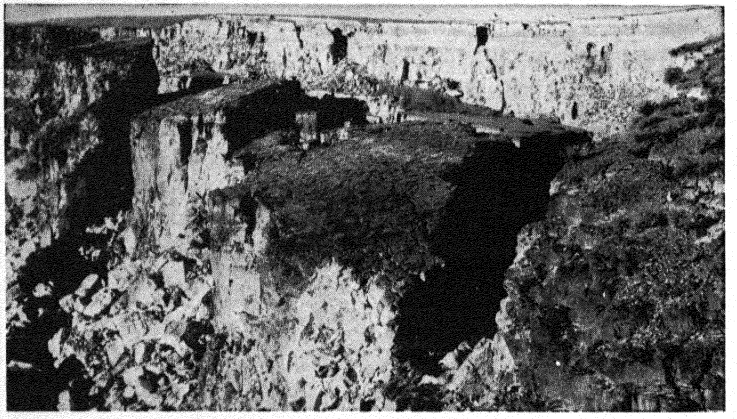
Mohr then considered the chemical weathering of individual minerals by first listing certain chemical and water weathering liquids (pure water, water containing carbon dioxide, calcium bicarbonate, sea water, etc.) having different pH values, and then considering the attack of these liquids on the minerals themselves. He concluded, for example, that quartz, chalcedony, and tridymite are extremely resistant to the attack of liquids of



Fig. 16-10. Acidic flows overlying jointed rocks and other materials. The contacts are striking, as are the flow layers in the lava, the landform, tonal differences, etc. (*Colorado. U.S. Forest Service.*)



Fig. 16-11



Figs. 16-11 and 16-12. Oblique views of a lava plateau, with its columnar edge, and a typical land slippage along such an edge. [*Arizona, Canada. RCAF (16-11).*]

Fig. 16-12

pH less than 7.0 and only dissolve slightly in liquids of pH greater than 7.0.

He then gave a long and remarkable treatment of the weathering of the feldspars. This is too long to reproduce here, but makes very interesting reading when one reflects upon its period (1933 to 1938) and the handling of the variables and complexities. In outline, he considered the various crystal lattices in which silicates occur and the direction of attack on the lattice that is followed by weathering fluids (omnidirectional—garnet; along the chains giving fibers—serpentine; along the chains giving flakes—the feldspars; and non-directional except with difficulty—quartz); the chemical affinity of sodium feldspar (albite) to potassium feldspar (orthoclase), in spite of its isomorphism with calcium feldspar (anorthite); the products of weathering of the various feldspars (orthoclase and albite yielding kaolin and free silicic acid, and anorthite yielding gels of free aluminum hydroxide and silicic acid); and the selective action of the various aqueous weathering solutions on the feldspars, resulting in a general rule that *"alkali feldspars weather much more*

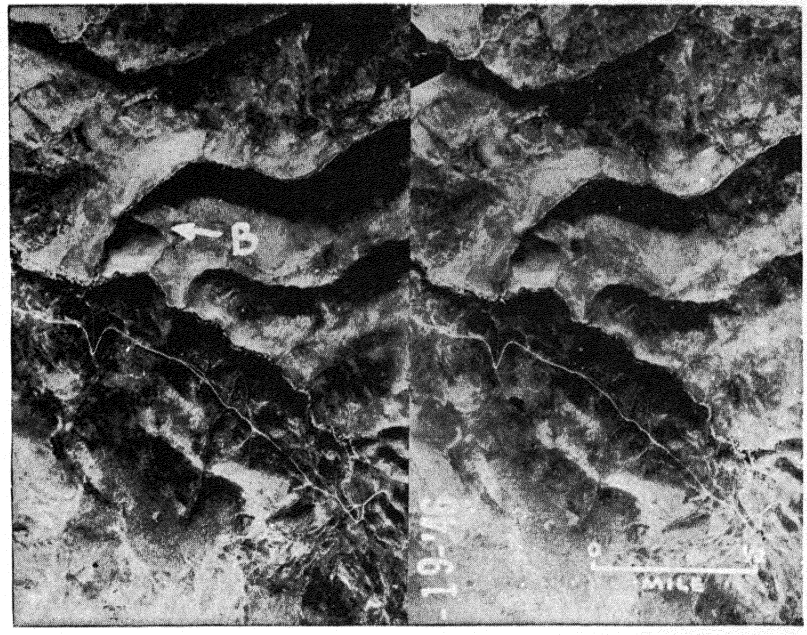


Fig. 16-13. Rhyolite interbedded with tuff. Well shown is the curvilinear parallelism of the drainage pattern. Bedding indications, as at B, are visible. (*Puerto Rico. U.S. Geological Survey.*)

slowly, and apparently in a different manner, than calcium feldspar." [1]

Mohr also considers weathering of the micas, the amphiboles, and hornblende, olivine, etc. He shows that the dark minerals possess single and double lattice chains and weather, with relative ease, to fibers, while olivine is the "most easily decomposed of all silicates in weak weathering liquids."

He also mentioned some effects related to the mass-surface texture and density of the materials:

In the weathering of natural glass there is found one peculiarity of which there was no need to speak in connection with the preceding minerals. For the course of the weathering it is very important, whether the glass is exposed to weathering in a completely massive and compact form, as obsidian or peckstone, or as a porous mass, as ash or pumice. The difference in attackable surface is extraordinarily great and owing to this a fine ash, for example, can be thoroughly weathered during a time in which the weathering of large obsidian blocks of glassy lava streams has not penetrated more than a few mm. deep. What that difference signifies for soil formation—a difference which likewise may be established in the weathering of thick plutonic rocks as granite and diabase as contrasted with the porous rocks as tuffs and limestones—will presently be spoken of more in detail under the heading of "erosion."

[1] Except in sea waters and those having a strongly alkaline reaction (limestone waters).

The sum of the remarks, not only of Mohr, but of all authors, indicates that rocks and minerals are weathered differentially; and that different minerals and dominant mineral combinations have different weatherability both specifically and *massively.*

16-6. Justification for the Applicability of the Aerial-photographic Approach to Petrologic-Petrographic Survey. The broad justification for the aerial-photographic approach is *convergence of evidence* (Secs. 1-15 and 1-16 and Chap. 8). With a number of factors visible on the aerial photograph, each of them bearing some relation to the rock type, if enough of them *indicate the same conclusion,* then that conclusion should be correct on the basis of convergent evidence, and usually is in actuality.

In terms of *igneous* rock typing, what fac-

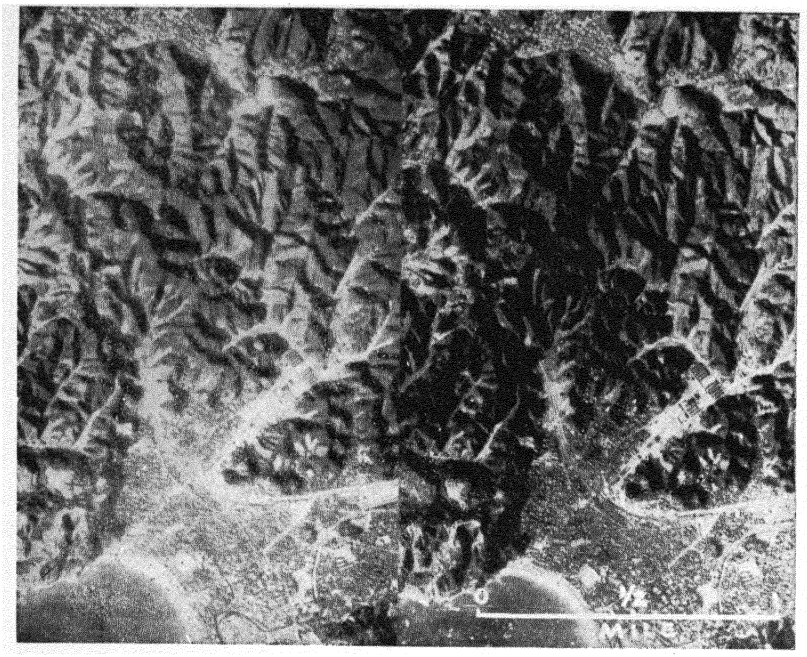


Fig. 16-14. A good stereo example of tuff in a humid-temperate climate. The uniform dense dissection and sharp-crested hills are well shown. (*Far East. U.S. Army.*)

tors are of significance? According to Sec. 16-3, they are *mode of occurrence; color; major mineral components; surficial texture; relative amounts of the various feldspars; and proportions of alumina to soda, potash, and lime.*

As explained and illustrated in Chap. 19 and as emphasized throughout this book, the mode of occurrence of rocks should be ascertainable by means of aerial-photographic interpretation. Whether the mode be sedimentary (horizontal or tilted layers, various structures, jointed, etc.), igneous (dikes, stocks, pendants, batholiths, flows, sheets), or metamorphic variations, the air photo should allow the identification of the majority (greater than 75 per cent) of modes of occurrence (Chap. 19.).

Color should also be distinguishable, even on panchromatic photos. Though certain complications are imposed by the technical, atmospheric, and other factors mentioned in Chap. 5, the color differentiation considered in current rock classifications is so elemental and broad that it should be susceptible to relatively easy separation. With the additional tools of filters and color photography (Secs. 5-22 and 19-21), color should be resolvable with fair confidence.

The above factors can be identified by direct interpretation or recognition. The remaining highly important factors must be analyzed via the medium of indirect interpretation.

The major mineral components are partially indicated by gray tone or color. For example, very light tones (integrated over the surface to avoid the effect of surface orientation with respect to the sun) should indicate a *probable* presence of quartz, feldspars, and feldspathoids and a probable absence of olivine and biotite, together with a probable deficiency of augite and hornblende. Dark tones should indicate deficiences of quartz, feldspars, nepheline, leucite, limonite, or muscovite, with probable excesses of pyroxenes, amphibole, biotite, and consequently some olivine. The pyroxene-amphibole versus quartz-feldspar tonal zones may be important combinations in this respect.[2]

There are other indicators to mineralogic composition. As discussed in Sec. 16-5, because the various minerals have different crystalline faces and compositions, they should also have different resistances to weathering. Their texture, because it

[2] Color photography, under favorable conditions, will also be helpful (Chap. 5).

is proportional to the number of interfaces, individual crystals, specific surface, etc., should also promote different reactions to weathering. The net result should be different macrolandforms, mass-macrosurface textures, drainage, erosion, and fracture patterns, etc., which would serve as bases of successful differentiation.

Quartz should be resistant, and rocks containing it as the major constitutent should be bold landscape formers and have different surface textures, e.g., quartzite, sandstone, and some quartz-silicates.

Materials containing appreciable serpentine, talc, clay minerals, some silicates, and nepheline should *tend* to be associated with softer landscape forms and have typical surface textures, e.g., clay shales, limestones, serpentinite, some quartz-silicates. Tuffaceous materials should be erodible. Certain rocks, such as lava, should have their own genetic surfaces.

These differently composed rocks should show varying drainage patterns (shale versus sandstone, slate versus gneiss or schist, granite versus basalt, tuff, rhyolite), varying densities and orientations of fracture patterns, striations, etc., and possible typical erosion forms (Chaps. 4 and 5).

Through a process of extensive and comprehensive field and photo study, it should be possible to devise an inductive and deductive, progressively subdividing system for the successful separation of broad petrologic-petrographic types.

Even if such separation cannot be definite from a mapping standpoint, it certainly can be used to plan selective field work, for if the rock types cannot be definitely identified, their boundaries (zones) and transitions can (Chaps. 3 and 19).

16-7. The Importance of Climate. It is fairly evident that climate imposes a pronounced pattern upon the weathering, and consequently the air-photo patterns, not only of soils but also of rock bodies. The effect of climate is easy to understand. It controls the nature of biotic, chemical, and physical weathering, the nature of vegetative growth, and the hydrology of the area. Some illustrations of the effect of climate upon drainage patterns in rocks appear in Chaps. 16 and 3.

16-8. Necessity for Research. The unprejudiced reader of this chapter, and this book, will have become convinced by now that aerial-photographic interpretation supplies a wonderful aid to the

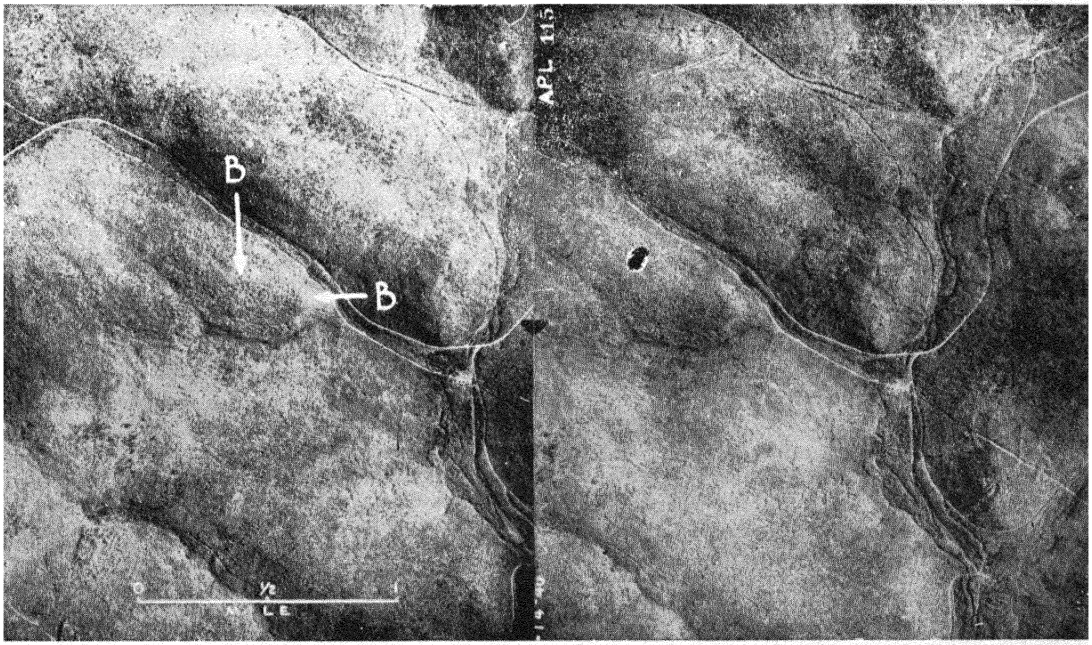


Fig. 16-15. Massive sandstone with occasional layers of sandy shale. The conformal hill summits, steep sides, widely spaced drainageways, lack of erosion, and indications of bedding *B* and the over-all light tone are well shown. (*Pennsylvania. U.S. Department of Agriculture.*)

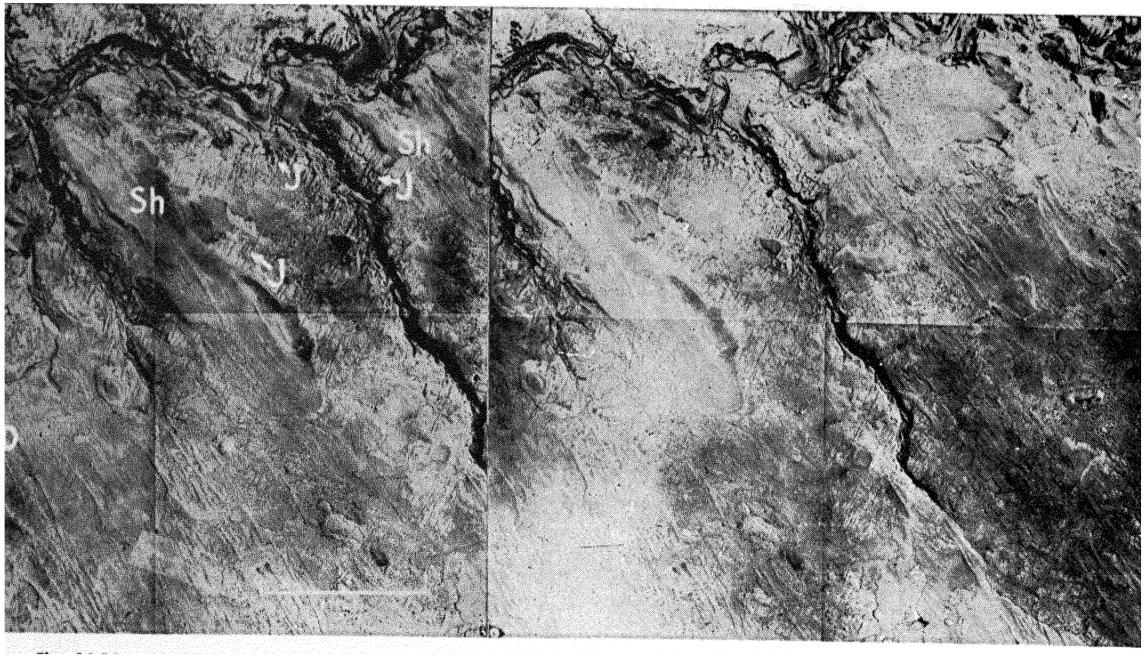


Fig. 16-16. Massive sandstone with an intricately developed joint system *J*, light tones, and lack of drainage. Dunes *D* and shale beds *Sh* overlie the sandstone. These figures were originally selected and annotated by the Cornell group (43). (*Arizona. U.S. Department of Agriculture.*)

study of various earth sciences and is, in truth, a natural science in itself (Sec. 7-23). Further, he should have accepted, tentatively but openly, the hypothesis that aerial-photographic interpretation can be successfully applied to fairly detailed petrologic-petrographic mapping, to an extent far beyond what is currently called "photogeology"—a word describing an activity that is too often indiscriminate, unorganized physiographic recognition (photo reading and photo analysis, Secs. 1-6 and 1-7), supplemented by the use of some clever photogrammetric mensurational instrumentation and techniques (Sec. 19-15).

However, even with such an acceptance, the reader must have been impressed by the many factors and variables, together with their effects, that must inevitably be considered in order to be successful in even broad petrologic-petrographic mapping. This must have convinced him of the necessity for an extensive and comprehensive, soundly planned, well-evaluated research program of photo and field study in various climatic regions of the world, before effective results can be expected from earth and extraterrestrial surveys.

From the completion of such a program, who knows what will develop? A new universal field and laboratory classification of rocks that is realistic and easily mappable? Air-photo separation of rocks having various alkali ratios? Stranger things have been done with air photos and will be done in the future.

16-9. Mode of Occurrence. Mode of occurrence is discussed and illustrated in Chap. 19 on structural geology. However, the following words from Mohr are of interest and significance with respect to occurrence, particularly since they are a bit removed from the usual ideas on the subject:

A great deal must happen geologically before plutonic rocks lie exposed at the surface of the earth. To make this possible, much time is necessary for the folding of the crust of the earth and for the weathering away of the layers lying above. In order for plutonic rocks to have become accessible to us, they must be relatively old. Along with the plutonic rocks—effusive rocks, lava, and volcanic ash also occurred. The longer ago those processes of formation occurred, the longer the processes of weathering went on, in order to break the rock up and as such to cause it to vanish. And now—taking into consideration the stronger weatherability of the more porous effusive rocks etc., and at the same time the greater susceptibility to attack of the products which have less silicic acid,

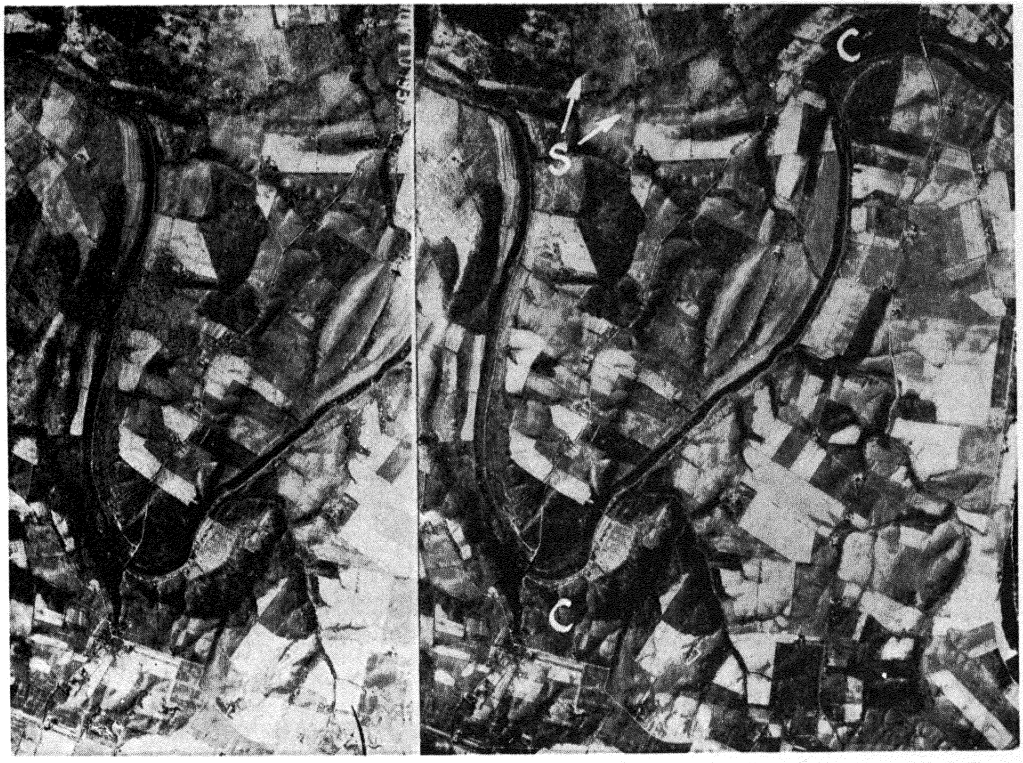


Fig. 16-17. The effects of climate upon the air-photo pattern of rocks which are roughly comparable to those in Figs. 16-18 and 16-19. This stereopair shows shales in a humid-temperate climate. Note the smoothly rounded hills, numerous drainageways, and gullies, typical of clayey soils (Chap. 4), and the medium-gray color tones and gradual tonal gradients at some gully ends. Sinkholes S indicate the bordering limestones, while several steep slopes C indicate recent cut banks, now being back-weathered and smoothed (Chap. 4). (*West Virginia. U.S. Army, Photographic Survey Corporation.*)

(the more basic products)—it may be said that out of those older formations the ash, pumice stone and lava have certainly to a great extent, weathered away, and of the solid effusive rocks the more acid, i.e. those richer in silicic acid, have survived the longest, and consequently are the most prominent today.

It is an obvious fact that among the visible magmatic rocks a larger proportion of the geologically oldest should on the whole be plutonic rocks, that is, toward the acid side (granite), while the youngest must practically all be volcanic, and must exhibit those more porous forms with a relatively greater percentage of them on the basic side.

16-9a. Stress-Strain Patterns. Some years ago (1952) the author became interested in the use of aerial photographs as a method of investigating the stress-strain patterns of the earth's surface, correlating these patterns with tectonic features and rock and mineral occurrence and using the results as an aid in predicting both the surficial and subsurface aspects of rock structure and the occurrence of similar minerals.

In the process of conducting some preliminary research, recourse was necessary to the various phenomena of elastic and plastic deformation, including Lüders' lines, Mohr's theory of rupture, the equations of elasticity, etc. The author also had the opportunity of conferring with Dr. Paul Bijlaard regarding his theories of deep-seated plastic deformation and the repetitive patterns exhibited (19 to 21).

Using some of the conclusions of the latter theory, the author began plotting loxodromes on a base map of the United States, according to preselected patterns. He found a rather interesting degree of coincidence between such loxodromes and tectonicism and mineralization.

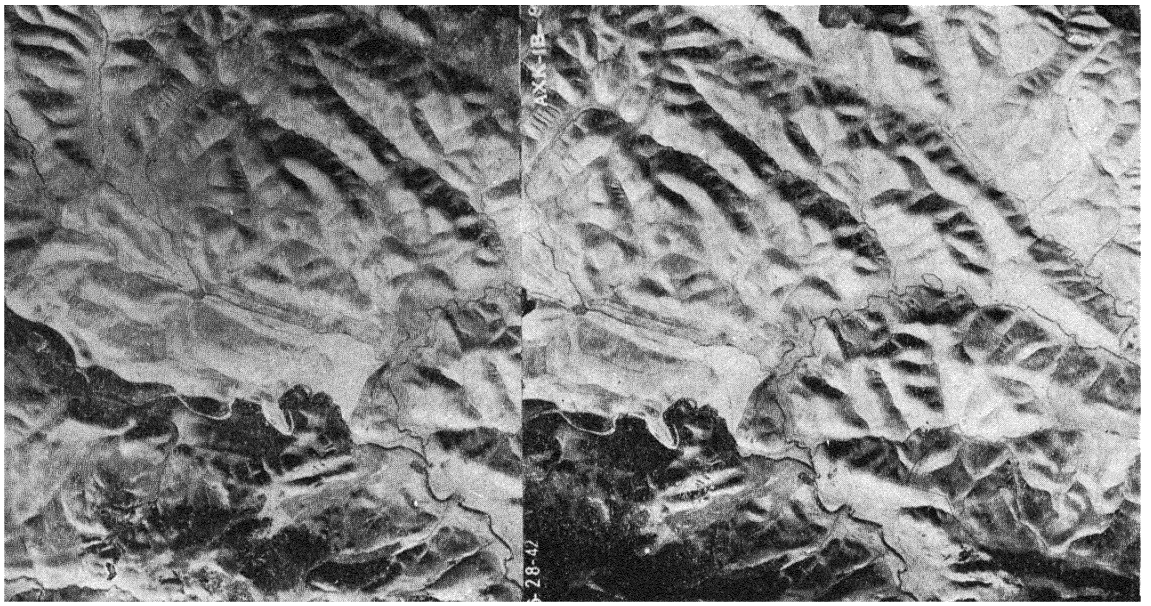


Fig. 16-18. Shales in a subhumid area. The hills are still rounded but are steeper and much more intensely dissected, largely because of the hydrology of the storms. Uniformity of color tones is striking. ***(California. U.S. Department of Agriculture.)***

Unfortunately, more pressing matters prevented further studies, and results of these early efforts were largely wasted. Recently, however, it has been possible for the author, together with T. A. Cheney, to resurrect interest in fracture patterns by virtue of smaller, but more specifically practical applications.

The applications have had to do with the plotting of linears, i.e., straight lines, for purposes of oil and gas exploration. One of the initial plots, covering an area considered largely devoid of linears, appears as Fig. 16-1*f*.

This pattern, undoubtedly reflective of fracturing, is developed in sedimentary rocks having only a shallow soil cover. It is characterized by high density and considerable complexity that might be expected when one considers that it results from stresses of different origin and magnitude, acting on different rocks in different directions at different times. Nevertheless, the number of structural and stratigraphic possibilities that are indicated at first glance are quite deserving of study.

The author has seen intersecting, radial, and parallel lineal patterns in almost every portion of the world that he has inspected from aerial photographs. They do not always have the density and complexity of the patterns displayed in Fig. 16-1, but they are always there, being revealed by loci of tonal change, slight to major topographic differences, vegetative anomalies, leaching lines, improved ditches, and very frequently by drainageways of various orders (Chap. 3). Even in areas covered by deep unconsolidated to semiconsolidated deposits (Alberta, Manitoba, the Middle West of the United States, the Atlantic Coastal Plain of the United States, the Gulf Coast of the United States) ranging up to 2,000 feet in depth, the linears are there—faintly in some cases and strongly in others, but there, nevertheless.

In fact, it may almost be said that linears are ubiquitous, and even densely so. Various geologists and scientists (Umbgrove, Hobbs, Lapworth, Bijlaard, Meinesz, et al.) have noted that fracture (linear) systems are a dominant characteristic of the earth's surface, without making much headway regarding their specific origin. Hapgood (72*a*), in his recent, most remarkable book, and aided by the mathematics of his collaborator, J. H. Campbell, advances a most intriguing theory for the basic, large-scale systems in a manner that appealed to no less an authority than Albert Einstein. During recent years, the regional, local, and

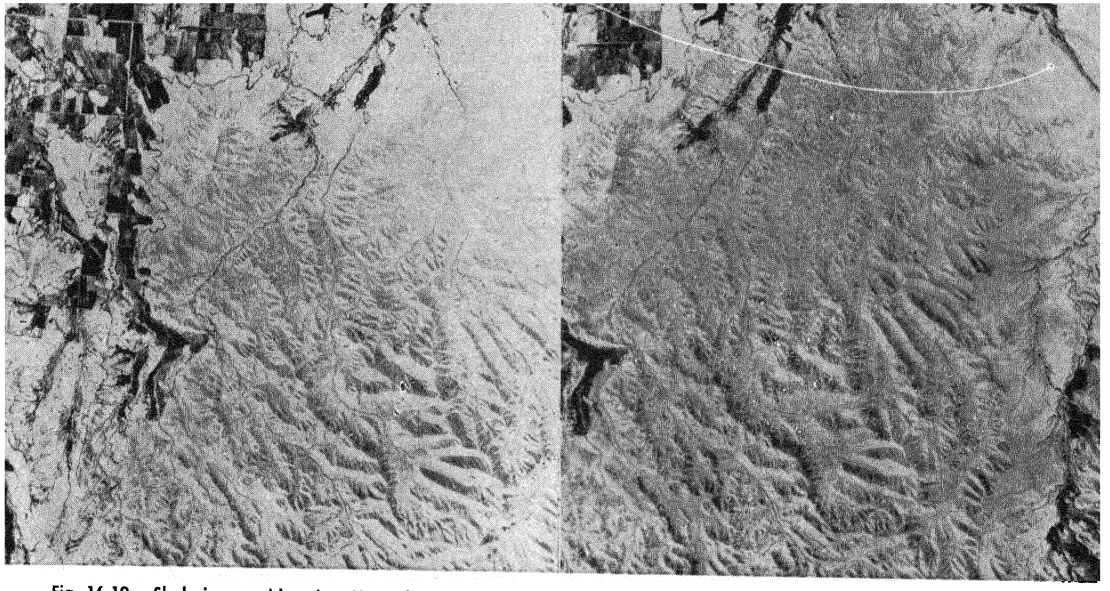


Fig. 16-19. Shale in an arid region. Here, the erodibility of the shale, combined with the intensity of the infrequent storms and their rapid runoff have allowed the rock to be dissected almost minutely into a series of steep, sharp-crested ridges and hills. Even the original accordance has been destroyed, although a single flat-topped hill remains in the lower right. The uniformity of erosion and tones indicates uniformity of materials. Originally selected and annotated by the Cornell group. (*Colorado. U.S. Department of Agriculture.*)

more specifically practical aspects of lineation and fracture patterns have been explored by such people as Blanchet, Mollard and Dishaw, Lattman, and Tator. Of these, Mollard's paper (135*a*) and Tator's presentation (192) of air-photo drainage patterns would be of particular interest to the reader of this volume.

Of course, aerial-photographic interpretation is the most effective technique for discerning linears, systems of linears, and the surface traces (Chap. 19) of fractures. This is particularly true in areas of deep unconsolidated overburden, where, as mentioned before, lineation can persist through many hundreds of feet of nonrigid materials.

There is no further room in this volume for a treatment of this fascinating and complicated subject. However, the main general points have been covered. Persistent and short linears, probably representing the surface traces of various fractures, arranged in various superimposed or intersecting systems, are almost everywhere present on the earth's surface. They are frequently repetitive as to orientation over large regions; they are best located through the medium of adequate aerial-photographic interpretation; on the photos they often show through deep overburden, though they may be indiscernible on the ground; they are revealed by a variety of terrain indicators; and they are susceptible to analysis by a variety of methods, usually involving interpretive mapping, orientation evaluation, photogeological and field geological study, theoretical stress analysis, and specialized geophysical survey.

Lastly, the mapping and analysis of these linears is of tremendous importance to oil, gas, and mineral exploration and subsurface storage, groundwater studies, seepage studies, dam-site investigations, and overburden evaluations.

In addition to the various parts of Fig. 16-1, see the illustrations of Chaps. 3, 19, and 24 for examples of lineation as displayed by the aerial photograph.

16-10. Outcrop and Overburden. Two of the most frequent tasks that face the interpreter are the differentiation of areas of outcrop from areas of overburden and the separation of overburden depths into various classes (very shallow, very

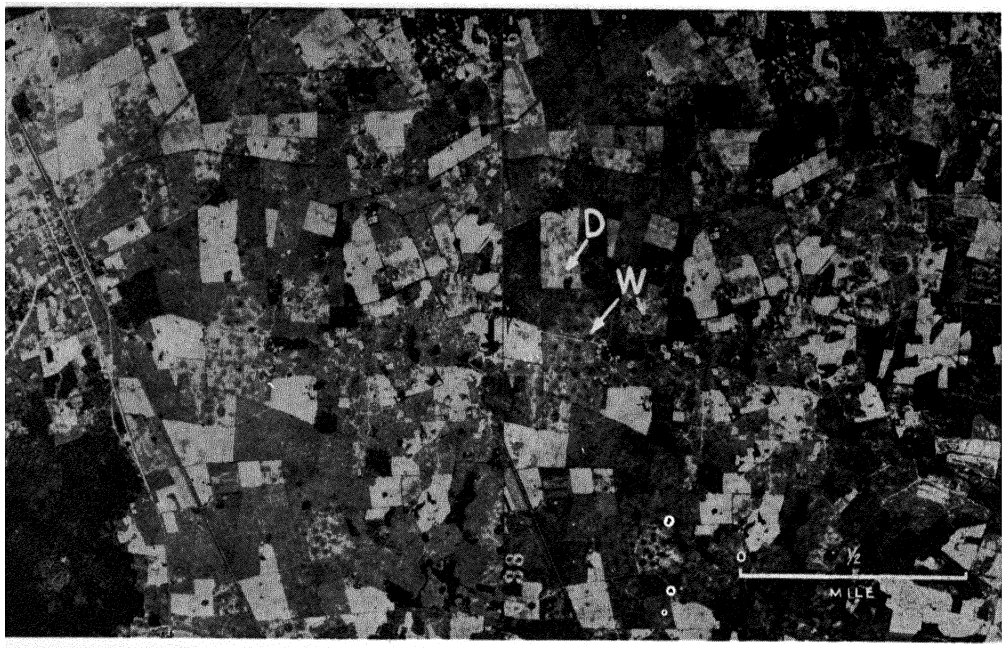


Fig. 16-20. This stereopair shows the effects of climate and age on soluble limestone. The horizontal limestone is dotted with sinkholes, both dry D and pond-filled W. Although sinkholes are numerous, undissolved rock predominates. See also the stereopairs in Figs. 16-21 to 16-23. Originally selected by the Cornell group (43). (*Kentucky. U.S. Department of Agriculture.*)

shallow but variable, shallow, medium, deep, very deep). Both of these tasks can be successfully accomplished.

The differentiation of bedrock outcrops from areas of overburden usually is fairly simple, if the photographic scales are not *too* small (greater than 1:40,000, although differentiation at 1:60,000 has frequently been made). Vegetative cover such as thick trees, caribou moss, etc., also makes outcrop differentiation difficult. Usually, however, a close inspection of surficial mass texture and microtopography, gray tones, and relation to environment will suffice to delineate outcrop. It may be safely said that outcrop mapping *usually* is one of the most dependable products of good interpretation.

The separation of overburden depths into various ranges is more difficult. However, it has been successfully accomplished, many times, at many scales, and under various conditions of cover. Generally, successful differentiation is a function of careful interpretation, extension of topography, logic, selection of range limits, and a certain amount of field check for the purpose of tying the interpretation to a proper vertical base. An example of successful overburden differentiation is described in Sec. 17-15.

16-11. Comments on the Use of Color Photography. The general types and characteristics of aerial color film were discussed briefly in Sec. 5-22. The limitations of the use of such films (transparencies) were also mentioned. Regardless of these limitations, it was said that color films had definite use in certain specialized fields, including petrologic mapping and mineral exploration.

The general justification for use in petrologic mapping and mineral exploration is included in Secs. 16-4 and 16-6. The specific justification is related largely to economic factors. As a broad rule, it may be said that color photography is most applicable to relatively small areas, where cover is thick or arid conditions predominate, and where considerable detail is required beyond that provided by panchromatic photography (Sec. 5-26).

Laylander (99) has done considerable work with colored photographs in the detailed geologic mapping of small areas for purposes of mineral exploration. Most of his comments, together with the

author's published remarks on the subject, are extracted in Sec. 19-21.

AERIAL-PHOTOGRAPHIC CHARACTERISTICS OF IGNEOUS ROCKS

16-12. General. The following three sections include discussions and illustrations of various igneous rock bodies. As mentioned in previous sections of this chapter, the total number of igneous rock types is great, and agreement has not even been reached regarding their proper classification and nomenclature. Hence, it will probably not be surprising to the reader to find that the following material is equally noncommittal. With the exception of certain effusive (lavas, particularly the basalts) and efflata (tuff) rocks, and possibly some of the true granites, the illustrations show various patterns displayed by definitely igneous rocks, but the discussions are necessarily brief and general.

The entire responsibility for this regrettable state must not be directed wholly toward the lack of a classification system. An equal or greater reason for it, as emphasized in Sec. 16-18, is the limited extent of air-photo knowledge. A third reason is lack of space.

Let the following sections, then, be introductory, tentative, exploratory, etc., *à la* Roget's Thesaurus. Also, it is to be regretted that space does not permit the inclusion of many stereo examples and that recourse must be had to many single aerial photographs.

16-13. Plutonic and Intrusive Rocks (Granitoid and Porphyritic)—Eucrystalline Textures. These classes of rocks include such well-known names as granite, syenite, diorite, gabbro, peridotite, etc., their porphyritic varieties, and possible cross-bred porphyritic combinations with the fine-grained rhyolites, trachytes, dacites, andesites, basalts, etc. In short, they comprise a most widely diversified group of the igneous rocks.

Because of this, aerial-photographic characteristics must be left largely to the imagination, supplemented by the examples provided by the illustrations and the directions indicated by Secs. 16-4 to 16-6.

One possible exception may be the true granites and closely related rocks. According to the Cornell group (14, 43), granitic rock bodies are generally characterized by large size, occasional pendants,

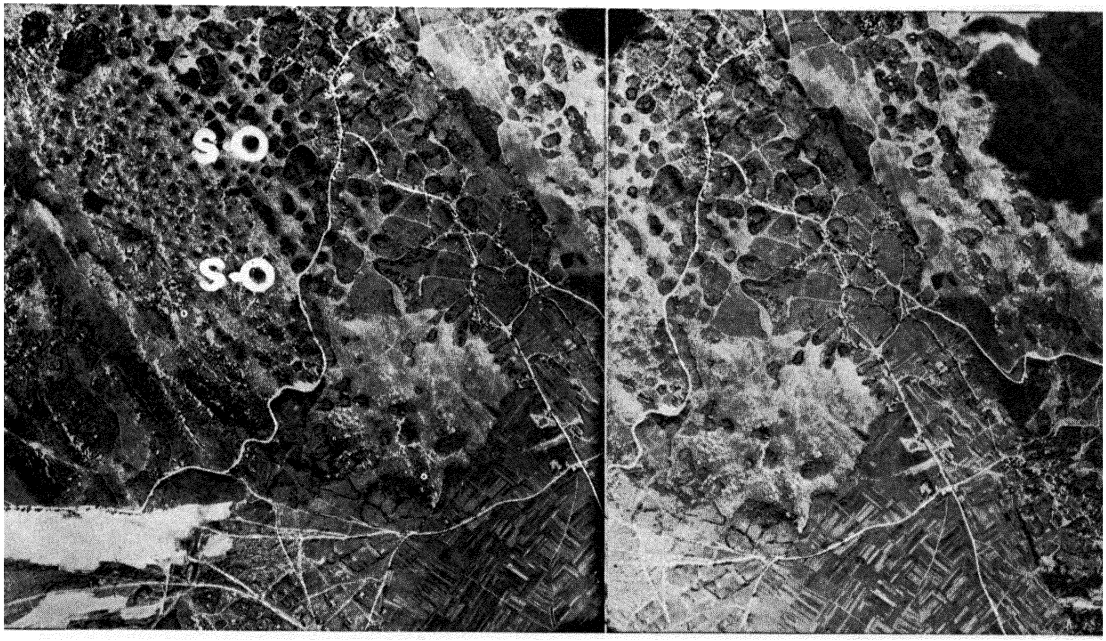


Fig. 16-21. The effects of climate and age on soluble limestone. Slightly tilted, soluble limestone in a semiarid area. Relative lack of moisture has been more than counterbalanced by age, and the sinkholes are coalescing around intersinkhole areas to form scalloped annular pits and elongated channels, i.e., *karst* typography. Originally selected by the Cornell group. (*Mediterranean.*)

and distinct, smoothly curving boundaries (except where faulted). Frequently, these boundaries outline areas of massive, dome-shaped hills having rounded tops and steep side slopes.[3] This dome-shaped appearance is apparently quite typical, but it has been the author's experience that the dome shapes may also apply to numerous small hills rather than only massive ones. Where soil mantles are absent or thin, characteristic *irregular* patterns of curvilinear fractures modify the smooth surface. Obviously, evidence of stratification is lacking.

Surface-drainage patterns are well integrated, nonoriented, and of varying density (depending upon climatic influences). The channels tend to have a rounded shape in plan. The intersections of tributaries with the main stream tend to resemble a right angle. However, they are slightly acute upstream.

The tonal range, as might be expected from the predominance of light-colored minerals that compose granitic rocks, is in the range of light grays.

Vegetation is variable, but is not usually noted for luxuriance. Productive land use is almost completely confined to the hilltops.

Figures 16-2 and 16-3 and various figures in Chap. 19 illustrate granitic and other rock types. It must be mentioned that many of the photos appearing in this chapter, as well as in various other places throughout this book, were located and selected by various members of the Cornell group. Their selections are given acknowledgment in the captions to the illustrations.

[3] It is interesting to note that Charles Darwin, in his "Voyage of H.M.S. Beagle," written over 100 years ago, mentions this characteristic of granitic rocks in Brazil.

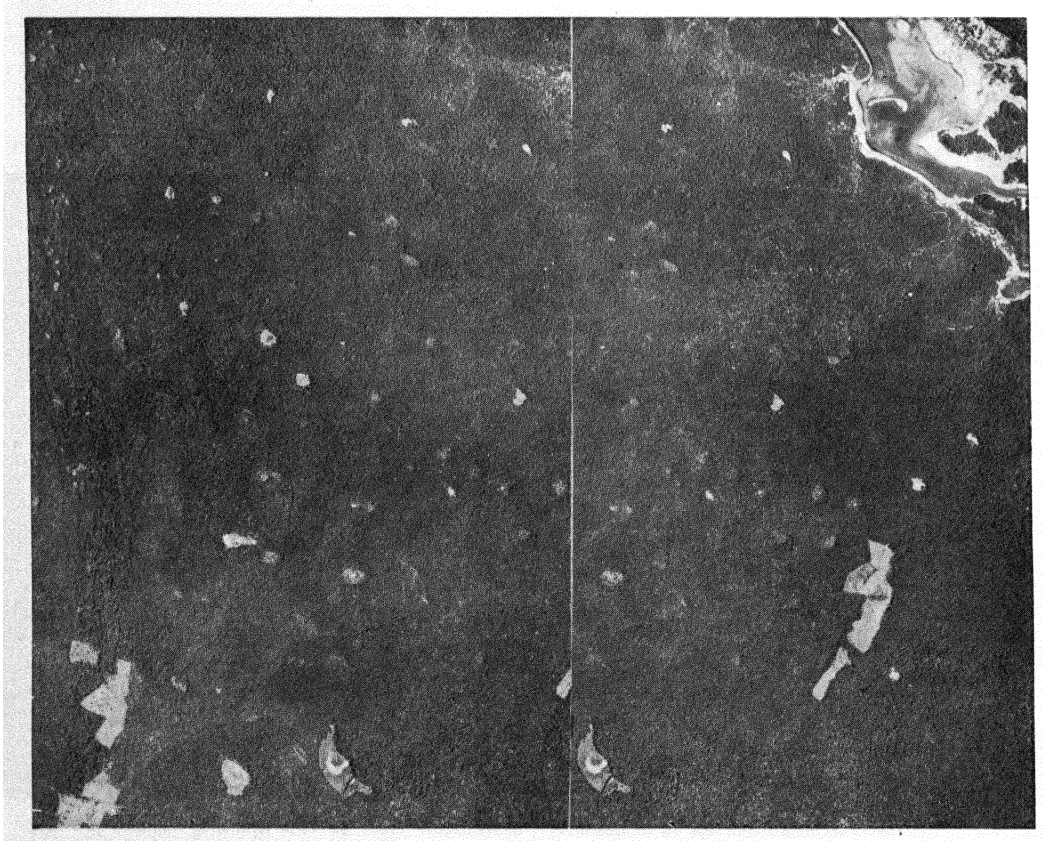


Fig. 16-22. This stereopair shows the effects of climate and age on soluble limestone in the semiarid tropics. It shows only widely spaced sinkholes, visible through fairly heavy jungle. In this area, a great deal of the *relatively* low precipitation is used by the transpiration of the plant life or is evaporated. (*Far East. Photographic Survey Corporation.*)

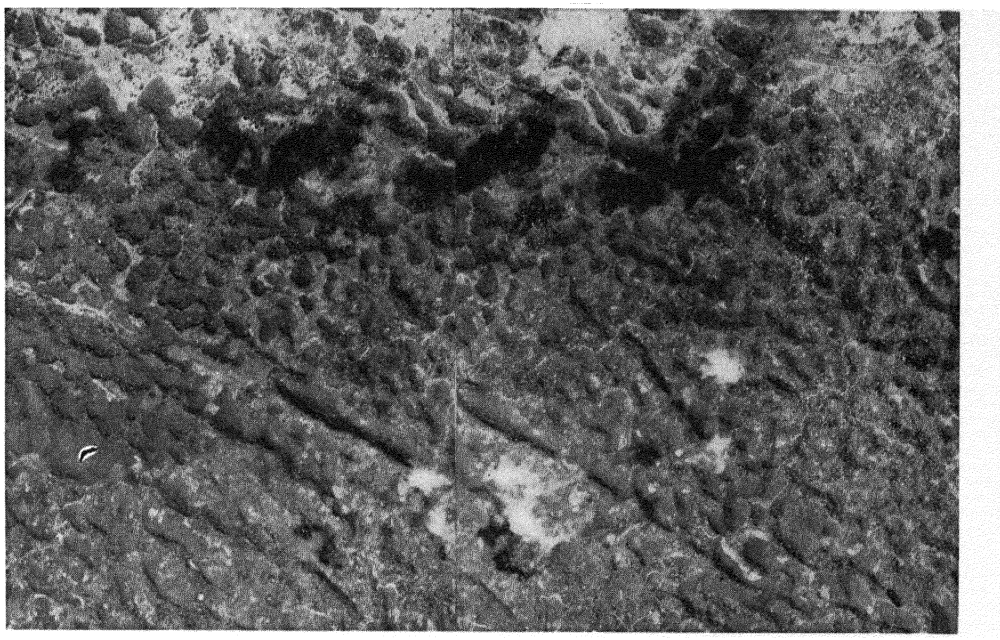


Fig. 16-23. The effects of climate and age on soluble limestone. High rainfall, possibly combined with age, has created the haystack topography typical of many limestones in the high-rain tropics. The sinkholes have become deeper and have enlarged and coalesced until the pits literally surround their own borders. In such areas, bauxite accumulation may be significant, and the aerial photographs may provide clues to its detection. (*Jamaica, Photographic Survey Corporation.*)

16-14. Effusive Rocks (Felsitic, Glassy, Cellular, Etc.)—Dyscrystalline Textures. These rocks include the true lavas in their various states of viscosity: the widespread, dark, variably dense basaltic lavas; the intermediate, more viscous, medium-colored andesites; and the truly felsitic types such as rhyolite, trachyte, and phonolite.

The basalts and basaltic lavas are most distinctive and important effusive rocks. They also can usually be distinguished by means of aerial-photographic interpretation.

According to the Cornell group (14, 43), primarily Liang in the case of basalts, basalt flows have definite criteria of identification, as follows.

In terms of boundary characteristics, basalt (columnar) is unique. The boundary must be relatively fresh (as along a river-carved canyon edge). When such is the case, the edge is characterized by a discontinuous to continuous vertical serrated edge that is often skirted by an apron of talus from the crumbled columns of "trap." Frequently these serrated edges have stratalike arrangements of columns. At the terminus of a lava flow, variable conditions are observed, depending on the viscosity and type. Near volcanoes both *aa* (blocky) and *pahoehoe* (ropy) boundaries may occur.

Topography may vary from flat to rugged. Flat to undulating phases are most common because of the essentially fluid nature of the lava. However, at the borders of large flows, and between the parallel valleys and on *aa* or *pahoehoe* flows, topography may be affected enough to become rolling, hilly, and irregularly rough (on a small scale). Other characteristic topographic features, particularly important in the identification of large-scale flows, are certain blisterlike wrinkles, vesicular, ropy, and scalloped fourth-order forms indicative of solidifying, gas-bearing flow. When the basalt or lava areas are highly dissected, there may be frequent mesa-like outliers. These are the remnants of a very odd pattern of backward weather-

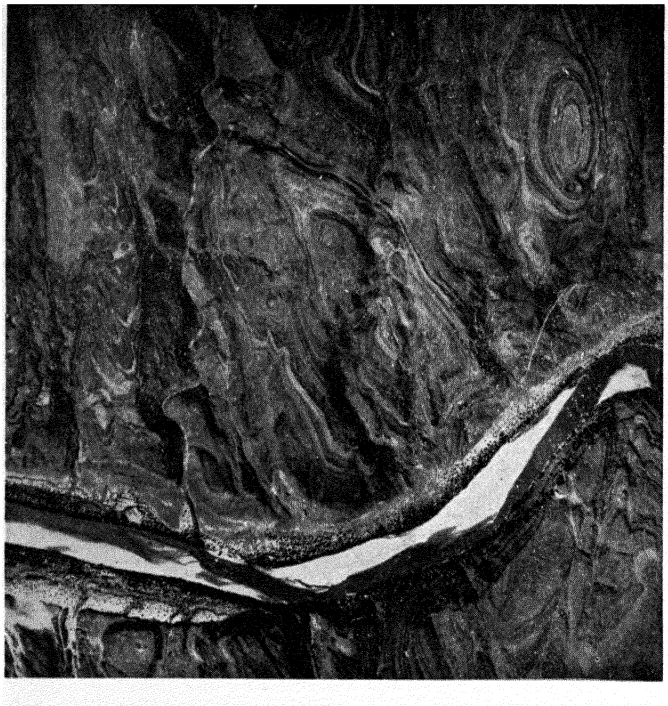


Fig. 16-24. Interstratified sediments. Sandstones, shales, and limestones in typical banded sequences. (*Africa. Hunting Aerosurveys Limited.*)

ing that results in the formation of ropy ridges from which extend many pear-shaped hills.

The surface-drainage pattern is characteristic. It may be absent because of porous channels provided by postflow shrinkage phenomena, or the inherently vesicular character of the lighter lavas and the resultant insoaking that occurs. It also may be of the parallel type, reflecting the original flow.

Erosion details, except those of back-weathering, rock falls, rock slides, etc., which are typical, are lacking.

Tonal ranges are dark to very dark, often with a certain amount of mottling of light and dark areas (presumably reflecting changes in the soil mantle, local moisture accumulations, etc.).

Vegetation is extremely variable, ranging from very sparse in young and/or arid deposits to luxuriant in tropical areas, where these materials develop a deep mantle of residual soil.

Figures 16-4 to 16-12 illustrate the appearance of basalt and lava (see also Chap. 19).

The identification of rhyolite and andesite is much more difficult than basalt and fresh lava. Rhyolite seems to have some characteristic criteria. One of the more prominent ones seems to be a tendency to develop fairly widely spaced, "sickle-like" curvilinear drainage. No explanation is evident as to why this development should occur. Another characteristic—as might be expected because of the high silicic acid content—is a generally lighter tone than would be associated with basalt. Jagged edges are common along hillsides. Many other flow characteristics also occur. Finally, perhaps because it tends to weather to kaolin (Sec. 16-15), rhyolite often gives an appearance of ropy viscous flow (Chaps. 19 and 3, for illustrations).

Andesite and other rock types have characteristics that vary between those of rhyolite and basalt, the variations consisting largely of tonal ranges, density of drainage, and topographic form (reflecting weatherability). These effusive types are often interbedded with each other as well as fragmental deposits (Sec. 16-15). An illustration appears as Fig. 16-13.

16-15. Efflata (Fragmental) Rocks. The efflata rocks are exceptionally variable. They include accumulations of all the materials that have been explosively ejected from volcanic openings and

outpourings. They include all sizes and shapes of material and go by the names of breccia (agglomerates), tuff, and ash. The ashes are unconsolidated. The tuffs are *fine* consolidated fragments, while the breccias are *coarse* (greater than 1 centimeter) consolidated fragments. The composition of both tuffs and breccias is practically infinite in variability, and the primary distinction between the two is the size of the original ejected fragments.

From the standpoint of aerial-photographic interpretation, little has been done on the identification of breccias, but some study has been devoted to the patterns characteristic of thick deposits of tuff.

In general, the air-photo criteria for fine-grained efflata rocks are similar to those for other fine-grained materials, largely because of their weakness and susceptibility to erosion. The rocks are characterized by very rough, dissected topography with sharp crests, steep side slopes, etc., and a well-integrated, uniform, dense, nonoriented drainage pattern. Tones are variable, depending upon composition and vegetative cover.

A fine-grained rock pattern is shown in Fig. 16-14.

AERIAL-PHOTOGRAPHIC CHARACTERISTICS OF SEDIMENTARY ROCKS

16-16. General. Sedimentary rocks are one of the easiest types to identify in so far as *origin* is concerned. This ease, of course, is related to their inevitable occurrence as layered sequences. Once definite stratification has been established and has been distinguished from the successive flow layers characteristic of some effusive rocks (Sec. 16-14), the origin has been identified. This separation is not *always* so easy as it sounds, but it *often* is. When the layers are tilted, or show typical sedimentary structure, identification is almost automatic. When the layers are horizontal or gently inclined, identification of stratification is frequently difficult, because recourse must be had to an examination of the valley sides. In certain areas of the world, of course, typical landforms (buttes, buttresses, etc.) indicate sedimentary origin.

In the following six sections, various major sedimentary rock types are discussed and illustrated. It must be emphasized that only the *major types* are covered. Variations, in terms of cleanliness, chemical nature, etc., are not covered except by



Fig. 16-25. Interstratified sediments. Vegetatively accentuated sandstone *SS* and shale *SH*. (*Texas. U.S. Department of Agriculture.*)

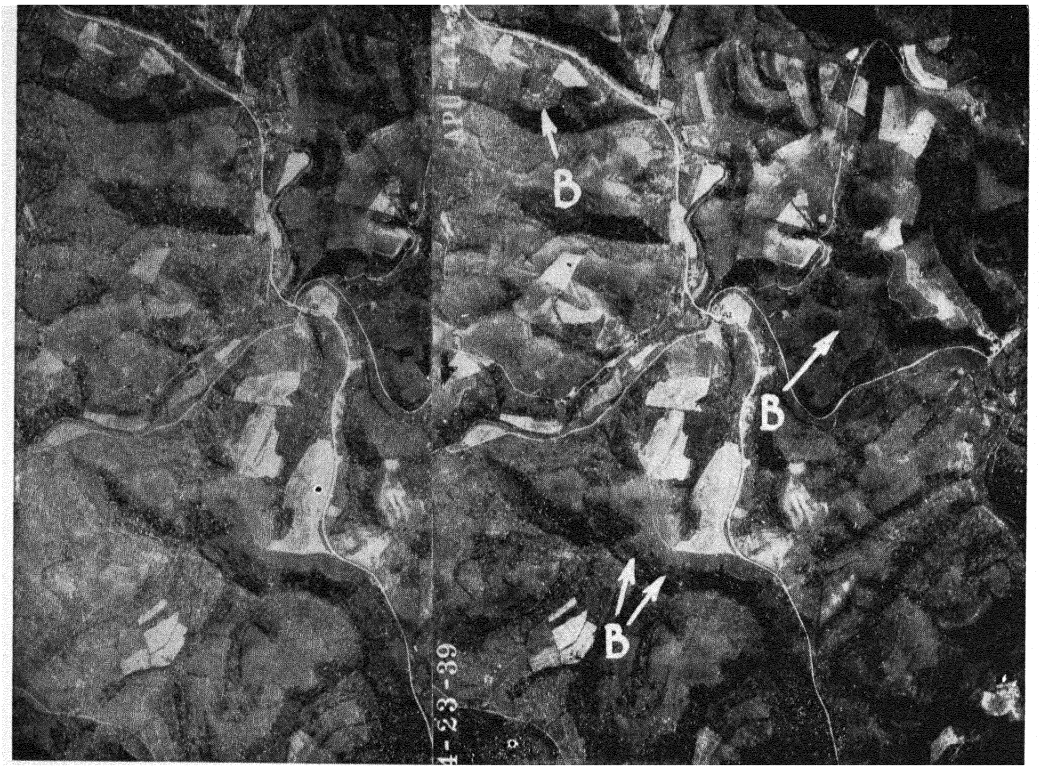


Fig. 16-26. Stereopair showing interstratified sediments in a humid-temperate area. Well-rounded hills and uniform tones indicative of shale are shown. Here, although the strata breaks *B* are subdued, they are still discernible. (*Pennsylvania. U.S. Department of Agriculture.*)

the inferences that can be drawn from a closer analysis of the photo elements as interpreted against local or regional knowledge.[4]

[4] In the classification of sedimentary rocks, geologists have not progressed even as far as they have in the igneous field. This is hard to understand and justify. Sedimentary rocks comprise the greater portion of the rocks exposed at the earth's surface. They form, in effect, the geological history book by virtue of the fossils, colors, inclusions, and textures that they contain. They are infinitely simpler, in all important compositional and lithological respects, than either igneous or metamorphic rocks. Finally, they tend to extend over relatively large areas with comparatively few significant variations.

Geologists, of course, realize this, but they do not seem to have arrived at a universally accepted system of describing or classifying sedimentary rocks on the basis of mineralogical composition of particles, nature of bond, strength, textural gradation and lithology, special depositional conditions, and possible normal environment during deposition.

This classification would not seem to be a difficult job, regardless of the contention that sedimentary rocks are composed of fragments having an infinite variety of compositions, origins, size gradations, etc., cemented together by an infinite variety of agents. This is true; it is also misleading. The range of specific compositions is only occasionally of significance and, in fact, is much less than we think, consisting usually of siliceous particles with a greater or lesser percentage of mafic types, all cemented by relatively few agents (sandstones); or consolidated, kaolinitic clays (shales), etc. In any case, the number of probable combinations is certainly much less than the number of those occurring as igneous rocks with their infinity of melts and reaction series. Also, it might be said that considerations of velocity of transport, carbonaceous content, etc., tend to classify sediments for us, not only with respect to texture, stratification, properties, etc., but also with respect to environment during deposition and extent and tracing of occurrence.

Possibly the difficulty has been partially caused by a tendency on the part of geologists to consider unconsolidated deposits, and even what are more nearly weathered soils, as sedimentary rocks. It is true that unconsolidated deposits grade into rocks and that the division between the two is arbitrary, but the arbitrary separation is easy to make at some value of unconfined compressive strength (say, 8 to 12 tons per square foot?) or other test. It seems that the classification of sedimentary rocks would be much simpler if the geologists left the unconsolidated Pleistocene and Recent materials out of consideration until they "came of strength."



Fig. 16-27. Interstratified sediments. Massive, tilted beds of sandstone, interbedded with thick eroded sequences of shales (valleys). (*Alberta. Photographic Survey Corporation.*)



Fig. 16-28. Interstratified sediments. Thin, steeply tilted interbedding (*Far East. Photographic Survey Corporation.*)

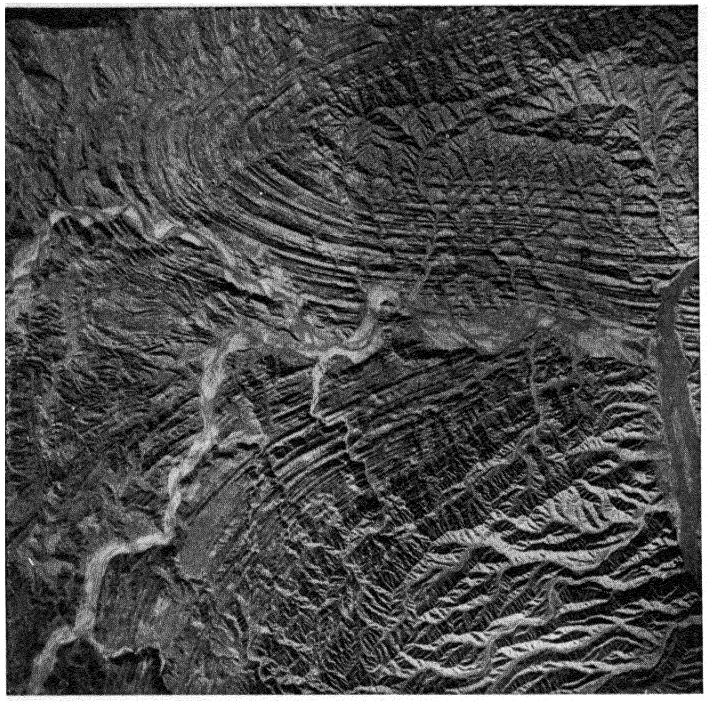


Fig. 16-29. Interstratified sediments. Steeply tilted, fine-grained sedimentaries that sharply delineate geological structure. Note the paddies on the few remnants of valley fill that once covered this area.

16-17. Sandstones. Sandstones, being almost invariably composed of the most durable remnants of the weathering processes (primarily quartz), cemented to a greater or lesser extent by various agents, might be expected to be fairly durable in their mass state. Such is the case, many sandstones being ridge formers, cap rocks, and flatiron formers.

Sandstones commonly occur as relatively thin strata, interbedded with shales and limestones. These are discussed in Sec. 16-20. Sandstones also occur in continuous sequences of layers having thicknesses of several tens of feet. These tend to occur near the great mountain ranges of the world, past and present, which, during the period of their original formation by uplift and distortion, provided copious and long-continued supplies of coarse-grained erosion products. Although fairly rare, their air-photo patterns are interesting. This section is primarily concerned with these "massive" occurrences.

The topographic characteristics of massive sandstones are distinctive. In humid areas they tend to form bold, massive, frequently flat-topped mesa-like hills, a rare occurrence in such regions. The edges at the tops of the mesas are usually rounded. Occasionally, the flat tops are remnantal only and slope gently away to steeper, lower areas. In most cases, the hilltops are accordant. In arid regions, the massive flat-lying sandstones are often mistaken for tilted sedimentaries. This is due to the usually well-developed system of joints, which tend to be of rectangular pattern, or dominant in one direction. Both of these types of jointing are uncommon in igneous rocks which tend to develop triple and/or irregular sets of fractures. Generally, these joints are well etched out by wind and water erosion and only careful examination will reveal remnants of horizontal bedding on the hilltops and hillsides.

In both arid and humid areas, the intersection of flat-lying massive sandstones with lower areas is abrupt. Often a steep, abruptly breaking talus apron lies between the sandstone and the lowlands.

Surface drainage is poorly developed. The pattern is poorly integrated, of low density, fairly uni-

form, and rectangularly oriented and displays a moderate to high degree of control and angularity, with variable but repetitive angles of juncture. The density tends to increase, and the angularity to decrease, in humid climates. These characteristics reflect the porosity, durability, and jointing of the rocks.

Fluvial erosion features are practically nonexistent, even in humid regions. Wind erosion is prominent in arid areas. Some of the wind features have undoubtedly been enlarged and partially developed by water and thermal changes.

Because of high quartz content and dryness, sandstone tends to display light tones.

Land use is rare. Vegetation is natural—forest in humid areas and scrub or brush in arid areas. Illustrations of massive sandstones appear as Figs. 16-15 and 16-16. Examples of the interbedded varieties appear in Figs. 16-24 to 16-29.

16-18. Shales. Being the most widespread of sedimentary rocks, shales should be of more than average interest to the interpreter. According to most classifications, the term "shale" is confined to those rocks that have consolidated from fine-grained, unconsolidated sediments. In a general way, such sediments include silts and clays predominantly, but may also include sands. All combinations of the three may occur, so long as the proportion of clay and silt sizes remains relatively high (greater than 50 per cent). Of course, the shales must also be laminated.[5]

This section is concerned with extensive, thick deposits of horizontally lying true shales—clay shales, silt shales, and silty clay shales.

Topography is an outstanding criterion for the identification of shales. Being fairly impervious, but relatively weak, most shales are susceptible to erosion, weathering, and mass wasting (Chap. 4). As a result, they are highly dissected. In humid climates, the result is a mass of gently to moderately sloping, *softly rounded* hills having variable summit elevations. In arid climates, where flash floods cause intensive erosion in susceptible materials and vegetation is largely lacking, dissection is much more intense and the hills have a sharper, steeper appearance. This latter effect is probably related to the relative ineffectiveness of chemical

[5] Varieties of shale that have been slightly metamorphosed often show no thin lamination and are called "argillites." Shales that are fairly well metamorphosed are called "slates."

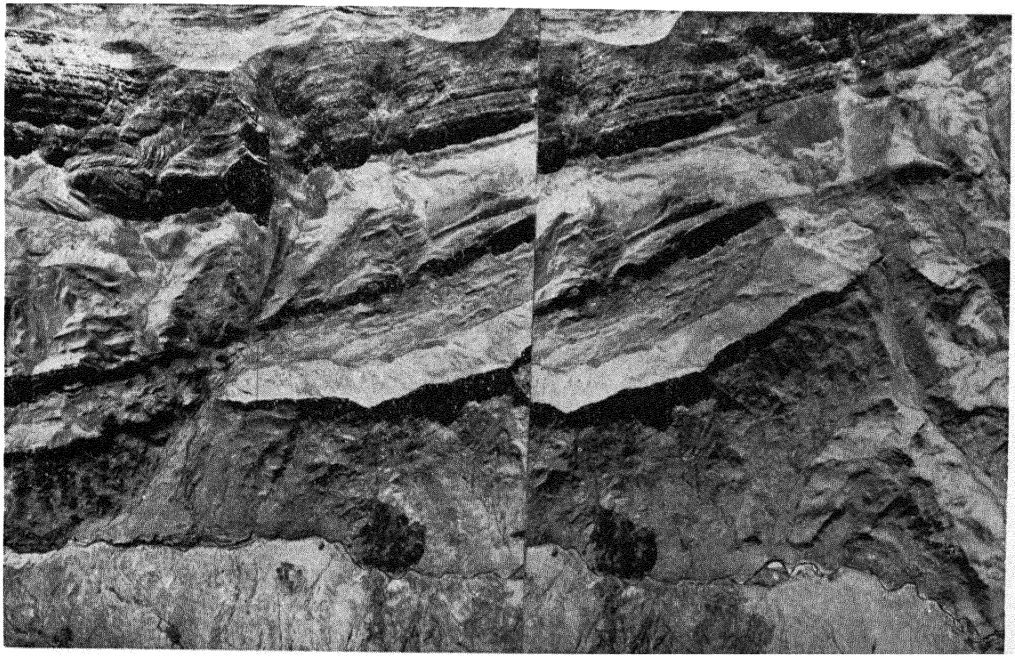


Fig. 16-30. Stereopair showing steeply tilted, sharply delineated sedimentaries in the high mountains. Note the fineness of detail, revealing individual rock blocks. Flatirons F are distinctive, as are the weatherability and etching of the various stratigraphic units. (*South America.*)

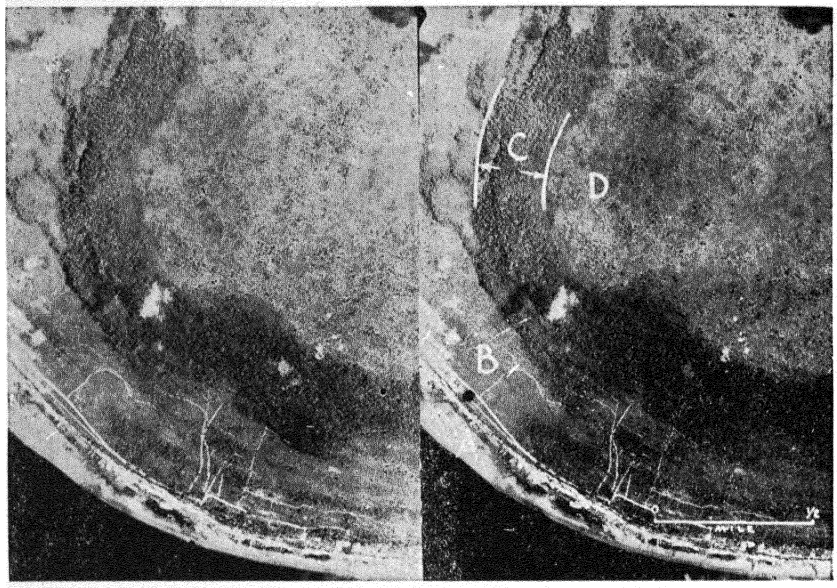


Fig. 16-31. Stereopair showing horizontal coral. A fringing reef *A*, step *B*, and the original reef *CD* can be seen. Note that the outer portion of the reef *C* is higher than the inner *D*. (*South Pacific. U.S. Army.*)

weathering, the dominance of thermal weathering, the infrequency but great intensity of water erosion, and the associated inhibition of mass-wastage processes with their dependence on precipitation and runoff of average characteristics. In tropical areas, the hills may resemble either the humid or arid types, depending upon the interrelations between density of vegetative cover, hydrology, and type or depth of surficial weathering.

The drainage pattern in all shales is almost invariably highly integrated, of very high to high density, uniform, and only remotely oriented and controlled, if at all. Angularity is generally absent. By simile, the pattern may be described as dendritic (Chap. 3). Generally, the lower the density of drainage, the more impervious or coarse-textured is the shale (all other things being equal).

Erosion details may be widespread or absent, depending largely upon the nature and density of vegetation or the nature of land-use practices. Sheet and badland erosion may be present, particularly in arid areas. When fresh gullies are visible, their characteristics are a clue to the composition of the shales (Chap. 4).

Tones vary widely. In humid areas they tend toward darkness with a certain mottled effect, like that found in heavy-textured glacial till plains, caused by the accumulation of water, fine-grained soils, and organic material in the topographic hollows. In arid areas, tones tend, like most materials, toward uniform tightness, reflecting their dry state. However, the proper colors may yield dark tones, like those displayed by certain sand dunes of the Middle East (Chap. 14). Also, different-colored bedding may show a streaked appearance (Figs. 5-1 and 5-2).

Vegetation and land use are not generally criteria of identification.

Illustrations of shales appear in Chaps. 3 and 19 and in Figs. 16-16 to 16-19. Interbedded varieties appear in Figs. 16-24 to 16-29.

16-19. Soluble Limestones. Soluble limestones are a most interesting subject for the photo interpreter. This is because of their reaction with water and the striking solution patterns that result in response to hydrology, age, bedding, and cleanliness. It is also a reflection of the importance that is attached to limestones in connection with engineering, construction, ground-water supply, and ore formation.

The topography characteristic of limestones is

extremely variable, whether they be horizontal or tilted. If the beds are horizontal and in a "normal" humid climate, their surface is pock-marked with sinkholes, pits, coalescing sinks, chains of sinks, etc. The individual sinks have a tendency to be round, or at most elliptical. The density of these features is proportional to the age and amount of solution. This latter factor is, in turn, dependent largely upon climate (hydrology) and composition of the rocks (solubility). If the beds are horizontal and in a tropical climate, or are very old, "karst" topography (see any book on geomorphology) may develop. This is a type of topography in which the sinks have coalesced around their borders—the holes surrounding the doughnuts—resulting in numerous closely space haystacklike mounds. In arid and semiarid climates the development of sinks is *usually* much less pronounced. However, this is relative only, and if age is great enough, even karst may result. All in all, inspection of the solution pattern in limestones is a most fascinating study, which can lead to many intriguing hypotheses and questions.

Another topographic feature in the limestones of humid areas was probably first observed by D. J. Belcher and seems to be of value as a criterion of identification. This is the observation that valleys in massive limestones are steep-sided, flat-bottomed, and almost devoid of "normal" tributaries. This characteristic, presumably, is a function of solubility, underground drainage, and cavernous collapse. Tilted limestones may have all the variations of horizontal ones, compounded because of increased access for water along bedding planes. In tilted limestones, the sinks are elongate.

A surface-drainage pattern, as such, is almost completely lacking. The sinkholes take care of the drainage and *are* the surface-drainage pattern Short streams may lead *into* the sinkholes in certain instances, and drainageways may occasionally occur along valley walls. Also, the author knows of one case where porous volcanic rocks formed the walls of a valley whose floor was composed of limestone. In this case, water flowed through the volcanics, into the limestone, and, during periods of high rainfall, *out* of the sinkholes, creating drainage patterns with sinks at the stream *heads*.

Erosion scars may be present around steep areas. It is indicative of composition, if developed enough (Chap. 4).

Tonal patterns tend toward the light gray but may vary considerably depending upon nature of weathering, recent climate, and other factors. The over-all tone is broken by the lighter- or darker-colored solution pits.

Vegetation and land use are not usually criteria of identification.

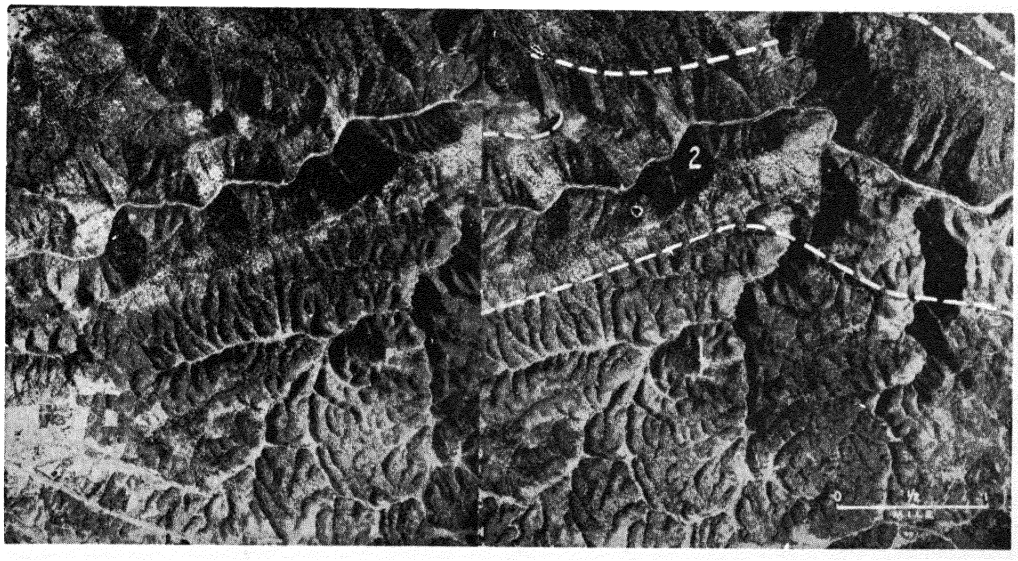


Fig. 16-32. A view of slate as well as the perfectly evident boundary between it and an adjoining rock. This figure was originally selected and annotated by the Cornell group (43). (*California. U.S. Department of Agriculture.*)

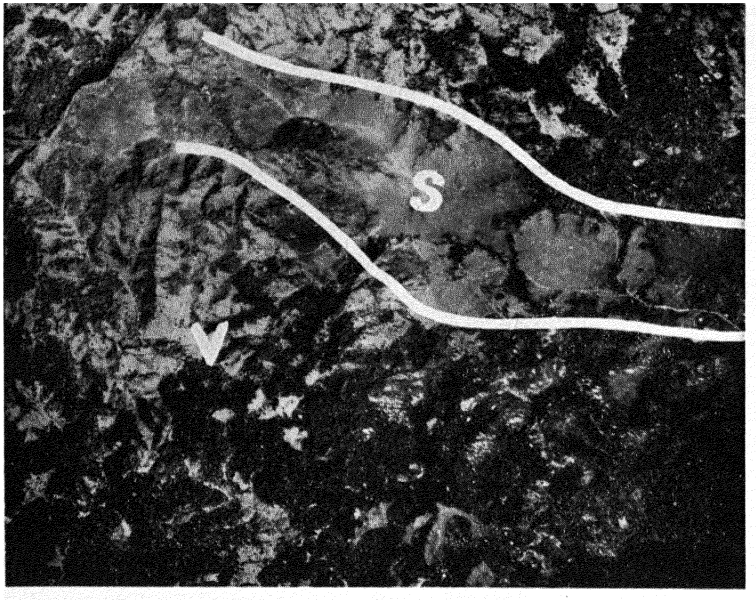


Fig. 16-33. Sharp contact between a typical serpentine S and surrounding effiata volcanics V. This figure was originally selected and annotated by the Cornell group (43). (*Puerto Rico. U.S. Navy.*)

Dolomitic, cherty, and other impure limestones are usually difficult to identify, although they sometimes have typical criteria.

Figures 16-20 to 16-23 illustrate some occurrences of limestone.

16-20. Interbedded Sequences. It is quite common to find sandstones, shales, and limestones in alternating layers. These layers reflect different conditions and sources of sedimentation at the time of deposition. Naturally, the interbeds may exist in either horizontal or tilted positions.

The aerial-photographic characteristics of interbedded sequences are quite variable in detail, depending upon the composition, thickness, and arrangement of the various layers, the climatic regimen, age, tectonicism, etc. In general, the criteria may be described as alternating ones typical of the individual layers. They are best presented by illustration rather than description.

Examples appear as Figs. 16-24 to 16-30, 19-17 to 19-19, and in various other places throughout this book.

16-21. Corals. The so-called "coral limestones," because of their varied predominantly organic origin (Secs. 2-8 and 2-9) are another interesting subject for interpretative study.

The formation of coral deposits as visible landforms is a function of the accumulation of organic remains (Sec. 2-8), resulting in upward growth; upward tectonic movement of rock masses to which coral masses have become attached; and, possibly, of subsidence in sea level. For a given coral deposit, any or all of these processes may have been operative. For a detailed discussion of the formation of coral deposits and landforms, the reader is referred to any standard text on geomorphology.

The following discussion of corals is largely based upon the work of the Cornell group (14, 43), particularly that of Belcher.

The boundary characteristics of coral deposits are indicative. Generally, the boundary of a coral deposit has the general shape of a smoothly curving line, which has a jagged microshape, similar to that of basalt (Sec. 16-14) but more irregular in detail. The line is generally parallel to the existing shore line, or a reasonable past shore line. According to geomorphic considerations, the edge of the coral deposits, in addition to paralleling the shore

line, as mentioned above, may occur as a seaward fringe encircling or fringing the land mass to which it is attached; as a ring surrounding a lagoon or island; or as a massive offshore island.

The topography of raised inland or island coral *masses* resembles that of a rock bench with a curved outline. The top is flat (although it really has a gentle landward slope), and the edge is vertical, steeply sloping, or overhanging because of wave-cliffing during emergence. There may be a series of successively higher benches.

Occasionally, the coral may exist inland as a fossil reef, in which case it resembles a section of an annual ring with either a flat or rounded top.

When the coral occurs offshore it may appear as an encircling island, or a series of islands, having flat or irregular surfaces and smooth or irregular boundaries.

When submerged, the coral has no visible subaerial topography, although subaqueous topography may be indicated by tonal variations indicative of depth changes, and occasional "heads" may protrude from the water.

Surface drainage is absent on coral formations, largely because of the porosity of the rock. Sinkholes, probably for the same reason, are rare.

Erosion is lacking.

Tonal characteristics are important criteria. Underwater accumulations, particularly if shallow, have variable but generally lighter tones than the surrounding water. Dark masses and streaks (underwater "gullies") also appear. Onshore accumulations of coral appear as bright white (beaches and recently emerged inner lagoon flats), light grays (lower, more recent benches), and medium grays (higher, older benches).

Vegetation tends to be thick on the near sea-level corals, where moisture is available, and scrubby on the higher and more droughty areas.

An illustration of a coral deposit appears as Fig. 16-31.

AERIAL-PHOTOGRAPHIC CHARACTERISTICS OF METAMORPHIC ROCKS

16-22. General. The aerial-photographic characteristics of metamorphic rocks, like the rocks themselves, are extremely variable. In general they resemble the characteristics of the rocks from which they are derived with superimposed or additional characteristics that reflect the processes of metamorphism, particularly strain and stress banding, alteration, and elongation. Thus, the metasediments resemble sediments in many ways, except that they are bulkier, more fractured, warped, etc.; the granitoid gneisses resemble granites with oriented lineations; etc.

Only a few rocks (excluding that vague group known as metasediments) can be said, at this time, to have anything approaching typical air-photo criteria. These include some slates, some serpentines (or serpentinized rocks), and quartzites.

Inasmuch as geologists have not yet decided upon the classification of metamorphic rocks, it is not surprising that their air-photo patterns have received even less attention than other rock types.

Figures 16-32 and 16-33 illustrate the appearance of some metamorphic rock bodies, particularly slate and serpentine (see also Chap. 19).

It might be mentioned that considerably more will be known about the air-photo patterns of metamorphic rocks after the current mapping in Ceylon and for Operation Overthrust is completed (Sec. 23-14).

III

The Applications of Aerial-photographic Techniques to the Various Fields of Earth Science

INTRODUCTORY STATEMENT

It is the purpose of this part of the book to describe and discuss the practical application of aerial-photographic techniques to a broad variety of engineering and scientific fields that deal with the land. Presumably, its content will be of greatest value to practicing specialists in such fields, who will be less concerned with the theory and practice of interpretation than with the use to which it can be put in solving their specific problems.

The preceding portions of the book have been devoted almost exclusively to the qualitative air-photo methods, primarily interpretation. Such limitation has not been considered advisable in Part III, since photogrammetry plays such an important part in the practical solution of so many terrain problems. Consequently, in this part, the use of photogrammetry has been included in the discussions, and a short series of sections on the specific subject appears in Chap. 24

In each chapter, there are summaries of the technical nature of the various fields (and their subdivisions) to which the aerial-photographic approach can be applied. These are not intended for the specialists, nor are they supposed to present any original information. Rather, they are intended to present the salient aspects of a given technical specialty, so as to better show the relation between such aspects and the specific contributions of the aerial applications that are thereafter described.

17 APPLICATIONS OF AERIAL-PHOTOGRAPHIC TECHNIQUES TO ENGINEERING

17-1. General. Civil engineering, in its planning, reconnaissance, preliminary, and construction stages, offers an exceptionally wide range of possibilities for properly applied aerial-photographic techniques. Generally, such techniques *provide a means for the rapid, economical, and dependable evaluation of ground conditions* that are usually completely investigated by field survey. As a result, *optimum conditions may be selected early in an engineering program, while difficulties can be evaluated in advance of actual planning and field work.* The fact that these studies may be completed in areas of difficult accessibility and climatic restriction is indicative of additional advantages that they enjoy over exclusively ground methods. (For other advantages, and some disadvantages, see Sec. 24-13.)

It must be emphasized at this point that the application of air-photo techniques does not eliminate ground surveys. It merely increases their efficiency. By the proper application of the proper technique *at the proper time*, there is no doubt that the preliminary stages of engineering development may be aided immeasurably. *Not only can substantial savings of time, money, and effort be realized, but also significant increases in the volume, extent, and dependability of basic information can be achieved.*

17-2. Outline of Applications to Engineering. Because the various subdivisions of civil engineering, surveying, and planning are so interrelated, the outline of applications that appears below is divided into headings indicative of the type of project under consideration rather than headings associated with engineering specialties such as highway engineering, hydroelectric engineering, soils engineering, etc.

Chapters 17 and 18 consider the following applications of aerial-photographic techniques in more or less detail:

1. Route location (highways, railroads, conduits, canals, communication lines)
2. Site location (airports, towns, industries, military installations, dams)
3. Materials location (gravel, sand, boulders, clay, rock, etc.)
4. Water-resources studies (ground water, infiltration, runoff, etc.)
5. Water-utilization and water-regulation studies (water supply, hydroelectricity, navigation, flood control, drainage, etc.)
6. Coastal and harbor studies
7. Special studies (construction problems; landslide studies; planning of field investigations; permafrost studies; contract and bid surveys; large job planning; progress estimation; salinity and corrosion studies; and municipal, urban, or regional studies)

As mentioned in the introductory note to Part III, the following sections will consider not only the applications of air-photo interpretation, but also those of air-photo analysis, air-photo reading, and photogrammetry (Secs. 1-3 and 24-5 to 24-9). This is done because of the close integration of the several techniques with respect to their practical contribution to the earth sciences.

ROUTE LOCATION

17-3. The General Problem. It is the general problem of route location to determine and investigate the "best" route between two extremes, and often some intermediate given points.

The term "best" route implies a number of things. It should be that of greatest economic justification; i.e., it should provide the highest reasonable expectation of enough revenue, or economic equivalent, to justify its total construction and maintenance costs. It should be the one of greatest service potential; i.e., it should provide the highest reasonable expectation of enough revenue, or economic equivalent, to justify its total construction and maintenance costs. It should be the one of greatest service potential; i.e., it should

provide the shortest distance, fewest adverse geometrics, fewest construction problems, least cost, and smallest maintenance.

From a theoretical viewpoint one of the best transportation routes obtainable would proceed in a straight line between a raw-material source and its ultimate market, passing along the way all the necessary facilities for its manufacture, while traversing a perfectly flat, high-strength, well-drained natural material with no temperature response.

Obviously, in any actual situation, such a route is unobtainable.

Furthermore, because most routes traverse large areas between the selected terminal points and because each of the general factors above mentioned have innumerable specific components, it is obvious that the selection of an *absolute* best route requires an accurate evaluation of every specific aspect of every possible route. Even if the obviously *possible* routes are limited to two, the infinitude of possible factor combinations makes such a detailed evaluation probably impractical (electronic approaches possibly excepted).

Yet, route-location engineers speak of a "best" route. How is such a route located under actual conditions? The answer to this question is that, in most cases, no one knows whether a given location is the best or not. Instead, we know that a given route has a *high level of feasibility*, based upon an evaluation of, and reasonable compromise among, such indicative factors as distance, geometrics, rise and fall, cut and fill, land use, land-acquisition costs, and major construction problems (bridges, culverts, rock, marsh, etc.) that experience has proven to be dependable criteria of feasibility and justification for construction.

The value of a route location, therefore, is directly proportional to the amount of dependable information that can be economically accumulated concerning such factors—and any other factors of importance to the various stages of study. In the *final* analysis, an intelligent and adequate route location should be determined in accordance with factual knowledge about the following:

1. Alignment possibilities
2. Grade possibilities
3. Construction-condition possibilities
   - *a.* Bedrock occurrence—surface and subsurface
   - *b.* Soil conditions—texture, profile contrast, porosity
   - *c.* Drainage conditions—depth to water table, local impeded drainage, surface drainage, marsh, swamp
   - *d.* Vegetative conditions—clearing and grubbing
   - *e.* Special considerations—roadside erosion, sidehill seepage, landscape potential, landslide potential, corrosive potential, etc.
   - *f.* Materials availability—sand, gravel, fill

A route location made without adequate knowledge of these items may be given the name by courtesy only. In so far as any one of the items is lacking, the location is incomplete. Yet, because of the expense and time involved for field surveys by older methods, too many routes are located according to line and grade, the design being based upon the assumption of an ideal subgrade, modified by consideration of whatever scanty soil data and drainage information may be available.[1] The project engineer is sent forth to do battle with nature armed, largely, with his experience and philosophy, while the maintenance engineer places a new peg in his status board. A few years ago, such a compromise with reality was excusable on the basis of time and money economy. It is no longer so. *Photo interpretation, and associated techniques, can provide usable or indicative information on most of the above items.* To show how this is so, it is necessary to discuss the conventional stages of route survey, and then the contributions that air-photo techniques can make to each one.

17-4. Stages of Route Location. A route location of high feasibility is chosen in a series of successively more detailed, more specific, and more expensive stages. These stages are (1) the reconnaissance survey (of the region, route corridor, alternative routes), (2) the preliminary survey, and (3) the location survey.

The *initial reconnaissance survey*, of the region, implies an examination of a relatively large area between two terminal points for the purpose of determining those general zones or corridors through which routes may pass. The general zones may be quite wide, being defined on either side by terrain that is inaccessible or unsuitable for various reasons. Wide rivers, lakes, swamps, and extremely adverse topography will limit almost any route to a series of corridors having greater or less width.

[1] The present 1957 program of Federal aid for highway construction requires continuous soil data even when land use and land cost dictate the alignment.

The *second phase of reconnaissance survey* is concerned with an inspection of each route corridor to determine that route, or those routes, within the zone that are most feasible in terms of certain fundamental criteria that have a significant effect upon the success of the type of route being located. The fundamental terrain criteria of railway location are ruling grade and basic geometrics. Highway location emphasizes similar factors, but with less emphasis on ruling grade. Conduit locations are concerned with changes in topography, distance, and additional considerations, depending upon the purpose of the conduit. All types of location have certain basic criteria of selection that tend to eliminate all but a few possible routes as initially feasible selections.

The *third phase of reconnaissance survey* is concerned with basic information of a more specific nature along each of the alternative routes selected. This information is concerned with a verification of the criteria used in the route-band examination plus rough data on items that have an effect upon the cost and difficulty of construction, i.e., cut and fill, slopes, bridges, culverts, general soil and rock conditions, etc. Frequently, reconnaissance topographic maps are also required during this stage.

After the completion of the third stage of reconnaissance, if the survey has been done properly, it should be possible to select one of those routes that has the highest level of feasibility of those that may be available and to estimate its cost. This cost, when compared with need, should provide the answer to the primary question of reconnaissance: should the route structure be built at all, and if so, where?

Preliminary survey is considered to involve detailed *topographic* and *qualitative* mapping of a narrow zone centered upon the reconnaissance location. Topographic mapping is always utilized. It is usually supplemented by a paper location, involving a plot of the projected center line upon the topographic plot. It is the purpose of this study to balance and minimize cut and fill as much as possible, determine quantities, the numbers of culverts, etc. Sometimes a field center line is staked during the topographic-mapping stage and other pertinent information determined at the same time by ground or electronic computational methods. Qualitative notes concerning soil conditions and marsh and drainage conditions are usually also requested, but are often given a secondary place. In some cases, the topographic crew is given this responsibility. In other instances, a soil-survey crew or contractor is placed in the field.

The final stage of location is the actual location survey. This involves accurate center-line layout as a minimum. Other items, such as cut-and-fill staking may be added.

17-5. Aerial-photographic Techniques for Road and Railway Location—Reconnaissance of Region and Corridor. As emphasized in Sec. 1-14, photographic techniques can provide usable or indicative information on most of the factors that are pertinent to a good road or railway location. This information, because it is obtained quickly, economically, and with fair to excellent dependability, can then be translated into better construction conditions, better design, and lower maintenance.

The general techniques that can be applied, and the nature of the information that can be derived from their application, are described in the following paragraphs.

In the *reconnaissance of a region*, photographic lay-downs (Sec. 1-3) and contact prints may be properly examined for general information about major topography, lakes, rivers, swamps, etc., between terminal points. During this examination, many large-scale manifestations of adverse bedrock conditions, perennial high-water-table situations, and unfavorable stream crossings also may be delineated.

Often, one day suffices for completion of the regional reconnaissance, and even for areas of considerable size (1,000 to 20,000 square miles, depending upon photo scale), a proper study should require little more than a week. After completion of the study, one or more route corridors of varying width (2 to 20 miles, depending upon nature of the area) should be obvious as the most satisfactory for further study. It must be remembered, however, that the above claims are based upon, and dated from, the availability of photographic coverage. If such coverage must be newly secured, it may be necessary to neglect the photo approach.

This stage of location is frequently done, in mapped areas, by examining topographic maps. Such a procedure, if the maps are sufficiently detailed (both quantitatively *and qualitatively*, i.e., with respect to rock, drainage, swamps, etc.), is probably acceptable, although a photo study sel-

dom requires more time and yields a far superior result in terms of qualitative details.[2] In unmapped areas, low-speed planes are often used for route selection. This technique, while it is roughly successful, has little to recommend it and can be compared to the engagement of a Cadillac for the purpose of handling gravel. While the job can be done, the cost is high, and very small results are achieved per unit of time and money expended. The difficulties are largely those of locating, evaluating, plotting, and extrapolating a continuous picture from the moving plane. Aerial-photographic examination, because it supplies a continuous terrain picture, as well as a mapping base, that can be examined, scaled, and annotated at leisure, is the better method.

Study of the selected route corridors may be accomplished in a manner similar to that used for regional reconnaissance. The only real difference is related to a greater intensiveness of examination over a lesser area. More attention is given to the details of topography, land use, river crossings, swamps, and other major criteria of feasibility. Even so, route strips of ½ to 3 miles in width should be selected within a period ranging from 1 day to 2 or 3 weeks.[3] Such strips should *definitely include the final route*, and all other terrain considerations should be eliminated.

A visual, air-borne reconnaissance of the terrain is of less value during this stage than the foregoing one, because topography and qualitative conditions assume even more importance, and these are difficult to evaluate from the air, even from the slow but expensive helicopters. Even if they were evaluated properly, as before, their pertinent details are difficult to locate, plot, and describe from a flying plane.

17-6. Aerial-photographic Techniques for Road and Railway Location—Reconnaissance Analysis of Alternative Routes. The *final reconnaissance stage, selection of alternative routes*, is based upon a fairly careful analysis of conditions within the route strip(s). At this stage, because of the exceptional importance of the reconnaissance conclusions, in terms of their effect upon policy decisions, cost estimates, and financing plans, considerable study is justified. Yet, it is at this crucial point that the old ground methods fall apart. Because of poor access, adverse weather conditions, insufficient time, lack of personnel, shortages of funds, *ad nauseam*, reconnaissance analyses are often based upon rules of thumb and average costs per mile rather than realistic appraisals of *actual* conditions along the route strips. Average costs and rules of thumb are no longer enough. Instead, knowledge of *differences* is required, as well as the probable effect of such differences upon construction.

The important factors that require consideration during this last stage of reconnaissance are *topography, cut-and-fill quantities, cultural detail, surface and subsurface water conditions, soil and rock conditions, vegetative conditions, special construction conditions*, and the *location of materials*.

There is considerable difference of opinion, as well as justifiable leeway, regarding the exact nature of the information that should be plotted or analyzed during this later stage of reconnaissance. There is also disagreement about the detail in which it should be studied and how much should be postponed to the preliminary stage. In the following paragraphs, a presentation of the information available from the aerial photographs is included. It is the proper job of the location engineer to specify which items he considers of importance to reconnaissance and which to preliminary survey.

Topography may be studied by a variety of methods:

1. Visual inspection, supplemented by simple spot stereocomparative measurements
2. Photogrammetric profiling or formlining by bridging techniques between points of known elevations, without benefit of ground control within the intervening areas
3. Photogrammetric profiling or formlining by standard photogrammetric methods, utilizing approximate ground control obtained by air-borne profilometric records instead of ground control
4. Standard photogrammetric mapping using adequate ground control

Visual inspection frequently may be used to locate a route adequately. The eye is surprisingly capable of estimating slope ranges and, in many cases, can be aided by the use of stereocomparative measurements. These instruments will provide approximate readings that can be translated into

[2] When aerial photographs do not already exist (a comparative rarity), initial photographic costs may be high However, with careful planning, the photographs can be taken at a scale suitable for subsequent photogrammetric mapping. Thus, the final cost is really low.

[3] Not a small amount of this variation is due to the necessity of working with different scales. In some cases, scales are so large, i.e., greater than 1:12,000, that mere handling of the photographs requires much time and expends much of the mental freshness that must be present for adequate photographic interpretation.



Fig. 17-1. A portion of the route study described in Sec. 17-10. Note that a simple photo lay-down (Chap. 24) has been used. Because of the reconnaissance nature of the study and the desire for speed and economy, no frills were used. Note also the complete drainage net and the areas and letters indicative of rock-soil-water complexes. (*Photographic Survey Corporation, Engineering Section.*)

local elevation differences and used as a guide in estimating slopes, bridge approaches, etc. In using these instruments, however, great care should be taken to choose points that are close together horizontally.

In areas where the route strips lie within a single line of overlapping aerial photographs (or at most cross back and forth from, but generally parallel to, two or three lines) and where elevations are available at both ends of the route, it is possible to use bridging techniques in various suitable photogrammetric machines to produce profiles and topographic maps of an approximate nature. The elevation points need not be ground points, but may be on lakes and streams. In most cases, lake elevations are considered best unless there is reason to believe that they are subject to large seasonal variations. In certain cases, where the routes tend to follow river valleys and where elevations are available at either end of the stream, approximate ground control may be computed for various points. This is done by stereoscopically examining the river, locating falls and rapids, measuring the approximate drop in each, subtracting the aggregate drops from the total stream fall, and distributing the remainder along the stream between falls and rapids.

Air-borne radar profilometric data (Appendix A) may be used as a substitute for ground control, and "formline" maps constructed therefrom. This method is particularly useful in remote, or relatively inaccessible, areas, through which long routes must be located. In essence it produces a terrain profile along a given flight line from which elevations of selected features can be derived. Such elevations are referred to an absolute datum by tying in the beginning and end of each profile to a feature of known elevation. It must be emphasized that the radar profilometer will *not* provide the profile of a given preselected line, largely because of air-navigational difficulties. Rather, data obtained from the air-borne radar profile can be used as a vertical reference and control for reconnaissance photo analyses and topographic mapping (Figs. 17-2 and 18-1).

Standard photogrammetric mapping is covered in Secs. 24-2 to 24-10, and its combination with electronic computation in Appendix C.

Drainage and ground-water conditions, of such importance to proper road location and design, are easily mapped by means of aerial-photographic techniques. Delineation of the surface-drainage network and of the watersheds contributory to major culverts is accomplished by the method described in Sec. 18-19. The location and outlining of areas having appreciable to slight accumulations of organic-mineral complexes (Chap. 15), high ground-water tables, impeded vertical drainage, excessive periodic or erratic surface-flow concentrations, or periodic fluvial inundation are outlined through the proper application of interpretative theory discussed and illustrated in Parts I and II. The author recently was asked to check the field locations of organic and poorly drained areas along some 80 miles of proposed right-of-way for a toll-road location in one of our most populous states. This he did, from the photos alone, in approximately 3.5 days. After checking with the result of the field survey, which occupied several weeks, the agreement was found to be 99 per cent

Soil and rock conditions have, during the past, been given something more than lip service, but something less than serious consideration, in designing and locating highways. This lack of engineering has been justified by various factors. One has been the impossibility of adjusting ground-survey methods and laboratory tests to the time requirements of design. Another has been the inescapable fact that ground-survey results were limited to the field of the observer's view or the dimension of the sample hole and that designs based upon such results were not much better than those based upon nothing but topography and excavation classification. A third has been the tendency to construct first-class highways on a thick pad of selected subbase material imported for the purpose.

The current expansions of highway plans, not only for first-class roads but also for second- and third-class roads (where expensive subbases cannot be afforded), the rapidly diminishing supplies of granular materials, and the high costs of select materials and maintenance are all combining to promote better designs based on *continuous dependable soil profiles and maps.* These maps can usually be best prepared by aerial-photographic interpretation.[4] A proper use of the technique should delineate *actual bedrock outcrops, areas of variable shallow* (1 to 3 feet) *overburden, areas of medium* (3 to 7 feet) *overburden, areas of deep* (7 to 15 feet) *overburden,* etc., together with those *soil areas* having significantly different char-

[4] Sometimes agricultural maps may be used effectively (Sec. 24-18).

acteristics of *landform, origin, vertical and horizontal homogeneity or heterogeneity, general textural composition, and profile contrast.* If road-location specifications call for quantitative tests and profiles, the interpretative method will aid the efficient preplanning of the drilling and sampling program. Instead of drilling every 200 to 500 feet, investigation may be made intelligent. That 90 per cent of the area giving 10 per cent of the trouble can be subjected to 10 per cent of the sampling effort, while the remaining 10 per cent of the area giving most of the trouble can be sampled intensively in advance, or possibly avoided.

In certain favorable areas, a knowledge of pedology for the area will even permit reasonable predictions of soil profiles, physical constants, and subgrade classifications (Sec. 7-9).

Vegetative conditions and *land use* may be mapped to the extent desirable. In general, for roads, this reduces to a delineation of different usage types (forest, scrub, brush, grass, tilled land).

Special construction conditions of important and possibly great, significance can often be located by careful air-photo analysis and interpretation. These conditions are discussed briefly in Sec. 18-30.

Quantities of cut and fill may be estimated by analysis of photogrammetric plots (if prepared) by either conventional or electronic (Appendix C) computational means.

The availability of materials can be investigated as described in Secs. 17-16 to 17-18.

17-7. Reconnaissance Estimates of Construction Costs from Photo Data. As mentioned in Sec. 17-4, the primary purpose of any reconnaissance survey is to select, in general, a route of high-level feasibility through an area (commonly called the "best" route) and, by estimating a rough cost, to determine whether this route is an economical venture for the service envisaged. The determination of cost is dependent solely upon the conversion of the above-listed terrain information into dollars on the basis of unit prices and experience. Therefore it is relatively easy to convert the aerial-photographic information to approximate yards of cut and fill (rock and common), acres of clearing and grubbing, number of culverts and bridges, number of miles, degrees of curvature, etc., and to translate these into unit and total costs. Estimates of cut-and-fill quantities will, at this stage, be highly approximate unless adequate topography has been completed. No statistical analyses of probable accuracies for the various combinations of techniques have been made to the best of the author's knowledge. Neither has there been enough comparative experience from which to draw indicative conclusions. It is equally true, however, that conventional methods have not been statistically analyzed, and if some actual comparative *reconnaissance* figures that the author has seen are indicative of accuracies obtainable, then the variation between estimated cut-and-fill quantities and actual quantities has been as high as 30 per cent and seldom below 5 per cent. This accuracy should be obtainable, or exceeded, through aerial-photographic techniques of the better types, particularly if electronic-photogrammetric approaches are used. In addition, any inaccuracy in quantity determinations over those obtained by field methods is usually counterbalanced by the additional information about the extent of rock versus common excavation.

17-8. Application of Aerial-photographic Techniques to Road and Railway Location—Preliminary, Location, and Construction Surveys—Determination of Final Quantities. The preliminary stage of route location begins as soon as a reconnaissance route has been selected, analyzed, costed, and approved. It is the purpose of this stage to collect enough information for detailed design, cost estimates, quantity estimates, and bid information. Conventionally, this information has been obtained by means of topographic survey, with or without a ground survey. Aerial-photographic techniques contribute in two ways, quantitatively and qualitatively. Through the establishment of adequately planned ground control, procurement of satisfactory photography, and application of photogrammetric mapping principles, excellent and accurate topographic strip maps of the selected route can be prepared (Secs. 24-2 to 24-9). These maps should be suitable for all preliminary-planning purposes. Maps having contour intervals of 5 feet, and horizontal scales of 200 feet per inch are quite common. If desired, larger intervals or smaller scales may be used (e.g., in South America 2- to 5-metèr contours are popular). In practically every case, costs and time are far below those for conventional ground methods. Qualitatively, the air-photo methods consist of a more detailed and localized application in the same directions as those discussed in Sec. 17-8. Areas of different

soil and construction conditions should be outlined in *detail*, their probable nature indicated, and the results used to plan and execute an efficient field-sampling plan. Because of the photographic perspective, the *soil, rock, and drainage plans and profiles that result from proper interpretation and field check should be continuous rather than fragmental or interpolated.* Such continuity should have a salutary effect upon design. For the same reason, the density of field drilling should be reduced.

The design stage intervenes between preliminary locations and final ground location. This stage may call for more detailed photogrammetric maps than those used in preliminary location. Intervals of 2 feet and scales of 50 to 100 feet per inch are common [5] (Figs. 6-1 and 6-2). Intervals of 1 foot have been used in certain special cases.

In the location and construction stages of route location, aerial-photographic techniques have little to offer except large-scale rectified enlargements of contact prints (for plotting of field notes and construction details, as well as permanent filing of them); sequential photography (for progress analysis, final quantity analyses, and legal records, Sec. 18-35); new topography (for route changes); and minor or supplementary interpretative analyses.

Photogrammetry has been successfully used (and checked in some cases) for the determination of final pay quantities to within 1 per cent. Williams (223) and Baker (5) have reported on these applications.

17-9. Canal, Pipeline and Transmission-line Location. The location of canals, pipelines, and communications lines is comparable, in most respects, to the location of roads and railways. The emphasis changes somewhat. For example, canals place considerable emphasis upon soil, rock, drainage, and erosion conditions, while communications lines are concerned almost wholly with topography, qualitative air-photo studies being limited to access determination and soil-rock mapping at the various tower sites.[6] Pipelines are intermediate between the two, some pipelines (gas) placing relatively little emphasis upon topography, others considerable. Most pipelines are concerned with corrosion conditions, both by ground water and salt water, plus subsurface information at proposed pumping stations. These can be generally evaluated by means of interpretative studies (Sec. 18-30).

In general, it may be said that aerial-photographic techniques can make contributions to the location of these facilities that are similar to those made to the location of railways and roads.

17-10. Example of Route Location. A typical application of aerial-photographic techniques to reconnaissance route location was the following:

The client wished to complete a reconnaissance road study along 110 miles of corridor in an area that was heavily forested; that had no roads (although a railway was within the area); and which was covered with 3 to 4 feet of snow. Data were desired prior to the spring thaw so that planning could be accomplished and field parties sent into the field immediately following thaw.

While topographic formline *maps* of the corridor were being prepared, route selections were made by *interpretative* methods. Drainage was plotted. Stream crossings were selected. The soils–rock–ground-water complexes were tentatively mapped.

An engineer was sent to the field, where he spent 10 days on snowshoes completing a *selective* field check of terrain conditions. The railway was used as a base line, side trips being made to areas where *representative, repetitive* photo patterns existed.

Finally, the photo interpretation was revised. Map units were selected and designated (Appendix B), and compilation was completed.

The preliminary report and rough maps of this job were forwarded in 7 weeks. The final report and maps were completed in 11 weeks.

A portion of the annotated mosaic along a part of the selected route appears as Fig. 17-1.

There are numerous other examples of reconnaissance and preliminary location, as well as the more detailed types of photogrammetric studies,

[5] The combinations of electronic calculation and photogrammetric mapping for purposes of analyzing trial preliminary routes, computing preliminary, design, and final quantities, as well as for many other purposes (bridge design, soil-mechanics analysis, drainage computations, and traverse calculations) were just coming into broad use as this book was written. Of course, this combination opens new vistas to engineering, removing much of the tedium and time and placing a premium upon engineering judgment and ability. See Appendix C for the presentation of typical offerings in the electronic-photogrammetric field.

[6] Microwave lines present a difficult problem for photographic techniques. The standard methods described in this chapter can be very nicely applied. Unfortunately, because the microwave client is interested only in the topography of potential tower sites, as well as those topographic obstacles that may cause attenuation of the first Fresnel zone between towers, he seldom needs or wants to pay for complete topographic photography plus radar control and photogrammetric bridging. He thus creates the paradox of fairly high accuracy requirements without the requisite operations for them!

in common use today that could be described if space permitted. Some of these are described in an ARBA bulletin (110) and in other publications.

SITE LOCATION

17-11. The General Problem. The general problem of site location is analogous to that of route location, e.g., location of the "best" site. This site should give the most economical utilization of the structure or structures contemplated and should allow the most rapid and economical construction of the structure or structures.

An airport should be geographically situated to provide the most efficient service to the greatest number of potential customers, but should also be in such a location that climate, winds, and topography do not curtail operation. In addition, drainage conditions, subgrades, materials availability, etc., should be favorable for rapid, inexpensive construction and economical maintenance.

The location of sites for dams, industrial developments, military installations, real-estate subdivisions, bridges, etc., has similar basic criteria, the emphasis changing somewhat according to the use of the facility being planned.

17-12. Stages of Site Location. The various steps leading to a good site location involve the usual common-sense procedures used in route location. First, there is reconnaissance, then preliminary survey, and finally location survey.

The reconnaissance stage is divided into two parts whose emphases depend upon the type of structure. The first phase of industrial reconnaissance, based upon research, presupposes a market within a broad general area. This area is analyzed with regard to items such as taxation, government, transportation, water supply, utilities, etc. The first phase of airport location analyzes the need for air service, and then proceeds to considerations of economical distances, available topography, and climatic factors. At the conclusion of initial reconnaissance, a decision is made regarding the feasibility of location, and one or more areas are selected for further investigation. These areas may vary in size from a few acres or square miles in well-built-up regions to several hundred square miles in outlying districts or undeveloped territory.

The second stage of reconnaissance is concerned with a more detailed evaluation of the factors previously enumerated, but has for an equally important objective the assembly of detailed information on area, soils, subgrades, drainage, access, materials availability, waste disposal, special construction problems, cut and fill, character of requisite foundation investigations, probable foundation problems, general topography, clearing and grubbing, and probable total cost of construction. At the completion of this secondary reconnaissance, there should be sufficient data to reach a conclusion regarding the most feasible site.

The next stage is preliminary survey. This survey concentrates effort upon the production of accurate maps depicting all present and future boundaries, topography, surface drainage, corners and base lines of projected facilities, qualitative delineation of major soil-foundation areas, etc. This stage also encompasses the layout and completion of any soil and foundation investigations.

17-13. Applications of Aerial-photographic Techniques to the Study of Large Sites. Contributions of air-photo methods to the study of sites for airports, industrial installations, military establishments, etc., are in every way analogous to those discussed for route studies (Secs. 17-4 to 17-10). The area has tended to become rectangular rather than striplike; the emphasis on individual items may be changed; and specific items may be added or omitted; but the skeleton is similar. Such changes as occur are those of detail and not of approach.

It should be obvious, after reading Secs. 17-3 to 17-11, that engineers who utilize aerial-photographic techniques in the initial phases of site location and analysis will have at their command a tremendous volume of information, quickly and economically obtained, with a high degree of dependability, that will give them the perspective required for sound engineering planning. The procurement of such details by conventional ground methods does not begin to compete with the air-photo technique unless special conditions inhibit the usability of the photographs. The use of the photographs is particularly valuable if interpretation and analysis are supplemented by a *day* of selective field check.

17-13a. Application of Aerial-photographic Interpretation to the Study of Small Sites (Foundation Investigations). Foundations for *bridges, small buildings, towers,* etc., are often of such minor areal extent that the concept of applying aerial-photographic interpretation to an examination of their pertinent ground conditions appears redundant. In many built-up or culturally complicated areas, such a viewpoint is justified. However, in non-built-up areas and virgin terrain, air-photo studies may often provide significant aid.

The point to remember about air-photo studies of small non-built-up areas is that they represent an increment of large areas. It is fast and economical to have the site examined by a qualified interpreter. Nine times out of the ten, nothing may be found in the photography, but the information revealed the tenth time may more than make up for the nine nonproductive instances. In some cases, it may save the cost of a complete subsurface investigation by revealing anomalous or possibly dangerous conditions. Holman (79) has recorded a specific case in which such conditions were detected prior to the expenditure of considerable money based upon false information. The writer has had several experiences of this sort. In view of the possible contributions of aerial-photographic studies of small sites and the small costs and time involved *it would seem wise to make such studies a standard procedure.*

17-14. Dam Sites. The location and analysis of dam sites by means of aerial-photographic techniques are described in Chap. 18.

17-15. Examples of Application of Aerial-photographic Technique to the Study of Sites. There have been many interesting examples of the application of aerial-photographic techniques to the study and analysis of sites. A representative one is described here.

A client wished to investigate the possible sites for a proposed large industrial development near an Ontario town. At the same time he wished to maintain as much secrecy as possible until a site had been chosen. Information was desired on topography, soils, bedrock, drainage, depth of overburden, vegetative cover, and access. Time was of great importance.

By the use of existing photography at a scale of 1:15,840, the general area (20 square miles) was examined and four sites were chosen for further study. Instructions were given for reflying of these areas at a scale of 1:10,800, required for topographic mapping. Meanwhile, the original photography was used to map soils, rock, and drainage conditions, a lay-down was prepared, and a selective field trip planned. A soils engineer was sent to the area for 4 days to complete a selective field check based on the interpretation. Upon his return, the interpreted data were finalized and compiled upon the mosaic, and a complete descriptive report was prepared on such items as access, materials, drainage, general foundation conditions, etc. During this latter stage, formline maps at 1:4,800 with 10-foot intervals were also completed.

An interesting aspect of this study was associated with the necessity of mapping narrow ranges of depth to bedrock even though the area was covered thickly with forest. The overburden ranges were mapped as 0, 1 to 3 feet, 3 to 10 feet, and more than 10 feet. A subsequent detailed subsurface exploration program revealed that the ranges mapped upon the photograph were correct, as were the interpretative estimates of texture, stratification, and depth to water table.

The entire study was completed in 8 weeks, and without revealing any intentions of the client.

The approach, nature, and results of this study have been so repetitive, in numerous instances, that it may be considered typically representative of site studies in general. Studies, including up to 15 check boreholes of up to 85 feet in depth, have been completed over areas as large as 4,000 acres in as little time as 6 weeks. This period also included time for report preparation.

NATURAL MATERIALS LOCATION AND SURVEY

17-16. The General Problem. When engineers speak of natural construction materials, they refer to materials that occur as a result of natural processes and that can be used in construction with only slight physical modification or treatment. Included in this category are bedrock, talus and boulder accumulations, gravel, sand, silts, inorganic clays, well-graded and common fill, timber, salts, and any other special materials.

To use these materials, the engineer must first locate them; secondly, estimate their quantity; thirdly, determine their suitability for the desired use; and fourthly, evaluate their accessibility. Frequently, he must also analyze their economics of exploitation.

17-17. General Value of Aerial-photographic Techniques. Aerial-photographic interpretation can be used successfully to *locate possible* and *probable sources* of materials having the *dominant physical characteristics typical of the desired natural construction materials.* The technique consists of an intelligent application of the principles outlined in Parts I and II. Some of the ramifications associated with surveys for different materials are discussed in Sec. 17-18.

Photogrammetric methods can be used to *estimate the gross volumetric quantity* of materials

occurring in talus accumulations and above-surface deposits of boulders, gravel, sand, silt, and clay. Timber quantities can also be estimated by stereographic methods. If the deposits occur mainly below overburden, or have only surface outcrops, only their planimetric area can be estimated. However, in such cases it is often easier to delineate, or at least predict, the subsurface boundaries of a given deposit from an aerial photograph than on the ground, largely because of the geological and areal perspective afforded by the photographs.

The accessibility of a given deposit can be evaluated by means of air-photo interpretation and analysis. In general, accessibility evaluation is merely a small-scale route evaluation as discussed previously, with dominant emphasis on length of haul, slopes, clearing and grubbing, culverts and bridges, cut and fill, and existence of swamps.

The suitability of a given deposit is associated with both its workability and its quality (which also affects workability). Workability is concerned with the probable maximum lengths and heights of working faces; the natural water content; the depth to water table; the possibilities of water seepage, liquefaction, and slippage; the depth, extent, and type of overburden; the types and density of vegetative cover (boulder fields); the danger of rock falls (talus); and the types of equipment and treatment that will be required to meet special or general specifications. Quality is concerned with the stratification of the deposit, i.e., the horizontal and vertical extent of various textural components; the gradations available; the mineralogical, chemical, and physical characteristics of the materials (soundness, action in concrete, shape distribution, composition, strength, etc.); and the response to explosive removal.

Aerial-photographic techniques are only of *indicative value* in assessing *workability* and *quality*. Normally, such an assessment requires careful field investigation and may call for test pits, borings, sampling, and testing. Air-photo interpretation can provide a key to field investigation by estimating the various items of workability and comparing two different deposits (in some cases) as to their probable general quality and by laying out a scheme of field boring. However, it *obviously cannot by itself,* provide *conclusive* factual data concerning the quality of the material. This must remain the province of the field engineer, chemist, and physicist.

Little direct use is made of the aerial photographs in analyzing the economics of exploitation associated with materials survey. Usually, however, because the interpreter has used air-photo techniques for other stages of study, he has better, and more, comparative data upon which to base his calculations.

In summary, the general value of the air-photo techniques to materials survey is associated with their application to the location, quantitative assessment, and access evaluation of possible sources. In addition, they provide indicative information concerning workability and quality, thereby establishing the priority and direction of field investigations concentrated upon these items. However, air-photo techniques cannot provide, by themselves, conclusive information regarding quality and workability.

17-18. Aspects of Air-photo Techniques Associated with Location of Various Materials. The location of sand and gravel is one of the most useful and common facets of materials survey. Aerial-photographic interpretation can be applied successfully to the location of materials having typical landforms, effective grain sizes, and/or permeabilities that are normally associated with sand and gravel. The word "normally" is used because of the existence of "functional drainage," as discussed in Sec. 3-18. Functional drainage usually can be predicted in terms of climate or formation and can therefore be expected or even eliminated as a factor, during interpretation. However, there is no doubt that the existence of functional drainage inhibits materials prospecting, to a certain extent, in tropical areas.

In many cases, the sand-gravel pattern consists almost exclusively of an identification of landform. This is particularly true in areas of heavy vegetative cover. The author remembers one case, in New Jersey, where a gravel deposit was being sought within an area of some 15 or 20 square miles. This area was relatively built up and well crossed with roads. All the gravel deposits were presumed to have been located, and even the "local experts" were stumped. However, a search was being made. A small glacier esker, located in the area, had been cut through, many years before, by a county road. During the intervening years, the cut banks had been overgrown with shrubs, and since the esker was small, narrow, and partially buried, its typical elevated, sinuous landform was undetected by the reconnaissance engineer.

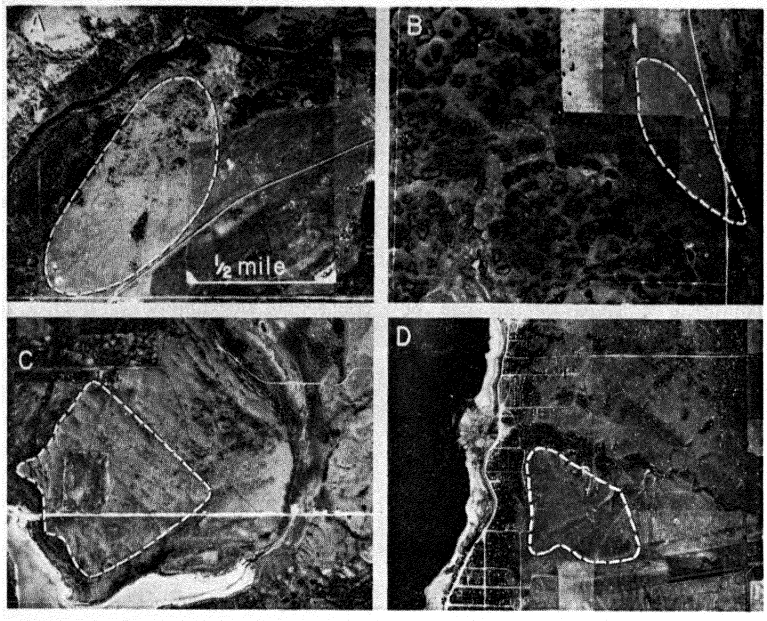


Fig. 17-2. The four air-photo patterns seen here were located from air photos and marked as good coarse gravel prospects. *A* is situated on one major construction job, *B* and C on a second, *D* on a third. For the scale of all photos, see the half-mile bar on photo *A*.

Specifications on all three projects called for one-half to three-quarter million yards of crushed material graded between ¼ and 1½ inches. In nature each deposit shown above ranged from 65 to 75 per cent retained on the ¼-inch sieve and 35 to 45 per cent retained on the 2-inch sieve. Each deposit is capable of producing the required quantity of finished material and is located within 3 miles of the closest point on the principal transportation system where the material will be used. These coarse-gravel gradations are extremely uncommon in the regions in which they were discovered. In this region a very high percentage of granular deposits contain 65 to 75 per cent passing a ¼-inch sieve, that is, sand sizes which, on projects like these, must be wasted. (*Saskatchewan. J. D. Mollard.*)

One stereoscopic look at the air photo, not even involving interpretation, was sufficient to reveal its existence—an ultimate source of 80,000 cubic yards of usable gravel.

In this case, interpretation was hardly necessary. Landform identification sufficed. Figure 9-15 provides another example of a deposit that is completely obscured by vegetation but revealed by landform. However, the real tests of interpretation are those areas where all the elements of the pattern must be analyzed.

The identification of talus and boulder fields is related simply to a large enough scale for visual identification on the photographs. Talus accumulations are illustrated in Chap. 10.

The identification of bedrock outcrops is often difficult because of small-scale or unfavorable environmental conditions. However, it is usually possible, even under adverse circumstances, to identify either rock outcrop or bedrock with shallow overburden (Sec. 16-20). Where the rock is exposed, and in some cases where it is only thinly covered, it is possible to identify the origin and general type of the rock (Chap. 16).

The identification and evaluation of timber are described in Chap. 22.

The identification of silts, silty clays, and clays is a matter of careful interpretation (Parts I and II and illustrations included therein). However, even careful interpretation will not serve as a means to distinguish organic from nonorganic clays, except in special-inference cases related to existing swamp or marsh covers (Chap. 15).

17-19. Examples of the Application of Aerial-photographic Techniques to the Location of Materials. The author, and members of his staff, have had the opportunity, during the past few years,

of locating many (more than 2,000) sources of construction materials. Most of these have been sand and gravel deposits and have been comparatively easy. However, there have also been rather challenging cases.

One of the most interesting of these had to do with a proposed earth dam in the Province of Quebec. Well-graded till was desired for the interior zone of the dam. The ideal gradation specifications for this material were those of a gently curved line crossing the sand-gravel boundary at 60 to 70 per cent, the sand-silt boundary at 30 to 35 per cent, and the clay line at 5 to 10 per cent.

The general area was filled with granular materials—sand and gravel—mostly in the form of glaciofluvial terraces, but also comprising the till. The consulting engineers had already spent several weeks, unsuccessfully, looking for the desired materials. The best samples they had obtained were fine to medium sands with some gravel, but only 5 to 10 per cent minus 200.

The area was heavily forested with coniferous-deciduous cover (Fig. 9-11). The scale of the only available photography was 1:60,000! Yet acceptable till was located after a few days of intensive photo interpretation, largely upon the basis of landform and gully shapes.

The client was pleased, although he expressed a mild disappointment that the located material had only 25 to 30 per cent passing 200, instead of the desired 30 to 35 per cent!

Mollard and Dishaw (130) have written an interesting and contributive, but unpublished, paper concerning the application of photo interpretation to materials prospecting. Many interesting comments are included, but those of greatest significance have to do with the quantitative results of the authors' activities in prospecting on the Canadian prairies. To quote from the paper:

> In the last ten years the authors have mapped 2,165 granular-material prospects (on the Canadian prairies) from aerial photographs. Individual deposits mapped from the photos, and later checked on the ground, range in quality from dirty gravelly sand to clean coarse gravel, and in quantity from a few hundred to several hundred thousand cubic yards. . . .
>
> The photo-identified granular-material prospects referred to above are distributed over a search area of roughly 32,000 square miles; all deposits were mapped in connection with preliminary engineering studies on 75 different projects. However, not all prospects mapped from the air photos were examined in the field, since the more promising looking deposits were checked first. Wherever an adequate supply of satisfactory granular material was confirmed on the ground, field exploration was usually discontinued. . . .
>
> While the areal extent of outlined granular-material prospects varied from one-half acre to ten square miles, by far the greatest percentage of mapped deposits ranged between two and twenty acres. In fact, only 206 of the 2,165 mapped deposits covered an area greater than one-quarter square miles. . . .
>
> A controlled test of the airphoto method made in 1951 revealed that granular-construction materials were found at 305 of 340 prospective deposits identified in aerial photographs. Further, 227 deposits out of the 305 deposits at which sand and gravel was found in the field had no existing pits in them at the time the photographs were taken. . . .
>
> Six construction projects having geologic terrains typifying better-than-average, average, and below-average granular-material prospects were statistically analyzed to indicate the type of assistance that might be expected from airphoto searches.

Other interesting quantitative facts are presented. Some of these were summarized in the author's discussion of the paper:

> One of these shows that physiographic setting, i.e., relation to surrounding topography, was of importance to materials location more than 90 per cent of the time, while such things as microrelief, gully shapes, and soil tones also were helpful approximately half (or more) of the time. . . . Once again, this points up the exceptional importance to a materials engineer of an adequate knowledge of geomorphology. At the same time, it corroborates the contention that air-photo interpretation is not done by landform alone, but also depends upon a coincidence of evidence as provided by other elements of the air-photo pattern.
>
> The other conclusion shows that air-photo interpretation, by qualified people, should be successful 75 to 100 per cent of the time. . . . It also shows that the technique is not a method for assessing the quality of granular deposits, but rather one for identifying deposits having characteristics commonly associated with sand and gravel. In other words, while interpretation may be successful 75 to 100 per cent of the time and the located deposits will yield subbase material for approximately the same percentage, highly select material may be expected about 10 to 20 per cent of the time. These figures do not, of course, have any regard to the objective of the search and are over-all.

Figure 17-2, from Mollard and Dishaw's paper, includes some typical gravel and sand patterns in the area of their activities (see also Figs. 18-5 and 18-6).

18 APPLICATIONS OF AERIAL-PHOTOGRAPHIC TECHNIQUES TO ENGINEERING (Continued)

18-1. Scope of Chapter. This chapter discusses the applications of aerial-photographic techniques to the important fields of *water resources* (hydrology of surface and ground water), *water utilization* (hydroelectricity and water supply), and *water regulation* (flood control and drainage). The chapter also briefly considers the use of air-photo methods as a means of aiding *coastal and harbor studies*, the *location and assessment of special construction problems, landslide investigations, permafrost surveys*, the *planning of field surveys*, and certain miscellaneous engineering activities.

Each of these topics is discussed under a separate heading.

To aid in presenting the air-photo applications, brief consideration is given to the technical nature and scope of each of the technical specialties covered. To the author, this seems an ideal way to knit the subjects together. It also places the applications on a more realistic and specific level.

WATER-RESOURCES STUDIES

18-2. General. The field of water-resources studies is essentially the same as that encompassed by the science of hydrology (Sec. 7-19), although hydrology is often mistakenly presumed to be solely a mathematical and statistical evaluation of basic records and observations. Both the specialist in water resources and the specialist in hydrology are concerned with one problem: how much water, of any type of occurrence, will be at any given point(s) at any given time(s). Obviously, the solution of this problem calls for training and experience that go far beyond mathematics alone.

The field of hydrology—and therefore water resources—can be logically separated into five major divisions. The five are *precipitation, evapotranspiration and interception, infiltration, ground water,* and *runoff*. The applications of aerial-photographic techniques to the water-resources field may be discussed in a similar order.

18-3. Application of Aerial-photographic Techniques to the Hydrology of Precipitation. Precipitation is the collective term assigned to the aggregate amount of atmospheric, condensed water vapor that comes in contact, or tends to come in contact, with the land. It may occur as rain, snow, hail, dew, or frost.

Aerial-photographic techniques have few applications to the study of precipitation. In general, there are only two. One is the inspection of aerial photographs and mosaics as an aid in locating new, representative rain-gauging stations and snow-sampling courses or evaluating existing ones. The other is associated with the weighting of data from various rainfall- and snowfall-gauging stations and courses. Both of these applications are more or less simple and obvious, as well as of limited value, and it is doubtful that they will be used with any frequency except in undeveloped areas of the world. The use of selective sequential photography might well provide considerable aid in evaluating snowfall, and thereby prove an exception.

18-4. The Nature of Evapotranspiration and Interception. A major type of hydrological problem is the determination of long-term water yields and the variations in such yields. The solution of this type of problem calls for a fairly reliable estimate of water losses. Such losses, deducted from total precipitation, leave a residue of surface and subsurface runoff that is, in essence, water yield.

Water losses may be defined, then, as the difference between precipitation and total runoff. They are caused by evaporation from land and vegetative and existing water surfaces; transpiration by plants; and, for a given watershed, surface or subsurface leakage into an adjoining catchment.

"Evaporation" may be defined as the change of water in the liquid or solid states to water in the gaseous state through the transfer of heat energy (2). Evaporation from water surfaces is well known and easy to understand (though difficult to measure!). Observations have shown that the quantity of evaporation from such surfaces may frequently exceed the precipitation falling upon them so that their effect upon the yield within a given catchment may be disproportionate to the percentage of the catchment's area that they occupy. Further, water surfaces need not be confined to those unencumbered by vegetation. Areas covered by water for substantial portions of the year, i.e., swamps, marshes, river bottoms, etc., also have an evaporation opportunity of 100 per cent, and their contribution to water losses must be included in any realistic evaluation of them. The evaporation from soil and vegetative surfaces has been said to be largely due to the evaporative power of the atmosphere rather than to characteristics of the soil (2), although this probable fact has not been definitely proved. The amount of such evaporation is, however, partly related to terrain and soil characteristics (Sec. 5-11).

"Transpiration" may be defined as that process, carried on by plants, that involves the absorption of water from the soil by plant roots, its passage through the plant, and its discharge back into the atmosphere as water vapor. Transpiration is very important in yield problems because it constitutes a large proportion of water losses, particularly in areas where heavy vegetation is associated with high ground-water tables (marshes, swamp bottomlands, old lacustrine areas, etc.). A case has been mentioned where an area was covered by dense deciduous forest having a heavy undergrowth. The area received an annual average rainfall of approximately 70 inches and had an average annual temperature of 55° F. Measurements indicated that some 17 to 22 inches, or approximately 24 to 31 per cent of this yield, was lost through transpiration alone!

"Interception" may be defined as that portion of precipitation which does *not* reach the ground but is held on the surface of vegetative cover until evaporated. Actually, interception should be considered as a component of total evaporation. Studies have indicated that the quantity of evaporation depends primarily upon the evaporative capability of the atmosphere, not upon the nature of the soil-vegetative complex (80).

"Evapotranspiration" and "consumptive use" are two terms for expressing the *combined* water losses that can be attributed to evaporation (including interception) and transpiration.

18-5. Application of Aerial-photographic Techniques to the Study of Evapotranspiration. Air-photo methods are of aid to studies of evapotranspiration in several ways.

By means of air-photo analysis and interpretation, it is possible, easily and economically, to delineate and measure those lakes, stream surfaces, river bottoms, marshes, and swamps that have 100 per cent evaporation opportunities. Further, it is comparatively easy to estimate those fluvial areas that are only seasonally inundated. In many locales, if the photographs are taken during the right season, the low water levels may be compared with the high levels. Water areas, accurately measured, may comprise a surprisingly large proportion of the total area included within a given catchment. As mentioned in Sec. 18-4, they may evaporate more than their proportionate precipitation. This compounded effect would seem to demand careful measurement of areas having high evaporative opportunities, and unless accurate, detailed maps exist, such measurement can only be gotten by means of photographic interpretation and analysis.

Aerial-photographic interpretation may also be used to delineate areas having different vegetative densities (Chap. 22) and probable interceptive fractions, if such data are considered important.

Through the medium of interpretative study, as explained in Parts I and II and Chaps. 21 and 22, investigations of the innumerable vegetative–soil-drainage–land-use complexes that affect transpiration, soil evaporation, and consumptive use (via infiltrative capacity, Secs. 18-7 and 18-8) may be completed to any degree of detail. If such studies are detailed, they will inevitably involve considerable selective field checking and measurement (Sec. 24-14).

18-6. Nature of Infiltration. "Infiltration" may be defined as that portion of precipitation which, upon coming into contact with the mineral soil, enters the soil profile by downward lateral flow.

Infiltration may be divided, with regard to its disposition, into three components: (1) that which becomes a portion of water losses, (2) that which becomes a portion of total runoff, and (3) that which becomes a portion of the ground-water body. Some infiltrated water is absorbed by the root systems of vegetation and is ultimately tran-

spired. Another portion is retained in the contact-moisture and capillary zones (Sec. 5-10) of the soil and is ultimately evaporated. Both of these portions combined are *contributions to water losses.* Some infiltration moves rapidly and laterally beneath the ground surface, quickly returning to the surface and entering the stream-flow runoff. This is termed *subsurface runoff.* A third portion of infiltrated water percolates to the ground-water table, enters the *ground-water body,* and either goes into storage or returns to the surface at some distance and after some time.

The amount of infiltration that can be assigned to any or all these categories is affected by an imposing list of independent and dependent variables. These include soil factors (texture, aggregation, profile, chemical nature, surface condition); vegetative factors, (type, density, variation in protective ability during growth); moisture factors (natural moisture, relation to water table, extent of frost and ice, rate of inflow, capillary potential); and special factors (temperature, chemical nature of water, topography, orientation of cultivation, swelling capacity of soil, rainfall energy).

Infiltration theory and data provide methods for the estimation and analysis of surface runoff. These estimates may be related to the study of specific rains on small areas such as airports, urban developments, small drainage plots and watersheds, etc. They may be related to studies of mass runoff over large, complex areas composed of numerous soil-rock-vegetative-topographic components. They may involve the effect of land treatment on floods, erosion, and soil-conservation practices.

Data on infiltration are usually secured by establishing infiltrometer stations at representative locations in the field, or by establishing and carefully measuring the flow from typical small watersheds and drainage plots.

18-7. Application of Aerial-photographic Techniques to the Study of Infiltration. To obtain realistic estimates of infiltration, it is necessary to have realistic infiltration data. The realism of such data is directly proportional to the accuracy and dependability of information that can be obtained regarding the factors mentioned in the third paragraph of Sec. 18-6 and the relation between such factors and infiltrometer measurements or drainage-plot and watershed analyses.

Specifically, aerial-photographic techniques, as explained in the preceding portions of this book, as well as in Chaps. 19 to 23 following, make it possible to divide any area into its various infiltration components. This division can be made initially on the basis of rock conditions, soil conditions (depth, texture, etc.), vegetative cover, land use, surface-drainage network, and topography. Even factors affecting ground-water recharge can be indicated (Sec. 18-9). Representative areas can then be selected by air-photo examination, checked in the field, and subjected to infiltration tests run during periods of representative dominant conditions. The results of tests can finally be combined to provide incremental and total analyses of total infiltration, lost infiltration, subsurface runoff, etc.

There may be some who will say that the infiltration approach is interesting, but that it has never worked and never will, because of the multiplicity of factors involved. This may be correct. However, it seems to the author that it *is* an approach and that its failure in the past may be due to a lack of dependable and detailed data regarding the location and extent of the various infiltration complexes. This lack has not been caused by an absence of desire or ability to map such complexes, but rather by the unavailability of time and money required to do so. As the "Hydrology Handbook" (2) says:

> The collection of plot and watershed records is time consuming and costly. For this reason rainfall and runoff measuring facilities are seldom installed on more than a very few of the numerous complexes of soil, cover, and condition that make up a river basin. Estimates for the great majority of these complexes are either secured by judgment, interpolation, or, increasingly in recent years, by a quick survey with infiltrometers. In many investigations, limits on time and cost preclude any measurements under natural rainfall and use is made of plot and watershed records on similar complexes outside of, and often at considerable distances from, the areas under study.

The aerial-photographic techniques now provide an approach that is reasonably consistent with time and money economy and that can provide relatively dependable data in the first instance. Consequently, before discarding the infiltration approach, the air-photo techniques should be incorporated in it.

18-8. Nature of Ground Water.[1] Ground water, for the purpose of this discussion, is water stored or in transit beneath the surface of the earth and

[1] The author is indebted for this section, as well as for Sec. 18-9, to David K. Erb, Pleistocene and Groundwater Geologist, Engineering Division, Hunting Technical and Exploration Services.

available for use in any manner by the simple expedient of sinking a well to its level.

This discussion does not deal with ground water per se, but rather with techniques designed to locate and evaluate ground-water reservoirs and aquifers, and specifically with the technique of aerial-photographic interpretation as used in these investigations.

Assuming an initial source of water, the distribution of ground-water reservoirs and/or aquifers is controlled entirely by geologic factors. Ascertainment of these factors requires an interpretation of the surficial geology plus the use of experience and deductive reasoning to extrapolate the surficial features to the subsurface. Selective field investigation should be used to confirm the surficial geologic interpretation and to carry out subsurface studies designed to evaluate the rocks, water, and/or unconsolidated materials at depth.

18-9. Application of Aerial-photographic Techniques to the Study of Ground Water. Aerial-photographic interpretation is capable of delineating, in consolidated materials, such features as rock type, whether porous or nonporous, massive or bedded; if massive, whether jointed, fractured, or faulted; if bedded, whether steeply dipping, moderately dipping, or flat-lying (Chaps. 16 and 19); and many other things which are of importance from the point of view of their water-carrying or aquifer and water-storing reservoir abilities. In the case of unconsolidated deposits, air-photo techniques often provide considerable data for the analysis of geomorphologic features; the history of deposition or formation of such deposits; the presence or absence of porous sand or gravel beds and their extension at depth; the topographic expression of subsurface structures; and the presence of vegetative water indicators. If the information obtained by air-photo interpretation is coupled with a reasonable knowledge of ground water and its habits, the result should be a relatively comprehensive evaluation of the ground-water potential of the area under study.

The availability of supplemental data in the form of geologic, pedologic, climatologic, and hydrologic reports, and in some cases, actual water-well logs and performance figures, will obviously lead to a more accurate and more detailed evaluation of the conditions. However, the aerial-photographic technique, by itself, provides a method of at least making a relatively comprehensive initial evaluation where the other data are lacking or not available. It also can provide a very satisfactory basis for the planning of an exploratory drilling program in an unknown area.

18-10. Nature of Runoff. In general, runoff may be defined as that residue of precipitation that is drained from the land via surface channels, or subsurface connections to such channels, after the prior demands of evapotranspiration and capabilities for infiltration have been satisfied.

Runoff is probably the most important general element of hydrology, except precipitation. Runoff causes the floods, the soil erosion, the drainage problems, and the high sedimentation. It provides the water for towns, industries, irrigation, hydroelectric generation, navigation, and recreation. Ground water is also important for each of these purposes, sometimes dominantly so, but runoff is always in the picture and always must be considered.

One of the techniques of flood study—and an essential one for planning flood protection—is that of studying and predicting floods by means of the unit hydrograph. The construction of the unit hydrograph is usually dependent upon adequate rainfall and runoff data. However, where such data are insufficient, it is sometimes possible to synthesize a hydrograph and obtain approximate analyses. The synthesis is partially completed by investigating past work that shows the apparent relations between hydrographs and basin characteristics such as length, width, area, shape, stream density, stream slope, catchment slope, infiltration capacities, vegetation, topography, etc.

Another runoff approach that is widely used for small areas and basins (less than 1 to 100 square miles) is the so-called "rational method," which relates quantity of flow to such factors as vegetative cover, time of concentration, area, and intensity of rainfall. In some cases additional factors such as basin dimensions, slopes, and channel roughness are inserted in the equation. The time of concentration, an important factor, is very responsive to changes in infiltration capacity and slope.

Other techniques of drainage, sewerage disposal, yield estimates, etc., use information on the location and type of infiltration complexes to develop theoretical hydrographs. These are then analyzed to provide synthesized runoff data.

By far the commonest analytic method of evaluating runoff is that based upon the records of stream-gauging stations. These stations may be

set up to record a variety of factors such as stage and velocity of flow, sedimentation, etc. The records from these stations are statistically analyzed and compared with basin characteristics to provide predictions and evaluations of runoff.

18-11. Application of Aerial-photographic Techniques to the Study of Runoff. The major applications of air-photo methods to the study of runoff are related to the delineation of the surface-drainage net (Sec. 18-17), the determination of areal (basin) and river geometrics (Secs. 18-15 and 18-16), the determination of infiltration complexes (Sec. 18-7), and the study of sedimentation and river regimen (Sec. 18-18). Elements of information obtained from these determinations may be used in preparing estimates of runoff by the aforementioned methods.

Another very important application of aerial-photographic interpretation is the tentative selection of gauging stations for further field check. Areas of uniform width and straight length, rock floors, and suitable embankments may be located, and the chances of scour, sedimentation, or tributary interference evaluated. Since adequate gaging stations are the foundation stones of effective hydrological investigations, it is most fitting that modern methods be used in their initial selection. In this respect, photo interpretation is indicated.

If the primary purpose of a project is the selection of gauging stations and new photography is justified, a suitably large scale should be chosen. However, this scale should be compatible with further use as a means of studying geometrics, sedimentation, and regimen, since this is what it will almost undoubtedly be used for. The author believes that a scale of 1:10,000 or 1:12,000 is fairly convenient, economical, and multi-useful in this connection. In some cases, where gradients are low and details complex, a scale of 1:6,000 may be required. In other cases, existing photography at 1:20,000 may be used satisfactorily.

WATER-UTILIZATION AND WATER-REGULATION STUDIES

18-12. General. Water-utilization and water-regulation studies may be divided into two major classes, implied by the words "utilization" and "regulation," as well as subdivisions based upon the primary objectives of study: (1) those primarily concerned with the *use* of available water (water supply, hydroelectricity, navigation, recreation), and (2) those primarily concerned with the *control* of available water (flood control, drainage and sewerage control, erosion, reclamation, and conservation).

Of course, all combinations and permutations of the above types can occur.

From the standpoint of terrain consideration, all the above types require information on factors such as hydrology, geometrics, sedimentation, regimen, soils, land use, geology, vegetation, and possibilities for location and construction of engineered structures.

The nature of each of these latter elements, as well as the possibilities for its study by aerial-photographic techniques, is discussed in following sections.

18-13. Hydrology. The divisions of hydrology, and the application of aerial-photographic techniques to their proper study, have been discussed in Secs. 18-3 to 18-11. This discussion was concerned with generalities. Details of hydrology that are specifically related to various water studies vary from these generalities in detail, direction, and intent. In most cases, they are concerned with design or regulatory criteria, and their details may be quite complex. This is particularly true for multipurpose projects where the available sequences of water quantities, times, and locations must be apportioned or scheduled in accordance with the various project objectives. It is almost impossible, for example, to completely satisfy both power and irrigation demands with a single dam-reservoir combination.

Because of these complications, it is highly desirable that hydrological studies receive the best possible examination consistent with project magnitude and funds. For large projects, it is rare indeed when aerial-photographic techniques cannot be used effectively for the better collection or analysis of hydrological data. Unfortunately, it is equally rare to find them so used.

18-14. Nature and Value of Geometrics (Area, Rivers, Drainage Network). Though perhaps a poor term, geometrics, in so far as water studies are concerned, refers to the dimensional character and planimetric arrangement of the catchment(s), important streams, and total established runoff network within the area of consideration. Geometrics includes (1) geometry of catchment(s)—boundary, shape, area, length, width, topography, (2) geometry of major stream(s)—shape, length, width, profile, and (3) arrangement of the surface-drainage network.

Most hydraulic and hydrological studies use one or more catchment areas as units of study. Such units are logically justified because they include the total hydrological complex (excluding ground water) that affects the major stream(s) draining them. Further, they usually provide areas of sufficient size for rational hydrological consideration. Lastly, if the area of study is large enough, it often happens that a major catchment consists of an economic and geographic unit having land use, vegetation, climatic regimen, topography, etc., which are somewhat distinctive in comparison with adjoining areas. Accepting the catchment as a study unit, then, its geometrics becomes of moment as an index of its hydrological and hydraulic properties, behavior, and possibilites.

It is for the above reasons that the first element of information requested by a water-resources specialist is a map showing the watershed boundary

Having determined a boundary, the horizontally projected areas of the catchment and subsidiary catchments can be obtained by means of conventional or electronic planimetric measurement. All other things being equal and uniform, the areas of the catchments have a proportional effect upon total yield; i.e., for similar catchments having equal mean annual rainfalls, it may be expected that the largest basin will have the largest mean annual yield. Further, the area may be expected to affect the magnitude, rate, and sustenance of maximum and minimum flow, although the relation is general and often obscured or dominated by other factors.

The boundary also determines shape, width variation, and length variation. To an experienced specialist in water studies, these characteristics may be combined in various forms to provide quantitative indices that may be used to predict certain broad hydrological or utilitarian tendencies.

The topography of a watershed is of great importance to prudent and practical water use and control. In terms of averages, expressed by factors such as mean elevation, average slope, etc., empirical relations, based upon experience, may be established for temperature, precipitation, evapotranspiration, runoff, length of overland flow, etc. In terms of tabulations of areal-elevation components, comparisons between catchments can be made and the service areas for various outfall elevations of reconnaissance possibilities may be determined. In terms of specific detail, for the scales and intervals consistent with the study, a knowledge of topography provides the usual essential quantitative basis for engineering planning.

The geometry of the major rivers, i.e., those rivers that appear (after inspection of the drainage network) to be the ones most important for the contemplated project, is an element of great value to the proper completion of water studies. Knowledge of shape, length, and width variation is used frequently as an aid in the prediction of flood peaks, quantities, and routing; the evaluation of water losses; sedimentation and regimen; and the analysis of navigational or irrigational possibilities. A knowledge of the stream profile is equal in importance to information about the watershed area, for it is the profile that controls the location of the regulatory structures, storage areas, power and irrigational potential, runoff velocities, navigational possibilities, etc.

The geometry of the total surface-drainage network, i.e., its arrangement in plan, is another very important element in hydraulic and hydrologic studies. Not only does it give important information about the qualitative nature of the terrain (Chap. 3), but it also aids the development of hydrologic analyses (Sec. 18-11) and shows the existing pattern of runoff that is essential in planning for irrigation, sewage disposal, drainage, erosion control, subdivisional planning, runoff diversion, and waste collection.

18-15. Application of Aerial-photographic Techniques to the Study of Areal Geometrics. Aerial-photographic techniques are of immense value in completing any serious study of areal geometrics. In fact, it would seem ridiculous to use any other method, unless adequate, dependable, *sufficiently detailed* maps were already available. The author has seen a number of instances where fairly elaborate plans for water development have been completed using areal-geometric factors that were not only false, but seriously so—in short the proverbial "house built upon sand." He has seen other instances where areal geometrics has been neglected, not because it was unwanted, but because proper maps were lacking or the nature of the terrain was unfavorable (flat and swampy, subject to double drainage, etc.) to its determination.

There are two general aerial-photographic approaches for securing the desired data. That which provides the quickest and cheapest, yet practically usable, picture of areal geometrics is a proper combination of stereo analysis and photo-lay-down inspection. Photo lay-downs (Secs. 1-3 and 24-7) are prepared. These are examined to determine the nature of the primary (sometimes the sec-

ondary, Sec. 3-15) drainage network, the location of major swamps and lakes, etc. Those prints that cover the zone within which the watershed boundary should lie are selected for stereo analysis. The stereo analysis comprises a plotting of secondary and tertiary surface drainage (Sec. 18-17) along the probable height-of-land zone. This plotting is transferred to the lay-down and inspected for errors and inconsistencies, and the actual catchment boundary is drawn in. Variations on this approach may include the use of a proper semicontrolled or controlled mosaic rather than a simple lay-down. However, unless there is some extraneous reason for specifying such a product, the extra expense is seldom justified.

The second approach to a definition of areal geometrics is the purely photogrammetric one. This approach, if it is intended to be accurate, is expensive. If it is intended to be approximate, little advantage is gained over the stereo-analytic method. Where boundary information is highly important; where the terrain in the vicinity of the probable boundary zone is characterized by extensive marshes, flatland, and/or double drainage (common occurrences in Canada); and where adequate control either already exists for use in strip mapping or can be obtained with relatively little expense; in such cases the photogrammetric approach may be justified.

Once the boundary of an area is plotted on photographic lay-downs, mosaics, or maps, it is a simple matter to compute the actual area and analyze shape, length, width, etc. Occasionally, if very rough photo lay-downs using entire prints are used as a planimetric base, errors in measured area, the course of streams, depiction of boundaries, and outline of lakes will occur. These are caused both by the radial distortion inherent in an unrectified print and the overlap between adjacent prints, particularly in areas of severe relief. The extent of such errors cannot be evaluated easily, but it can be presumed as relatively insignificant for practical purposes. It can be minimized, if desired, by preparation of waxed lay-downs composed of the trimmed central portions of all photographs, or by the scale ratioing of all prints before laying them down. It may be eliminated by making fully controlled mosaics (Secs. 1-3, 24-7, and 24-8).

The topography of a given catchment, while it may be evaluated generally, is often neglected in detail. This is not true for very small (100 to 1,000 acres) to small (1,000 to 10,000 acres) areas, but is prevalent for larger ones. The reasons are largely related to expenditures of time and money, and in such cases even photographic techniques prove of less aid than usual.

Of course, it is possible to examine the general topography of the watershed on photographs, and to indicate its general nature by hachuring, but this is not quantitative. If the project justifies it, a series of photogrammetric methods, varying in order of dependability and area of applicability, are available for use:

1. Establishment of an "approximate-control network" and mapping to it
2. Use of an existing approximate or accurate control network and mapping to it
3. Establishment of a new accurate control network and mapping to it
4. Combinations of the above

The establishment of an approximate control network and photogrammetric mapping therefrom is, of course, a reconnaissance or preliminary technique. Vertical control may be provided by aneroid-barometric profiles or air-borne radar profiles (Appendix A). Horizontal control may be provided by existing triangulation (particularly that making use of the tellurometric or geodimetric techniques), shoran, selective astronomical observations, or pure estimation using existing planimetry. This technique is best used for large to medium-large areas (greater than 100 square miles); remote, relatively inaccessible, or climatically restricted areas; or areas whose exact conformation is not compatible with the objectives of the study and the funds or time available for its determination. Actually, the technique, properly applied (and particularly if some identifiable existing control can be combined with the approximate approach), gives rather good results. It can be very useful if its limitations are well understood. An example of its application to route location is discussed in Sec. 17-10.

Existing control networks commonly comprise barometric leveling, shoran, Airborne Profile Recorder (APR—see Appendix A) triangulation nets, base-line and coordinate or grid surveys, geodetic elevations, railroad and road surveys, and airport and municipal surveys. There are many instances where a careful investigation of both the possibilities and actualities of control will save considerable expense and time in completing an areal (and aerial) topographic map. Of course, this investigation may be two-edged, for there are equally nu-

merous instances where the costs and time required to evaluate existing data only show that they are inadequate, undependable, or unsusceptible to coordination.

The establishment of a new, accurate control network, and photogrammetric mapping therefrom, follows standard general procedures, as discussed in Secs. 24-5 to 24-9.

18-16. Application of Aerial-photographic Techniques to the Study of River Geometrics. The *complete* courses of major streams are displayed in unparalleled clarity and detail on aerial photographs and mosaics. Every curve, runlet, reach, bar, and channel (wet or dry) is apparent. The location of every rapid, riffle, fall, and shoal can be detected by careful examination under a stereoscope. The study of horizontal river geometrics, using air photos, is simply one of getting the right scale of photographs at the right time; assembling them in a way that is consistent with the needs and finances of the project; examining them stereoscopically for the detailed geometric information that is desired; and plotting or measuring at will.

In planning a study of river geometrics, it is important that careful thought be given to the choice of scale (Chap. 24). Care should also be given to the selection of a correct time for photography. It depends upon the objective of the project whether the photographs be taken during flood, low flow, or mid-flow. If existing photographs are used their date of exposure and corresponding flow stage should always be determined and recorded. In some cases it may be most useful to obtain sequential photography showing a variety or a complete series of flow stages.

It is also important to use the proper techniques for assembling the photographs. Because of the radial distortion (Secs. 24-2 and 24-3) that is present in every unrectified photograph, consideration should be given to the demands of the project as compared with the accuracies of photo lay-downs, scale-ratio mosaics, controlled mosaics, or planimetric-photogrammetric maps (Secs. 1-3, 24-7, and 24-8).

The above comments pertain to horizontal geometrics. A more important factor is the stream slope. Its determination, even using photographic methods, is not as simple. A true, accurate slope of the stream surface, at the time of photography, is obtainable through the medium of photogrammetric mapping (Sec. 24-3). If accuracy is required, there is a wide variety of photogrammetric techniques available from which to choose. However, while these techniques provide the least expensive *accurate* method, they nevertheless require the establishment of ground control. In remote areas, particularly, such an operation may cost considerable time and money.

A frequent problem in unmapped areas, usually remote or relatively inaccessible, is the determination of an approximate stream profile—one where the major slopes and breaks in gradient are located and determined quantitatively with *reasonable* accuracy. If the total fall of a given river, between the desired points, is known, aerial-photographic techniques provide a means of analysis. One way is that of Multiplex bridging, the major breaks in gradient being located before setting up and their approximate drop noted. The remainder of drop is adjusted by trial and error. A similar technique is the interpretative location of all drops, followed by their stereo analysis with simple parallax-bar devices of one sort or another and the adjustment of the remaining drop between the various points measured. A third method utilizes APR as a substitute for ground control, being followed by standard photogrammetric mapping and profile takeoff (Fig. 18-1). All these methods are approximate, but for reconnaissance and preliminary studies, they often prove most satisfactory, particularly when existing photography is used. It might also be mentioned that they are relatively inexpensive.

18-17. Application of Aerial-photographic Techniques to the Study of Surface Drainage. As noted and explained in Sec. 3-16, the most carefully prepared and large-scale topographic maps (including photogrammetrically prepared ones) seldom show the tertiary and rill and gully drainageways. Yet, these very unmapped drainageways often cause much of the trouble for small development projects. Also, it is these drainage channels that actually define the extent of any watershed, large or small. Consequently, their omission may be considered a serious flaw in many "maps" and a disadvantage in practically all.

Aerial-photographic analysis, combined with the preparation of lay-downs, provides a means of easily, quickly, dependably, and economically mapping the surface-drainage net in all its detail, including gullies, shallow swales of surface and subsurface flow, large springs, etc.

Aerial contact prints can be examined stereoscopically, and all the drainageways outlined by qualified photo analysts. The streams may be out-

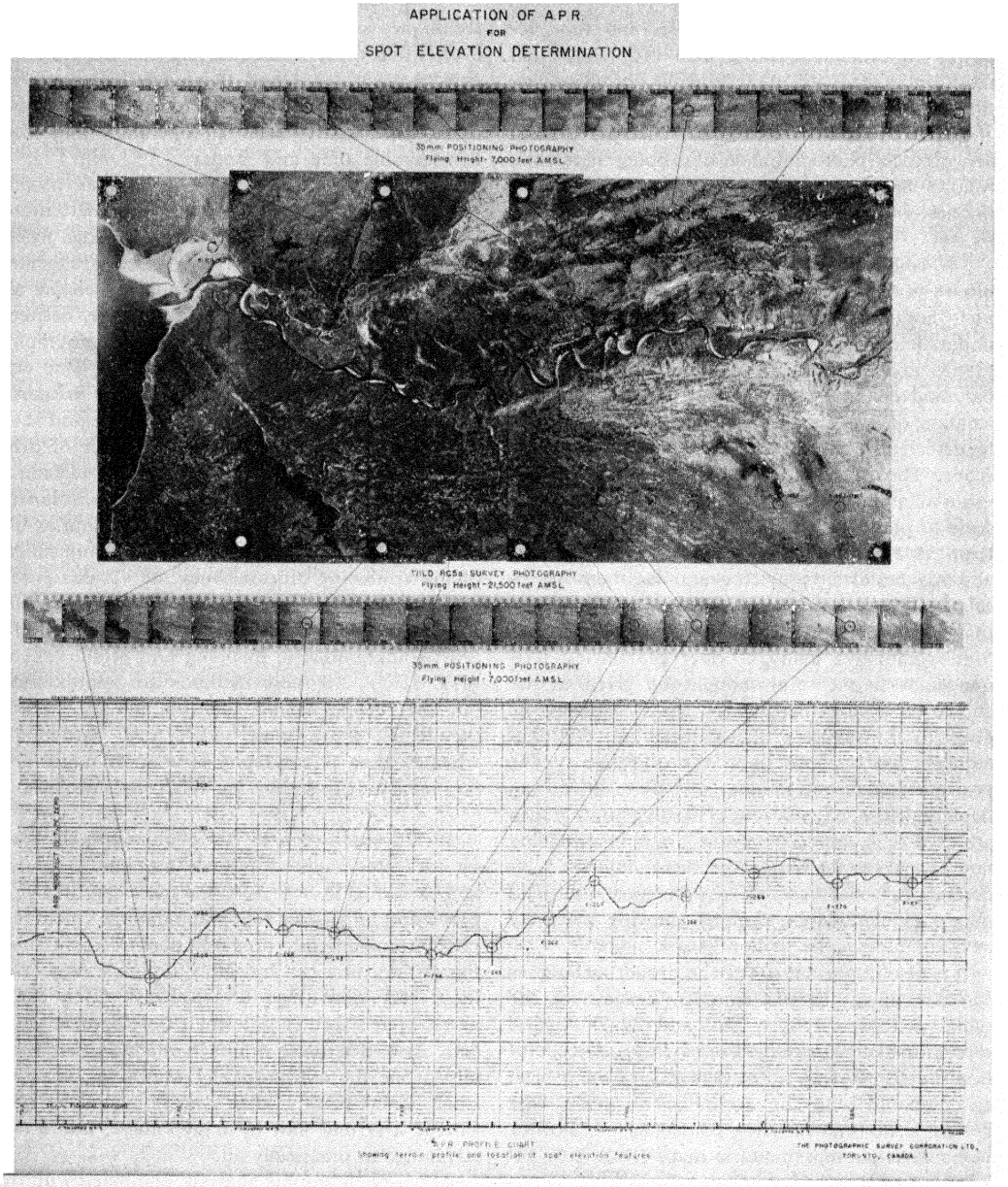


Fig. 18-1. Portion of a strip mosaic along a river, showing the location of control points selected for photogrammetric formline mapping. These points were selected from airborne radar profiles (*bottom*) taken on either side of the river by inspecting the 35-millimeter-positioning camera records (*small strips*) and correlating them with a stereo inspection of the terrain shown on the contact prints (Appendix A). (*Quebec. Photographic Survey Corporation.*)

lined according to some schematic classification that is decided upon, following a rapid initial inspection of the photography. The plotted drainage is checked by random inspection, and is then transferred to lay-downs or mosaics. If the base consists of lay-downs, only the central portions of the photos should be used. Overlays may be prepared if desired. Alternatively, by use of stereometric sketching instruments or other techniques, the drainage can be compiled upon town base maps, assessment maps, zoning maps, subdivision plans, etc.

Sometimes, estimates of width and depth may be made of the major channels (including the rivers, Sec. 18-18) to provide approximate values for the wetted perimeter and area. These may be transferred along with the net and, with slope, will allow estimates of runoff velocities and quantities.

Of course, once the complete surface-drainage net has been plotted, the delineation of any large or small watershed is largely a matter of drawing lines between its tertiary and rill and gully drainageways and those of its neighbors.

18-18. Sedimentation and Regimen. The pattern of sedimentation within a river's course refers to the variations in location, type, and time-quantity combinations that occur in the deposition of its suspended and bed loads. All rivers and streams engage in deposition. Some young, primarily erosive streams (Sec. 9-3) deposit only slight amounts of coarse sediments, at restricted locations. Other "graded" streams (Sec. 9-4) may produce tremendous quantities of variable sediments throughout their length. Some streams deposit throughout the year. Others do it seasonally. The types and locations of load may vary incessantly. All combinations of the various factors exist.

Most studies of streams involve some attention to sedimentation. For some studies, e.g., maintenance of navigation and estimation of long-term reservoir capacity, its consideration is highly important and its pattern must be investigated in considerable detail, as well as, it is hoped, with high accuracy.

The regimen of a stream includes its pattern of sedimentation, but is more comprehensive. Actually the term "regimen" implies the complete behavior pattern of a given river. The entire complexly shifting, highly integrated system of variations in suspended load, bed load, sedimentation, velocity, stage, flood, overflow, low flow, etc., together with their attendant variables (duration, frequency, time of occurrence, location) and their effects upon the stream bed and banks, may be termed the regimen of the stream.

A good deal is said about regimen, but not too much is done about it. In some highly important, well-financed projects, serious efforts are made to study regimen. In many more projects, the variations in a few of its component variables, commonly flood stage, sedimentation, and low flow, masquerade under its name. This is not because a study of regimen is deserving of neglect. The contrary is true. Rather, it is because it is such a difficult thing to study that its neglect is dictated by lack of time, money, approaches, evaluative methods, and pure patience. Blench (24*a*) has recently written a book that may aid the correction of this situation by providing a summary of quantitative methods for the study of regime. The combination of these methods with air-photo interpretation should be a powerful investigative method.

18-19. Application of Aerial-photographic Techniques to the Study of Sedimentation and Regimen. The applications of air-photo methods to a study of sedimentation should be obvious. The general sedimentation pattern of a stream is a function of its geomorphic history and stage of development. It is also a function of the type of terrain through which the stream passes. Both of these can be studied through a proper use of the methods described in Parts I and II of this book. Sedimentation tends to occur at predictable geomorphic and geometric points. These are easily identifiable on aerial photographs. Actual deposits usually may be outlined immediately on the photographs, and if properly analyzed geomorphically, their texture predicted. If the deposits are temporarily above water, such things as their tones and side slopes may be indicative of texture. In addition, their horizontal extent is partially or completely visible. Sequential photography should reveal their migration and variation. Finally, a broad index of the *relative* amount of suspended load may be got through the tone analysis of a stream at various points and times throughout the year. These may be coordinated with selective siltation sampling.

In addition to the aid that is provided in the analysis of suspended and bed loads and sedimentation, air-photo techniques provide help in studying other facets of regimen. The width of flow at the time of photography, *but at all points,* is apparent on the prints. The height may be obtainable through sequential photogrammetry based upon fixed control points. These two factors alone

should do much to provide a continuous picture of important flow-stage variations rather than one interpolated between gages. Cameron (30) has recorded the results of photogrammetric measurements of current and tide velocities. These may be applicable to certain aspects of river behavior, particularly flood-crest routing. Oros (144) has recorded the use of aerial photography of floats to measure current velocities and directions in difficult reaches. The location and effect of various flow stages on stream gages may be studied to a certain extent. Possible overflow, incipient breach points, and new cutoffs may be located and subjected to field study. Areas of existing, past, and probable future bank erosion may be mapped. The extent of flooding may be determined (Sec. 18-20). Bank conditions, in terms of composition, roughness, and vegetative cover, may be evaluated generally.

With the new over-all survey of regime analysis, as provided by Blench (24*a*) in his fine book, it is apparent that aerial-photographic interpretation becomes a new tool for the more accurate quantitative-analysis design and evaluation of canals, meander treatment, river engineering, and flood control.

18-20. Some Examples of Application of Aerial-photographic Techniques to Study of Watershed and River Geometrics—Surface Drainage—Flood Damage. Although space limitations prevent a discussion of large and/or detailed projects, there is room for presentation of summaries on one or two elementary applications of the aerial-photographic technique.

An engineering client desired reconnaissance information on a watershed in a fairly wild portion of Quebec. The principal river draining this watershed had been observed to have substantial flows from time to time and was reputed to have good damsites, but no actual facts were available. Moreover, because of the nature of the terrain, the probable boundaries of the watershed were nebulous in the extreme. It was desired to determine the general characteristics of this watershed before spring so that its possible exploitation could be incorporated into a much larger scheme of operations and investigations.

The preliminary photo reconnaissance of this catchment was conducted in 11 stages. These included the preparation of a photographic laydown (waxed, Sec. 24-8) of the general area from *existing* aerial photography having a scale of 1:60,000; the interpretation and delineation of falls, rapids, organic areas as pertinent, surface drainageways, major topographic features (by rough hachuring) on the contact prints; the procurement, analysis, and compilation of existing APR data (Appendix A) and the use of them to determine rough profile data on the river; the interpretation of general structural geology and vegetative cover on the contact prints; the delineation of areas of unconsolidated materials in a zone bordering the principal river; the selection of field access routes; the selection of probable best damsite, spillway, and conduit locations and their rough cross-section measurement by parallax-bar methods; the indication of probable extent of reservoirs; the compilation of all data on six laydown sheets (two each, engineering, geology, and forestry); preparation of overlays; and preparation of a complete printed report.

The area of the watershed was approximately 600 square miles. The entire project was completed in 6 weeks, i.e., an average of 20 square miles a day of engineering, geology, and forestry, plus report. The client found this effort of great value, since it allowed him to make several *definite decisions* regarding exploitation of the watershed.

Another typical project involved the completion of a similar study of three larger rivers with an aggregate area of 8,000 square miles. The various maps and three reports for these rivers were completed in 11 weeks.

A third example involved the preparation of a surface-drainage map for a metropolitan township. This included the mapping of surface drainage on a mosaic; on the engineering base map; and finally, in great detail, on the tax-assessment maps. A portion of this map is depicted in Fig. 18-2.

As a final small example, during a recent catastrophic rainstorm, a major river overflowed and caused heavy damage in highly developed metropolitan and residential areas. A delineation of actual inundated areas was desired. Two methods, one based upon photographic interpretation and another based upon an extension of flood crests over detailed photogrammetric maps, were used. In several locales, the results of the two approaches disagreed to a considerable extent, the interpretation showing more extensive areas of inundation than the projected flood levels. Ground check proved the interpretation correct. The extension of flood levels had not accounted for the centrifugal

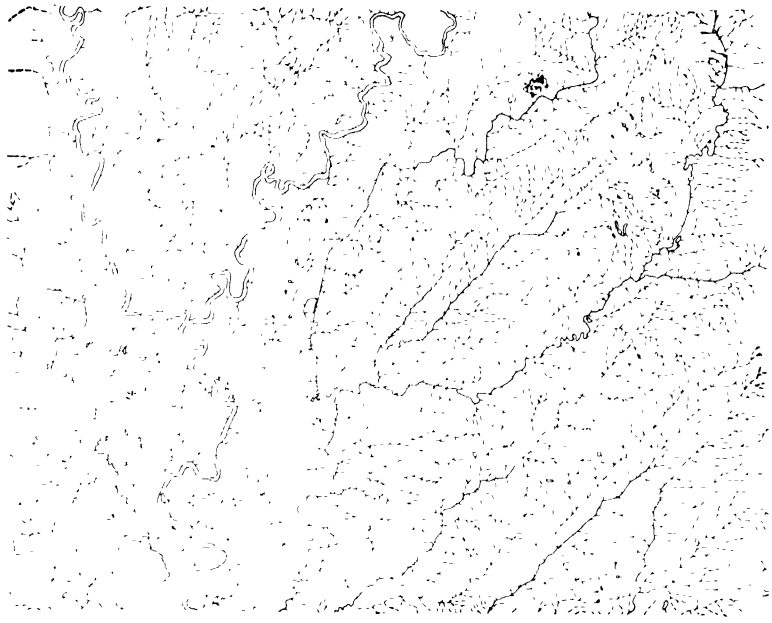


Fig. 18-2. A portion of a detailed drainage map showing (1) the primary, (2) secondary, and (3) tertiary drainage. Note the exceptional detail and accurate watershed boundaries that are obtainable by plotting the tertiary, shallow-surface subsurface swales. These practically never appear on topographic maps. (*Ontario. Photographic Survey Corporation.*)

effects of the swiftly moving water in the vicinity of sharp bends!

18-21. Soils, Land Use, Vegetation, and Geology. When water studies are made of an area, some attention must usually be given to the nature of geology, soils, etc., for hydrological and utilitarian reasons. The amount and details of such studies may range from general reconnaissance to detailed sampling and testing, depending upon the objectives of development.

The theory and principles of aerial-photographic interpretation as a general technique of securing data comprise Parts I and II.

The practical and specific applications of these theories and principles to mapping for the above scientific and practical fields is covered in Chaps. 19 (Geology), 21 (Agricultural Surveys), and 22 (Forestry, Botany, and Ecology).

18-22. Types of Engineered Hydraulic and Control Structures. The end result of most water studies is the construction of some engineered hydraulic or control structure(s) on a stream system, or along a water boundary within the system.

Almost any types of such structures may exist, but the most common are dams, reservoirs, channels, conduits, outfalls, and levees

18-23. Dam-Reservoir-Spillway Combinations. Of all the engineered structures that occur in connection with water utilization and regulation, dam-reservoir-spillway combinations are the most common In irrigation, water-supply, navigational, and hydroelectric schemes, they are built to hold water accumulated during periods of excess flow and release it during periods of deficiency. In flood control, erosion control, soil conservation, recreational developments, and reclamation schemes, they are primarily intended to retain or retard excess flows having short duration, gradually releasing them during periods of subsequent normal flow or in accordance with other project objectives.

If a dam-reservoir combination is intended to hold and release water for a single purpose, it is called a single-purpose dam and is relatively simple to locate and analyze. If it is intended to serve two or more purposes, e.g., power plus irrigation, it is called a multipurpose installation. This latter may be difficult to locate, analyze, and design, because it involves a compromise between the conflicting water supplies and demands, stor-

age volumes, design criteria, and operational factors associated with each purpose.

In any case, but particularly for multipurpose units, the dam-reservoir-spillway combination is the major element of a water-usage scheme, economically, physically, operationally, and catastrophically, and considerable effort must be given to the collection of information regarding it. This information may be listed as follows:

1. Information on the damsite and spillway
   a. Topographic cross section (including channel)
   b. Geological conditions at the abutments and foundation and in the vicinity of any possible or proposed ancillary structures (spillways, sluices, forebays, stilling basins, inlets, outfalls, penstocks, etc.)
   c. Materials available for construction
   d. Details of access to the proposed site(s)
2. Information on the reservoir
   a. Extent and topographic nature of the storage area in sufficient detail to develop storage-volume–area relationships, compute valley storage, locate probable or required cutoff dams, etc.
   b. Geology of the storage area in so far as subsurface leakage or bank storage is concerned
   c. Economic and qualitative nature of the area to be inundated

18-24. Application of Aerial-photographic Techniques to Studies of Dam-Reservoir-Spillway Combinations. The first step in a dam-reservoir study is the procurement of dependable knowledge about the topographic possibilities on the stream that seem to offer a reasonable chance of satisfying the proposed scheme. This phase of study is often completed by using topographic maps and/or field reconnaissance, usually from fixed-wing aircraft. There are usually no particular advantages that these methods have over the use of proper stereo examination. The aerial-photographic perspective provides a three-dimensional view that is fixed; that can be definitely located; that is continuous; that can be studied in detail and at leisure (or with rapidity); and that provides a much greater amount of detail than can be obtained from either a flight impression or anything but the most detailed topographic maps. (Of course, any available topographic maps should also be used.)

If aerial photography already exists, the costs of purchase and stereo examination for this type of study are quite low. If new aerial photography is required, the procedure is still economical. The new photography, *if properly planned*, will serve as a base for future photogrammetric mapping, e.g., of the reservoir area, as well as for other qualitative mapping.

Following the first stage of study, there should be a reconnaissance investigation of the selected possible dam-reservoir areas for the purpose of deciding which of them are most deserving of preliminary study. Such a reconnaissance should cover the items listed in Sec. 18-23 in an approximate and general way.

Again, aerial-photographic techniques provide an ideal method of approach because of their speed, economy, and sufficient capability.

The approximate topographic cross section at the damsite can be obtained by a variety of methods, the selection of which is related to the accuracy required. If high accuracy is not required, a single-line cross section can be plotted by the use of any of the photogrammetric mapping devices, with the river surface at the site as local relative datum. Even the simple parallax-type instruments can be used. If control points can be located in the area and identified upon the photographs, a dependable topography can be plotted, the accuracy depending upon the control and technique that are used (Secs. 24-5 to 24-9). A cross section can then be prepared.

The topographic nature of a possible reservoir is considerably more difficult to determine. Assuming the existence of topographic maps, even with a large contour interval, it may be satisfactory in the reconnaissance stage to compute volumes and areas by standard methods, estimating the effect of stereo-discovered discrepancies between the photographic views and the topographic sheets.

However, it has been said, with considerable justification, that the relations between reservoir volumes, areas, and heights are some of the most important facts that should be revealed by reconnaissance and preliminary investigations. If the engineer is a subscriber to this opinion, or if he has no other topographic information, he will desire topographic mapping of the reservoir to greater or less accuracy.[2] Such mapping may be done, by photogrammetric means, in one of the four general ways described in Sec. 18-15. The accuracies and general applicability of the various

[2] There should be a very great application of combined electronic-photogrammetric cross sectioning (Appendix C) to the rapid study of height-volume-area relationships of river valleys and reservoirs.

methods described therein are similar. The specific applicability of the methods is affected by the relative size of the storage area compared to the watershed. There will be storage areas where sufficient triangulation data do not exist, and unless the reservoir area has been included in a prior program of air-borne profiling or shoran control, it may be too small to justify expenditures for these purposes. For these reasons, and because of the ultimate importance of accurate storage-volume-area relationships, it can usually be assumed that relatively small storage areas can best be mapped by establishing accurate ground control followed by good photogrammetric mapping. Large, irregular, or inaccessible storage areas usually will receive similar treatment, although the reconnaissance methods of Sec. 18-17 will receive more frequent use.

The geological conditions existing at the damsite, and throughout the storage area, both bedrock and unconsolidated, can *best* be investigated during the reconnaissance stage, through the technique of aerial-photographic interpretation. Chapter 19 discusses various aspects of structural interpretation. It seems beyond refutation that the interpretative technique can provide considerable information, including a detailed map, of the following:

1. Location, origin, and extent of bedrock outcrop
2. Delineation of the traces of structural linears such as faults, joints, and features of tectonic activity (as folds, sills, etc.)
3. By careful measurement and mapping, the strike, dip, and attitude of such features
4. The location, extent, probable origin, general textures, and probable degree of stratification of unconsolidated materials in the area (but not under the stream surface), including swamps and marshes
5. The structural and soil characteristics of the watershed, which, together with interpretation on surface drainage, origin, rock type, and vegetation, can be used to obtain some idea of water-storage leakage and bank storage
6. The location and nature of special construction problems (see Secs. 18-29 and 18-30).
7. The location of field check points and the necessity and planning of future ground geophysical and boring surveys

During the preliminary stage, similar information can be accumulated by more detailed interpretation and considerably more detailed photo-planned field work.

During the reconnaissance and preliminary stages of materials survey and access study, the methods are those discussed in Chap. 17.

The study of qualitative and economic conditions within the area of inundation is a function of the proper application and integration of soils, forestry, agricultural, land-use, etc., studies as presented in this book, plus such economic computations as are required.

18-25. Some Examples of the Application of Aerial-photographic Techniques to the Study of Dam-Reservoir Areas. Figures 18-3 to 18-6 show actual qualitative maps that were prepared on various damsites for the procurement of various types of information.

18-26. Application of Aerial-photographic Techniques to Study of Canals, Conduits, and Other Engineered Hydraulic and Control Structures. In general it may be said that air-photo methods will have value to the study of canals, conduits, and other structures, in direct proportion to the necessity for, and value of, quantitative and qualitative terrain information to the planning and design of such structures. The quantitative information can be supplied by photogrammetric methods. Qualitative information can be obtained, for canals and conduits, through the proper application of the approaches discussed in Secs. 17-7 and 17-8. Information for levees can be obtained by similar methods, plus those discussed in Secs. 18-16 to 18-21. Information for other types of structures may be obtained from the proper use of the approaches and techniques developed or discussed in these sections, as well as throughout the book.

COASTAL AND HARBOR STUDIES

18-27. Nature of Coastal and Harbor Studies. Coastal studies, except for those of a military nature (Chap. 23), are almost exclusively devoted to studies of erosion, transportation, and deposition of mineral beach materials along a given shore line, together with the practical effects of such shiftings upon offshore profiles, channels, inlets, bars, etc. Engineeringwise, these studies are essential for the location and design of protective or regulatory structures (groins, breakwaters, seawalls), as well as specifically useful items such as sewage outfalls, water inlets, tidal and current



Fig. 18-3

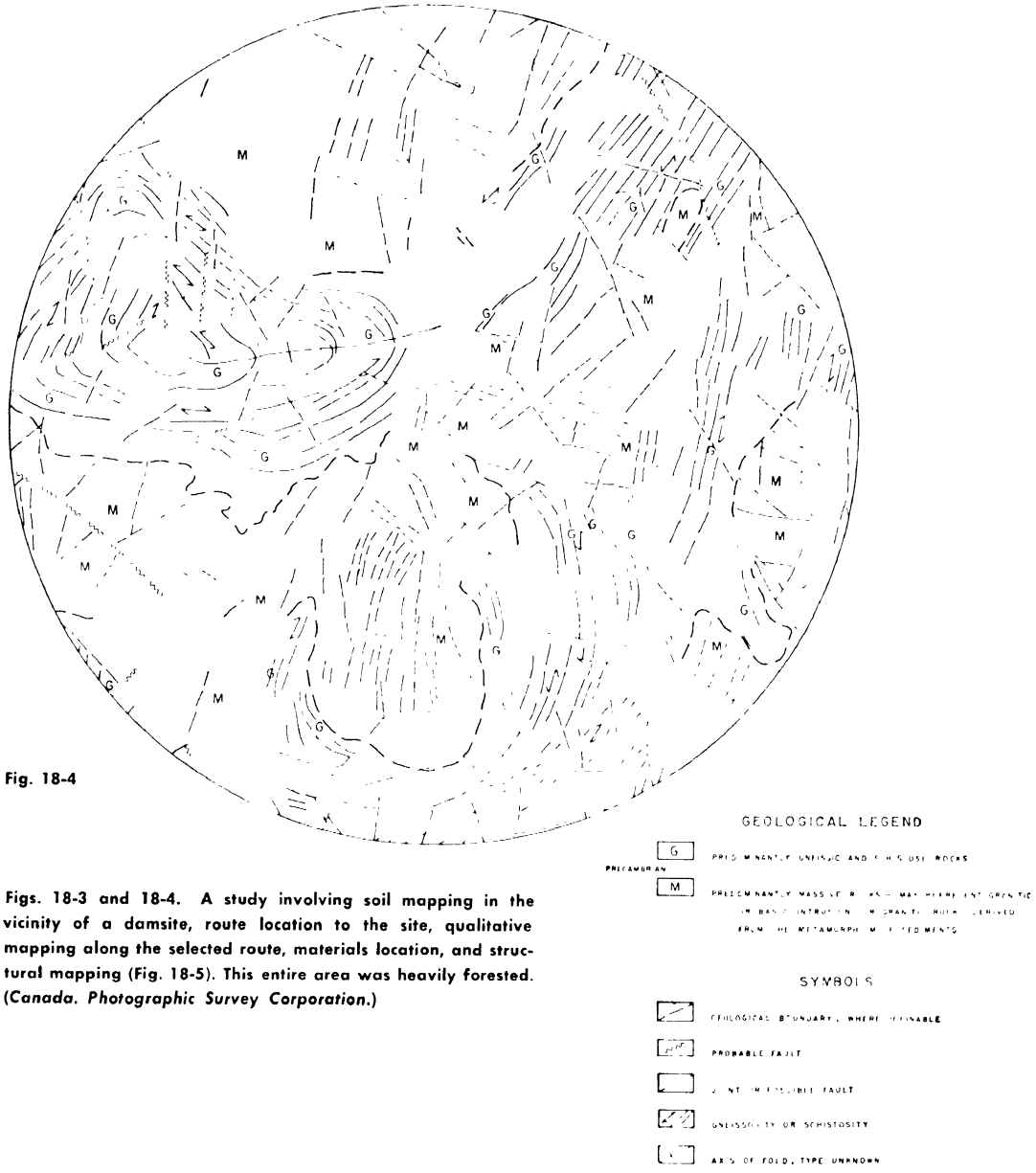


Fig. 18-4

Figs. 18-3 and 18-4. A study involving soil mapping in the vicinity of a damsite, route location to the site, qualitative mapping along the selected route, materials location, and structural mapping (Fig. 18-5). This entire area was heavily forested. (*Canada. Photographic Survey Corporation.*)

gages, buoys, beacons, lighthouses, radar stations, piers, etc.

Harbor studies, similarly to coastal studies, are concerned with erosion, transportation, and deposition of mineral sediments within the actual or proposed confines of actual or proposed harbors, as well as the wave and current characteristics within them. The results of such studies are used to improve, enlarge, or create harbors; maintain their capacity; locate and design adequate protective and regulatory structures; and build docks, piers, wharves, etc.

Both coastal and harbor studies, like some types of landform origin (Part II), are concerned with transitional environments between land and marine or lacustrine waters, often complicated by fluvial action. Because of this, they are complicated by numerous variables. These variables were

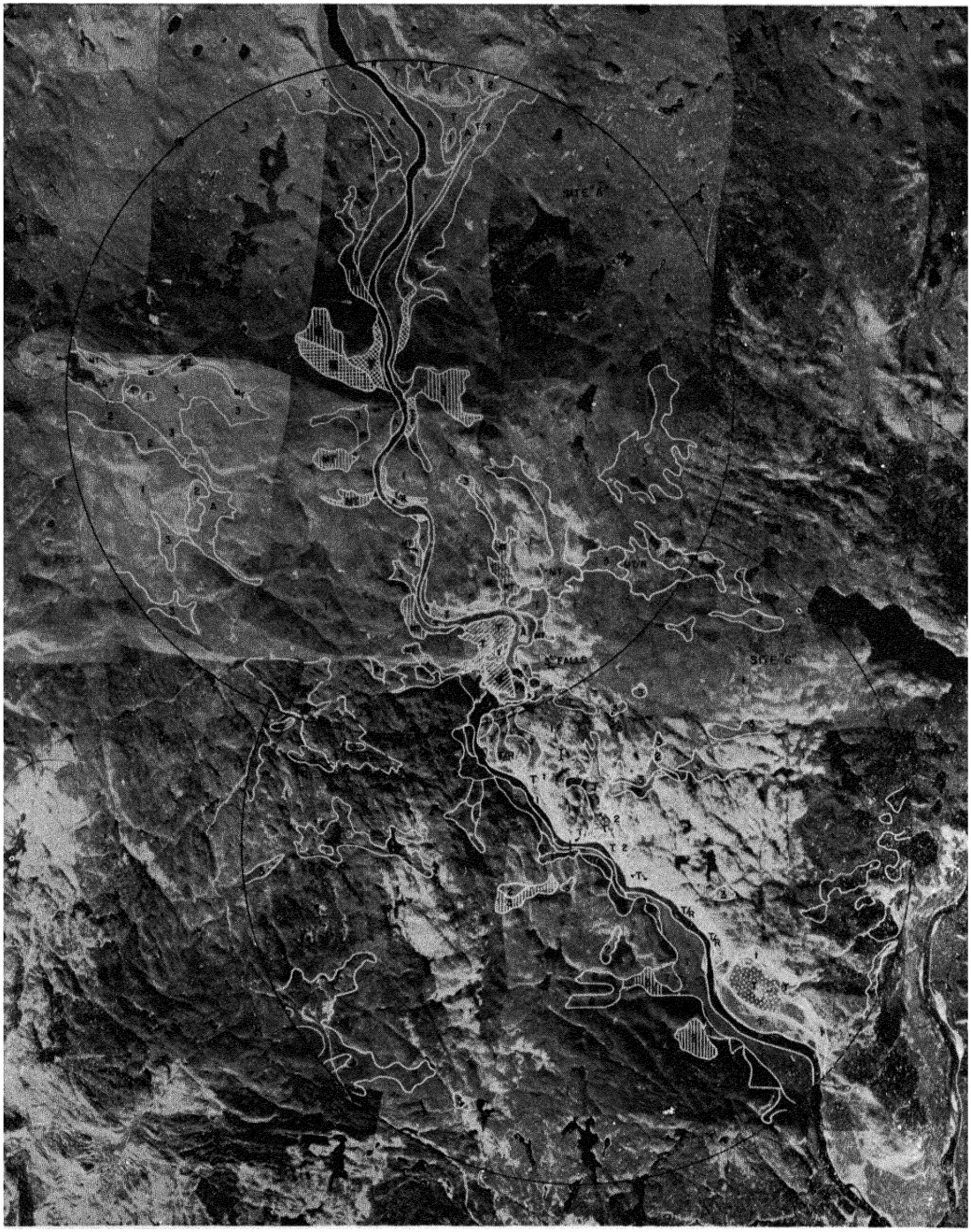


Fig. 18-5. A qualitative map of unconsolidated deposits and materials sources in the vicinity of two proposed dam-sites. (*Canada. Hunting Technical and Exploration Services.*)



Fig. 18-6. A qualitative map of rock and overburden conditions in the vicinity of a damsite and conduit location, combined with a materials study for concrete aggregates and selected materials for earth-dam construction. Of course, none of the figures included in this chapter show photogrammetric maps prepared at the various sites. (*Canada. Hunting Technical and Exploration Services.*)

once listed by the author (111) as the direction, velocity, fetch, duration, and persistence of winds; protective underwater features and surface features; frequency, duration, velocity, load, and direction of flow from river and tidal mouths; littoral currents; location and types of sediment-contributive sources; offshore profile; tides; height, frequency, length, shape, direction, refraction of waves; littoral currents; nature of sediment transportation.

None of these variables can be controlled by any normal means. Few can be evaluated easily by instrumental devices. Consequently, it is difficult to relate specific coastal and harbor features and proposed structures to the variable or combination of variables that produces, modifies, and affects them.

18-28. Application of Aerial-photographic Techniques to the Study of Coastal and Harbor Problems. Aerial-photographic techniques often can contribute much information of value to the studies mentioned in Sec. 18-30. Further, for the reasons indicated by the last two paragraphs of that section, any value that *can* be extracted from the photograph—consistent, of course, with the project objectives, funds, and time—*should* be extracted. The engineer who deliberately neglects any consideration of, or reference to, aerial photographs, and who can still perform his studies with maximum efficiency and economy, is indeed a genius and should be accorded his just due. This does not mean that aerial photography should always be used. Sometimes it may be of no value, nonexistent, too expensive, or impractical for other reasons. But under favorable circumstances, it can provide much information of value regarding both the land and water environment and the current, tidal, and wave variations.

Some of the factors visible on aerial photographs that have significance with respect to harbor and coastal studies are as follows:

1. Details of beach profile (width of zones, slopes, cusps, scarps)
2. Wave and surf details (length, frequency, shape, height, direction, refraction, pattern, wind effect, breaker patterns, rough measure of wind velocity)
3. Gray tones (beach sands, indications of relative depths, seaweed concentrations, turbidity stains, current effects, etc.)
4. Current details (location, direction, velocity)
5. Environmental features (all onshore features, indications of offshore topography, bars, river-mouth details, current ripples, etc.)
6. Effects of tidal inundation

To these might be added the important factor of underwater topography. To the best of the author's knowledge, this is not yet accurately determinable by means of aerial-photographic techniques,[3] although much empirical experimentation and theoretical research have been devoted to it. Apparently, as with other phenomena of a transitional nature, there are so many variables to counteract that the results cannot be used with confidence. About the best that can be said about aerial photography for underwater-depth determination is that a properly exposed and processed color or panchromatic aerial photograph will indicate *areas of different depths* without indicating their magnitude, provided that exposure is made at the proper time (with regard to turbidity, sun angle, and wave pattern). It is obvious that the ability to indicate areas of different depth is not only of qualitative interest, but can be used to plan and delimit hydrographic survey for various purposes. In fact, this is one of the major uses of photographic analysis for coastal and harbor studies.

Finally, it must be emphasized that air photography for harbor and coastal studies should be used in a sequential sense; i.e., sequences of photographs (covering any period and at any frequency) should be examined whenever possible, rather than for a single time. Harbor and coastal environments and forces are dynamic and should not be examined statically. Lest the reader think that this procedure would be too expensive, let him be reminded that an average photographic mission of a relatively small area, including prints and negatives, should range in cost between $5 and $40 *per square mile,* depending on scale and length. The cost per mile and per photograph need not be great if scales are properly chosen and mobilization or demobilization costs are minimized.

Figures 15-12*a* and 18-7 illustrate some of the coastal and harbor details that are discernible in proper aerial photographs.

LOCATION AND ASSESSMENT OF SPECIAL CONSTRUCTION PROBLEMS

18-29. Nature of Special Construction Problems. There is a variety of special terrain conditions that create special problems for construction. These include old and incipient land slippages of various

[3] The author has heard of a transparency method of determining water depths but is unfamiliar with its usefulness. Certain successful photogrammetric methods have also been reported, but the author is unacquainted, through experience, with their accuracy, and therefore with their adequacy.

types (Chap. 4); areas susceptible to land slippages on the basis of past history and/or environment; areas of shallow, variable overburden (Sec. 16-10); areas of sidehill seepage, springs, and other ground-water effluence; areas of permafrost and climafrost of various types; areas of existing, incipient, or potential severe erosion; areas of periodic scour by surface flood flows; areas of slumping due to solution phenomena; areas of high salinity or corrosiveness.

The subjects of permafrost surveys and landslide investigations are considered in Secs. 18-31, 18-32, and 18-35, etc. The nature of the other conditions and problems is either described elsewhere in this book or is fairly obvious. Salinity and corrosiveness, in terms of ground-water tables, organic waters, and actual surficial salt concentrations, are receiving increasing attention in these days of cables and pipelines.

18-30. Application of Aerial-photographic Techniques to the Location and Assessment of Special Construction Problems. All the conditions described in Sec. 18-29 can be located and assessed by means of careful air-photo analysis and interpretation.

The methods of studying land slippages through the use of aerial photography is discussed in the final sections of this chapter.

Areas of sidehill seepage and effluence can be located by means of careful attention to gray-tone, drainage, and erosion details. A special case of reversed-sinkhole effluence is cited in Chap. 16.

Permafrost and climafrost are briefly mentioned below.

Areas of existing, incipient, or potential erosion may be studied by means of the principles outlined in this book. In addition, the relative danger and economic loss attendant upon continued or new erosion in various areas may be evaluated. Schedules of erosion control may then be established. An erosion survey is one of the easiest of air-photo tasks.

Areas of scour due to fluvial action may be located and analyzed by a careful study of the fluvial landforms (Chaps. 9 and 10).

Areas of slumping due to solution processes may be located largely by identifying and analyzing limestones (Chap. 16).

Areas of high salinity and corrosiveness may be determined by careful study of ground-water and drainage conditions, the location of organic deposits, and a combination of careful field work and photo examination. Mollard (135) has written an interesting paper on the mapping of sulfates from aerial photographs.

PERMAFROST-CLIMAFROST STUDIES

18-31. The Nature of Permafrost and Climafrost. Permafrost and climafrost are discussed in Sec. 4-25.

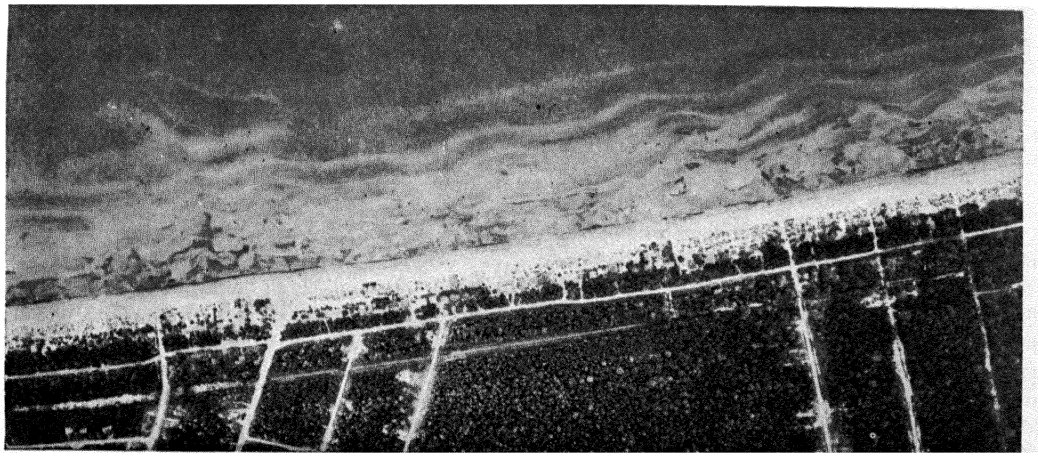


Fig. 18-7. An illustration of some of the offshore details visible with aerial photography. See also Fig. 15-11. Note the remarkable detail and clarity of offshore sandbars visible on an air photo of a large lake shore. (*Canada. Photographic Survey Corporation.*)

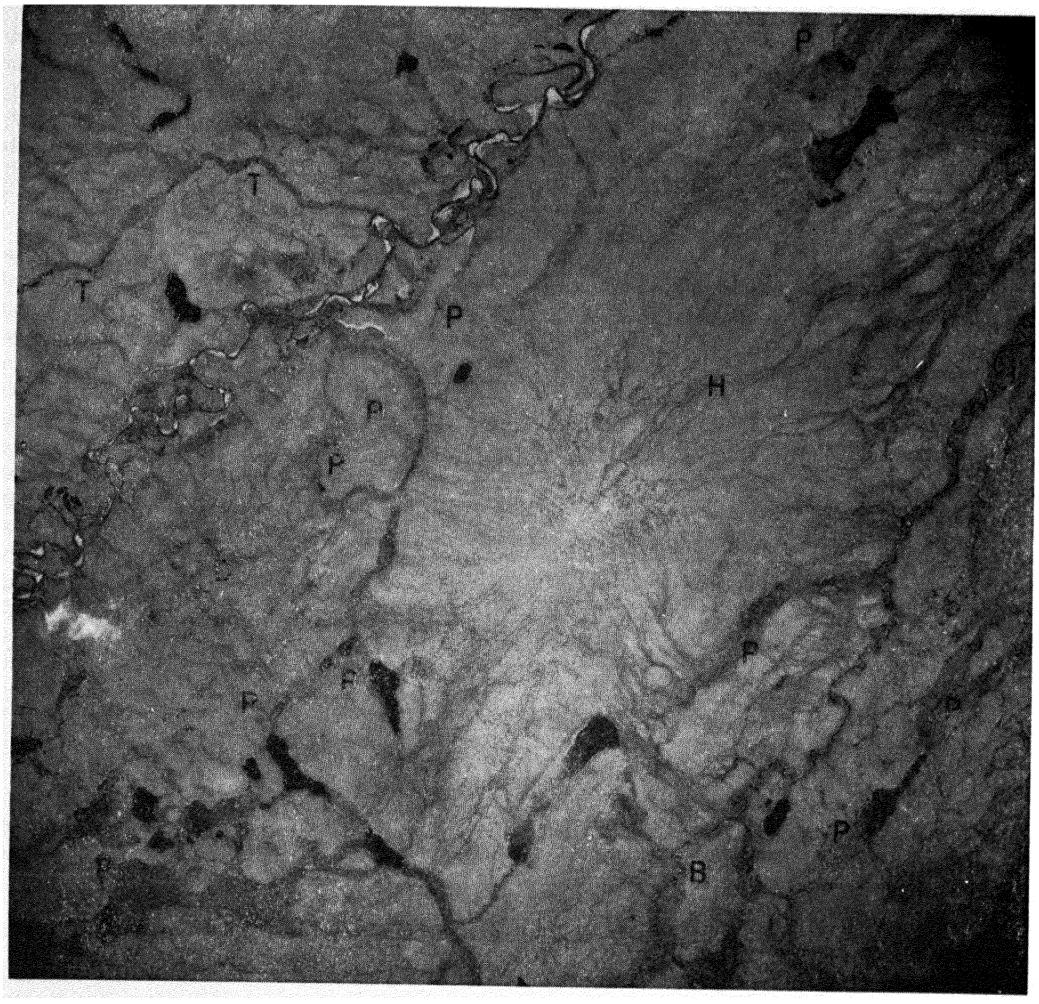


Fig. 18-8. A single air photo of some permafrost features. Included are horsetail drainage *H*, polygons of various shapes *P*, stream beds *B*, and thaw features *T*. (*Yukon. RCAF.*)

18-32. Application of Aerial-photographic Techniques to the Study of Permafrost and Climafrost. The discussion and illustrations of Sec. 4-25 should be sufficient to indicate that permafrost features of many types can be identified on aerial photographs. Since the development of such features is partially a function of the environmental complex, and since this is displayed incomparably and is quite analyzable, in a general way, on the air photos, it follows that air-photo interpretation provides a most feasible way to conduct reconnaissance, preliminary, and initial research investigations of such thermal features (Fig. 18-8).

PLANNING OF FIELD INVESTIGATIONS

18-33. General. It is repeatedly emphasized throughout this book (Secs. 1-14, 4-22, 17-6, 18-24, and 24-20, for example) that aerial-photographic interpretation can and should be used to the maximum in the planning and execution of field investigations of all types. The reason is simple, namely, that the photos provide an incomparable perspective which shows everything in terms of its environment and which, when properly interpreted, also provides advance information that will do much to reduce field expendi-

tures of time and money. Moreover, the field investigation can be expected to provide better information both by virtue of the fact that it has advance data and because it has a better appreciation of the terrain environment.

Regardless of the nature of the project—route engineering, site analysis, water investigation, harbor and coastal study, engineering geology, agriculture, ad infinitum—the aerial photographs should be used to plan the field surveys. Failure to so use them is simply negligence.

MISCELLANEOUS APPLICATIONS: CONTRACT-BID SURVEYS, LARGE-JOB PLANNING, PROGRESS ESTIMATION, INVENTORIES

18-34. General. There are places in this book where, the author feels, like a poll parrot, he has been repeating the same things over and over. This is one such place. It would seem obvious that aerial-photographic interpretation can and should be applied to the above activities whenever feasible in terms of time and money. Further, the methods of application seem apparent.

Proper qualitative interpretation of such terrain conditions and factors as materials sources, shallow and variable bedrock, adverse drainage, sidehill seepage, soil types, construction access and trafficability, clearing, and grubbing may be advantageously used in preparing advertisements for bids and in the tendering of them. In both cases, the practical results of a proper air-photo study should be decreased costs (to the owner or user) or increased profits (to the contractor). These "contract-bid surveys" should, of course, be discreet and also well in advance of actual legal actions. Moreover, the person who undertakes them should be highly aware of the specific types of information that are desired or required.

Similarly to contract-bid surveys, large projects may be planned by the use of air-photo interpretation. The location of construction camps, roads, bridges, water supply, materials, and actual operations may be evaluated and decided upon far in advance of actual movement to the job. Such plans as are approved may be reproduced cheaply and supplied at virtually no cost to anyone who requires them. Again, the ultimate results of these *large-project-planning* studies are economies (to the owner or user) or profits (to the contractor).

Obviously, sequential photography, selective photogrammetry, and selective photo analysis or interpretation may be used to check and plot progress of many types of activities on large jobs. It may also be used to record inventories of coal, sand, gravel, pulpwood, etc. What may not be so obvious is that the photograph serves as a *factual* and *legal record* of many of the important aspects of job completion, payment, time scheduling, quantities, etc., which should do much to decrease construction litigation.

LANDSLIDE STUDIES

By Ta Liang [4]

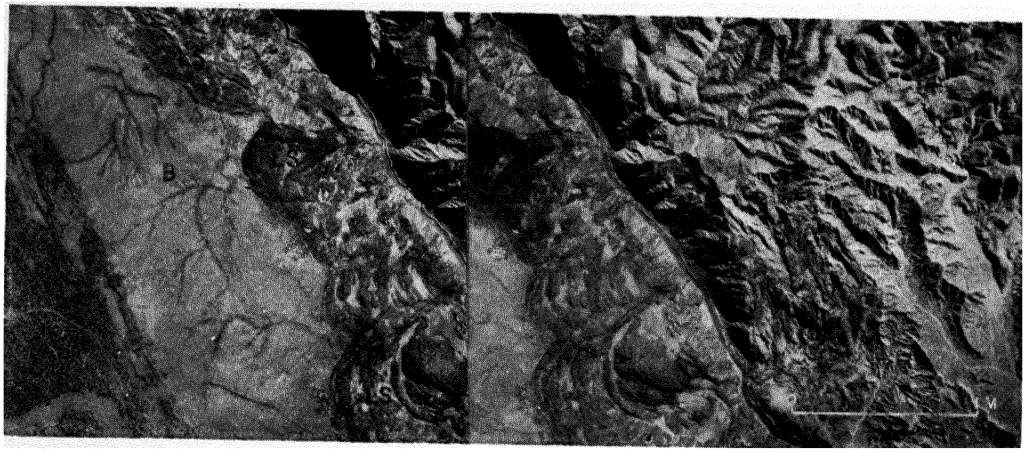
18-35. General. Aerial photography has proved to be a very useful tool in the investigation of landslides, both for prevention and control purposes. The diagnosis of potential landslides requires a relatively high degree of interpretative skill, whereas the investigation of slides that already have taken place is a more simple operation. In the latter case, the object of the investigation is to determine the scope and the cause, or causes, of the slide and to formulate plans for field investigation and corrective measures.

Aerial photographs often reveal the circumstances of a slide, including the topographic, climatic, soil and geologic conditions, surface and near-surface drainage, and pertinent human activities. Further, they clearly delineate the areal extent of the slide. If air photos showing both before and after slide conditions are available, a comparative study is possible and helpful from both a technical and legal viewpoint.

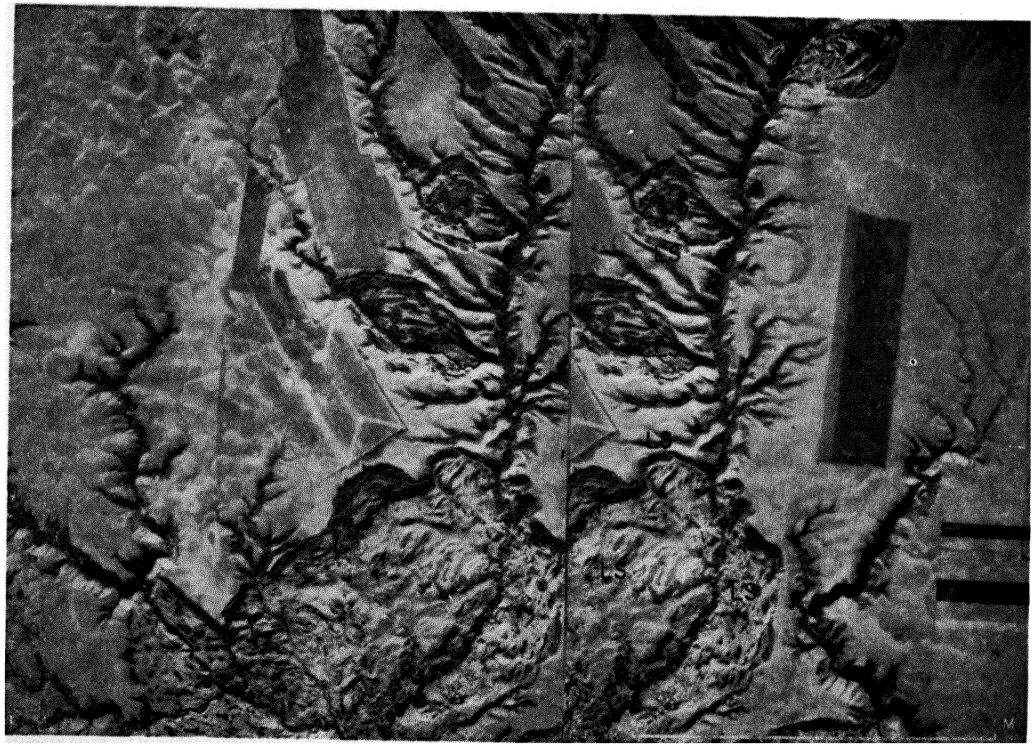
There are some limitations to air-photo analysis that should not be overlooked. The size of a slide is sometimes a limitation. While large slides are easily recognizable, the detection of most small slides requires a careful examination and a close understanding of local conditions. Urban development is occasionally a limitation to air-photo study of a landslide because it disturbs or conceals natural ground conditions.

The scale of aerial photographs in use is important. The most common scale of existing government photographs is about 1:20,000. While this scale is generally good for evaluating the larger land units, it is often too small for detailed investigation. Sometimes a scale of about 1:5,000 might be desirable. When both large- and small-scale photography are available, an examination of both would yield the best results.

[4] Associate Professor of Transportation, School of Civil Engineering, Cornell University.



(a)



(b)

Fig. 18-9. Two vertical views of landslide topography. (*a*) Typical scallops *LS* in effusive rocks. Note the "blisters" *B*. The original photos of these have a scale of 1:30,000, making these slides quite large. The original of (*b*) shows similar slides in tills over sediments (1:15,840). Selected by Ta Liang. (*New Mexico, Canada. U.S. Department of Agriculture.*)

When the scale of photography is sufficiently large, the most directly recognizable photographic features of landslides are the scarp, or the break, at the head of the slide; the hummocky topography and the haphazard drainage pattern in the disturbed mass; and the strikingly different tones and vegetative characteristics between the slide area and the adjacent stable land. All these features become less prominent as the slide gets older.

Figures 18-9*a* and *b* show some unusually large landslides. Although most slides are of a much smaller magnitude, their characteristic scarps, slide topography and drainage, vegetative and tonal patterns are similar, only proportionately smaller.

Recognition of certain other features associated with slides would greatly facilitate their investigation, particularly in the case of smaller slides that are not readily discernible on photos. These features are vulnerable locations and formations and old slide areas.

Locations vulnerable to landslides include areas attacked by river currents, oversteepened earth slopes, and seepage zones. Formations most vulnerable to landslides include clay shales, tilted sedimentary rocks, basaltic hills, and dissected coastal plains. Special attention should be directed to such locations and formations both in photo examination and field checks. Old slides are indications of old instabilities and call for careful examination. However, unstable conditions prevailing in the past might not exist at present. Conditions often have changed, particularly in glaciated areas. For instance, there are many old slide areas in western Canada which are now generally stable except for local wet spots or critically steep slopes. (See also Figs. 4-19*a–c*.)

19 APPLICATION OF AERIAL-PHOTOGRAPHIC TECHNIQUES TO GEOLOGY

By R. N. Parkinson and D. R. Lueder

19-1. Scope of Chapter. This chapter is primarily concerned with the application of air-photo techniques to structural geology and mineral exploration. Applications to other subdivisions of geology are covered in other parts of the book. For convenience, the pertinent cross references are made herein under headings for the particular branch of geology concerned.

The major portion of the chapter—on structural geology—is written by R. N. Parkinson.[1]

The latter portion of the chapter—on mineral exploration—is written by the author. Like his remarks in Chap. 22, the presentation is mainly expository and by means of extracts. While he does not qualify as a specialist in this field, he has had some experience and is convinced that effective mineral exploration, like other types of terrain investigation, is based upon the *progressively* more detailed and expensive procurement of *dependable* terrain information. The general photographs are of great aid in the initial stages of such accumulation. Consequently, his presentation is the result of conviction, not of a desire to merely provide coverage of an important field.

PETROLOGY

19-2. General. The applications of aerial-photographic interpretation to petrological mapping are discussed in Chap. 16 and in Secs. 19-3 to 19-19, which follow.

STRUCTURAL GEOLOGY

19-3. General. According to Nevin (140):

> Structural geology [Sec. 7-4] may be defined as a study of the framework of the earth's crust and the causes that are distorting it. However, in its broader phases, structural geology is not limited merely to crumplings and fractures of the crust. Although we see only a thin rind and although information about the unseen vast interior must, of necessity, be based on indirect evidence—yet it is deep-seated adjustments within the earth that cause many of the surface structures.
>
> The central theme of structural geology, then, is the deformation of the earth, its causes and effects. Unerring interpretation of rock structures is the goal sought.
>
> A true understanding of the structural failures produced in the earth's crust, whether they be simple fracturing or complex mountain-building, involves a knowledge of:
>
> 1. The physical properties of rocks
> 2. The external forces that are applied, transformed or transmitted
> 3. The internal stresses and strains resulting therefrom
>
> Apart from a knowledge of the mechanics and mathematics of earth deformation, the student of structural geology must have a thorough grounding and ability to visualize in three dimensions. He must have a natural facility with such problems as three-point strike and dip and complex fault displacements.
>
> The structural photo interpreter must have, in addition, a good facility with stereoscopic study and appreciation of relief.
>
> While the criteria upon which structural and lithologic interpretations are based differ fundamentally, they are indirectly related. In practice they should never be separated in the interpreter's mind, even though it is usual to examine the structure on a photograph before the lithology.

19-4. Lineation and Linears—Definitions, Interpretative Hints. Since, in the ensuing discussion on the relationship between structural geology and "photostructural geology," repeated reference will

[1] Project Manager, Canadian Colombo Plan Survey of Ceylon.

be made to "linears," it is necessary to define the term as it applies, uniquely, to geological photo interpretation.

Any linear feature in the landscape which possesses an abnormal degree of regularity is immediately viewed by the interpreter with suspicion. Such linears, whether straight or gently curving, are generally believed to be the surface expression of some structural feature in the bedrock. Experience and careful judgment are required, in many cases, to distinguish a diagnostic linear from random river stretches, hills, and similar results of random erosion.

There is a distinct difference between linears and lineation. "Lineation" refers to geological features which are true lines in space, such as elongation of pebbles, the trace of bedding on cleavage surfaces, or axially oriented crystals. Bedrock linears, on the other hand, represent the surface traces of such geological planar features as faults, contacts, joints, and bedding planes.

Linears may represent one of several structural features: faulting, bedding, jointing, schistosity, gneissosity, contacts, or narrow dikes. In some cases, with additional information from other sources, it may be possible to identify the linear as one of these features. However, they often must remain as "unidentified linears" and, when plotted as such, commonly produce a linear pattern of texture which is of considerable value in isolating rock masses with differing characteristic "fracture patterns." The jointing pattern in a granite, for example, may help to identify other bodies of this rock (Chap. 16) in the region, even though its precise identity as a granite, granodiorite, or diorite may have to await field checking. Some linears may assume a greater importance when studied in conjunction with later data in the form of field-survey results or aeromagnetic survey data.

The amount of detail which is desirable in plotting linears is a matter of experience and judgment. The chief trends and character of the linear pattern must be shown, as well as its relative density. In the initial phase of the interpretation, it is probably better to err on the side of too much detail; the pattern can always be thinned out at the final interpretation if it tends to obscure other information.

Linear representation should be sufficiently complete to show on a base other than a mosaic or photograph. Much drainage actually doubles as linears, but it should nevertheless be emphasized by linear symbols; in this way, the drainage linears may be given interpreted bedrock significance. (Also see Sec. 16-9a.)

19-5. Strike and "Trace"—Definition, Interpretative Hints. Strike is one of the fundamental concepts of structural geology, but the photo interpreter may easily lose sight of its precise meaning. It is frequently confused with trace, surface trace, or trend.

"Strike" is the line of intersection between a geological surface (contact, foliation plane, or joint) and the horizontal. It is observed and measured in the horizontal plane only, with one exception noted below.

"Trace" is the intersection of a geological plane and another surface of reference—in the case of photo interpretation, the earth's surface. It is the outcrop of a planar feature such as is seen on a map, aerial photograph, or in the field. In the general case, it is not equivalent to strike.

Only where the topography is horizontal are all traces parallel to strike. However, there is a special case for which strike and trace are the same, regardless of topography. The condition applies where the planar feature is vertical: it crosses hills and valleys without deviation unless folding is present.

In contrast, horizontal beds have no strike; or, in other words, they strike equally in all directions. Nevertheless, their surface traces, which parallel the topographic contours, may be mistaken for strike direction.

The influence of topography on strike and the relationship between strike and surface trace are illustrated in Fig. 19-1.

For dipping planes, the true strike may be determined simply by joining any two points on the same plane at the same elevation. This may be done accurately, provided the interpreter has a good sense of the horizontal. A useful alternative rule is that trace is equivalent to strike where the

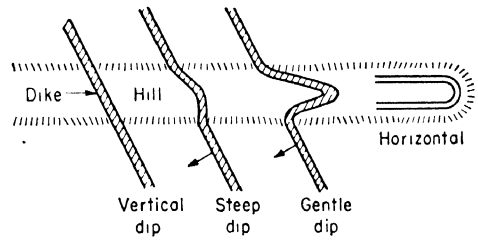


Fig. 19-1. Diagrammatic sketch to illustrate the influence of typography on strike and the relationship between strike and surface trace.

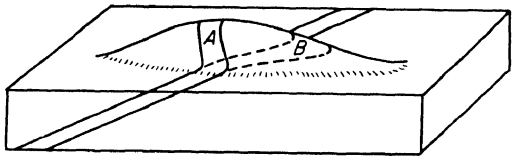


Fig. 19-2. The effect on bedding of a hill formed by the folding of the bedded formations. *A* is the position of bedding trace where the ridge represents the axis of a cross fold (anticlinal). *B* is the apparent position of surface trace where the ridge is purely a topographic feature.

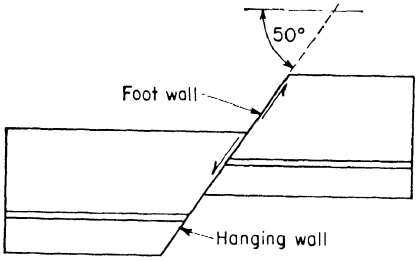


Fig. 19-3. The gravity, or normal, fault.

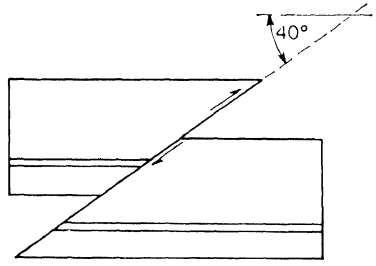


Fig. 19-4. The thrust, or low-angle-reverse, fault.

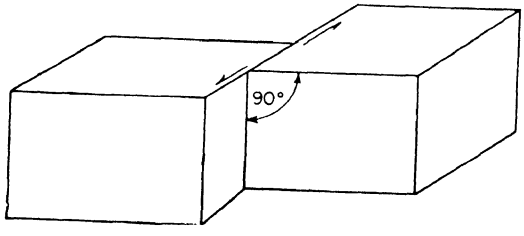


Fig. 19-5. The transcurrent fault.

former is parallel or tangent to a topographic contour. Most bedding ridges, whose apexes approximate the horizontal, meet this requirement when taken over sufficient length.

The geological interpreter must be aware that where bedding crosses a hill or valley, it may be coincident with a fold, which, in turn, has governed the position of that hill or valley. Figure 19-2 illustrates this possibility. A sharp anticlinal fold has probably been the chief factor in the location of the ridge. Obviously, folding tends to invalidate the foregoing discussion, unless it is parallel to the topographic trend. To minimize possible error, strike determinations should be based upon as small a strike length as is consistent with the measurement being made.

19-6. Faults—Definitions. "All fractures in the earth's crust result in some displacement. A fault is that type fracture in which the major displacement is parallel with the surface along which the break occurs. A fault is therefore a shear" (140).

It is a common failing of many interpreters to assume that any strong and persistent linear is a fault. There is a certain amount of justification for this assumption in that joints do not usually persist for a matter of miles. Certainly strong linears, especially those which cut across regional trends or foliation, should be examined carefully for fault characteristics.

However, it must be remembered that all faults are not straight, nor does all fault displacement appear in plan on aerial photographs. In order to develop criteria for the recognition of fault types, it is necessary to recall the most common types of faulting and their characteristics.

Gravity, or Normal, Fault. The usual conditions for normal faulting (Fig. 19-3) are relief of pressure in all horizontal directions and maximum pressure in a vertical direction. The hanging wall has moved down in relation to the foot wall, and the fault plane is generally sharp, tensional, and brecciated. The dip of the fault plane is 45° or more, and the surface trace of the fault is undulating.

The Thrust, or Low-angle-reverse, Fault. The requisite conditions for thrust faulting (Fig. 19-4) are greatest, and intermediate pressure is in a horizontal direction and least pressure in a vertical direction. The hanging wall has moved up in relation to the foot wall; the fault plane is generally less than 45°; and the surface trace is very irregular.

The Transcurrent Fault. For transcurrent fault-

ing (Fig. 19-5) the greatest and least pressures are in the horizontal plane, with the intermediate pressure in the vertical direction. The relative movement is horizontal, and the fault plane is sharp, with possible shearing and brecciation. The fault plane is vertical, and the surface trace is straight.

19-7. Interpretation of Faults in Aerial Photographs. Fault interpretation is based on one or more of the following features, listed in order of increasing reliability:

1. Persistent linear, usually clearly defined. More reliable where it crosses the trend of stratification (Fig. 19-7).

2. Linear scarp, usually erosional, but may be an actual fault scarp.

3. Persistent linear feature, near and parallel to a proven fault (Fig. 19-8).

4. Offsetting of pattern of linears (undefined, but commonly joints) with or without a change in trend.

5. Major regional change in lithology and/or structure (Fig. 19-6).

6. Offsetting of bedding linears, outcrop ridges, formations. This is the best criterion, and it may be recognized only after careful detailed lithologic study (Fig. 19-7).

The interpreter must bear in mind the *probable* direction of movement, with special reference to the influence of dips and topography on the apparent horizontal displacement.

Strike faults and bedding-plane faults are, of

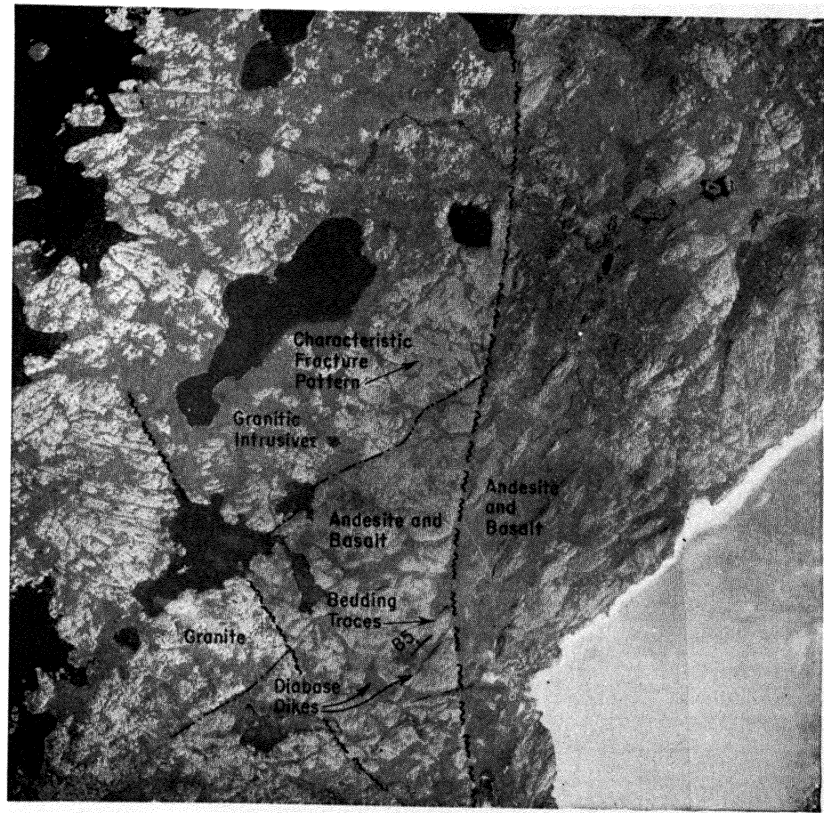


Fig. 19-6. A classic example of faulting in the Yellowknife area, Northwest Territories. Movement along the two faults is indicated by displacement of the granite-volcanic contact. Note the difference between the two rock types, both in tone and in texture; also the characteristic jointing in the diabase, upper left. (*RCAF.*)

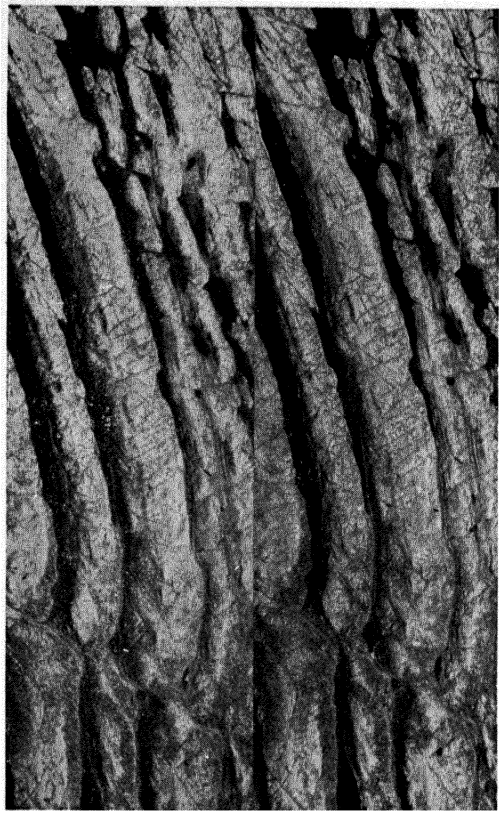


Fig. 19-7. Close observation will reveal not one, but many, faults in this stereopair, all with a definite displacement of the resistant sedimentary formations. (*Labrador. RCAF.*)

course, difficult to detect. They may defy detailed ground studies for years. Where their surface traces can be observed along considerable lengths on the aerial photography, however, the chances of detection are improved. Many long faults branch before dying out or diverge from their strike orientation somewhere along their lengths.

19-8. Joints—Definition, Interpretative Hints. "A joint is a type of fracture along which there has been little if any movement. Both the relief and the major movement have been perpendicular to the surface of the fracture and not along or parallel to it" (140).

To distinguish between jointing and faulting is often very difficult, and in the absence of conclusive fault evidence, it is common practice to consider the longer, stronger linears as faults and the shorter, crisscrossing linears as joints (Fig. 19-8). Only where linears intersect clearly visible stratification or contacts is an absolute determination possible; even there, a trace-slip fault will show no apparent displacement.

For the purpose of photo interpretation, strike joints (bedding and secondary foliation) can be classified as stratification linears. Others (dip and transverse) cut across the stratification linears, across each other, and tend to be more continuous.

Joints are useful from a structural point of view and, if for no other reason, should be recorded. However, they play a more important role in geological photo interpretation. Joints tend to "fingerprint" a formation so that it can be traced more readily or recognized in a new locality under similar conditions. Syenite plugs, quartzite ridges, diabase or gabbro dikes (Fig. 19-11), and flat-lying sandstone are usually typically jointed, but even where the identity of the formation cannot be established immediately, the joint pattern is nonetheless helpful in determining its distribution (Chap. 16).

Some extremely complex joint systems can be set up in the more homogeneous rock masses, such as even-grained granites, syenites, limestone, shale, and slate, so that the patterns presented on aerial photographs can be extremely varied and, in many cases, diagnostic.

19-9. Interpretation of Bedding. The basic clue for the recognition of sedimentary bedding is the fact that successive beds generally differ in physical and chemical characteristics. They are laminated throughout, both between and within the constituent beds. The resulting topography rarely fails to show the strong influence of bedding.

Where beds dip steeply, persistent close-spaced linears transect the topography with little deviation of trend. The linears consist of bedding joints and, more important, fundamental differences between adjacent strata. Thus prominent ridges, bands of different color tone, and bands of contrasting weathering patterns (Fig. 19-9) are conspicuous within the linear pattern.

Where beds are flat-lying, they tend to follow topographic contours. Mesa terrain may result, and certain beds may prove to be "cliff makers." The joint pattern is usually regular, with discrete, wide-spaced linears which cannot be attributed to bedding-plane foliation itself (Chap. 16).

Bedding should ordinarily conform to the regional structure; i.e., its interpretation should meet the test of geological probability.

In the northern areas of Canada and in tundra-covered areas in northern Alaska (154), where

outcrops are scarce, bedding can be interpreted from indirect evidence in aerial photographs. This can be accomplished by observing breaks in topography which suggest resistant formations and changes in vegetation.

In Pakistan and the Middle East (Fig. 19-9), where outcrop is abundant, the determination of the attitude and continuity of sedimentary horizons is relatively simple.

In most regions in central Africa, the recognition and correct interpretation of the few clues to bedding which do exist are quite a different matter and depend largely on experience of the interpreter.

19-10. Schistosity—Definition, Interpretative Hints. "Flow cleavage is the result of flow and recrystallization in consolidated rocks. It is characterized by platy minerals which are stable under these conditions. The capacity to cleave is due to easy partings between the platy minerals, and to mineral cleavage in the minerals. Another name for this type of cleavage is schistosity" (140).

Schists are highly foliated, but unlike most sedimentary strata, they display considerable homogeneity of composition and physical properties. The resulting foliation linears thus display less continuity, and ridges tend to be small, close-spaced, and of fairly uniform development. The sharper ridges are commonly related to harder quartzitic strata within the schist. Flat-lying schistosity is, of course, relatively rare.

19-11. Gneissosity—Interpretation. Here again, metamorphism has reduced abrupt lithologic changes between adjacent strata, but to a lesser



Fig. 19-8. Two distinct systems of jointing are clearly shown, creating a distinctive pattern in massive granite. Movement along the fault, indicated by the dislocation of the jointing pattern, can be observed in many places in adjoining photos. (*Algoma District, Northwest Ontario. RCAF.*)

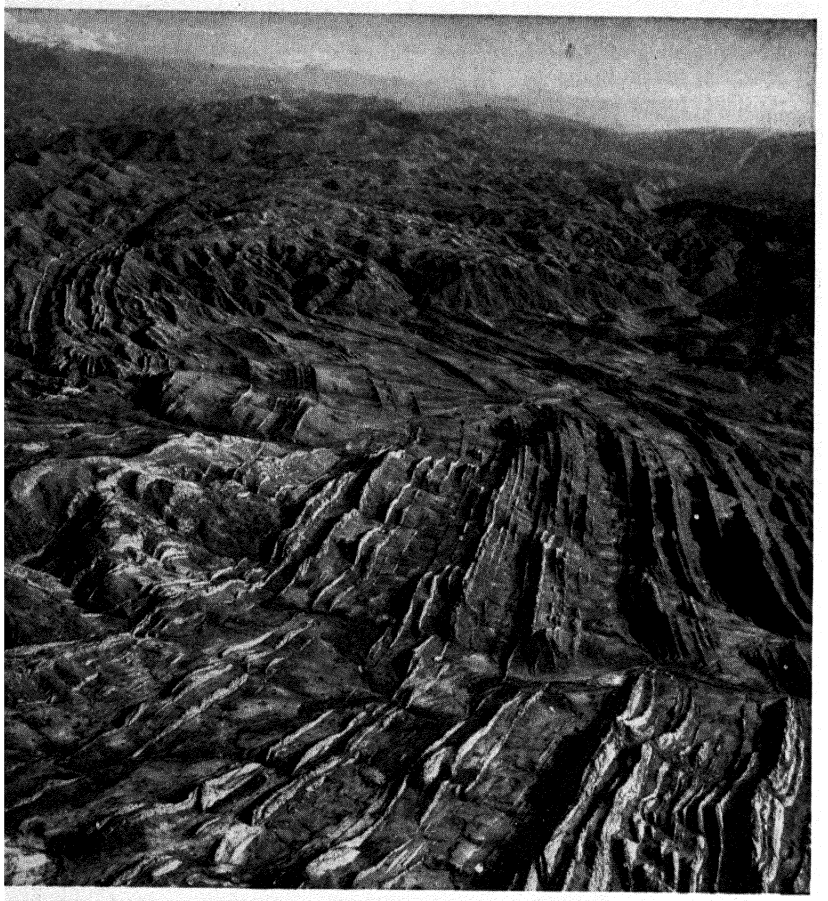


Fig. 19-9. A striking example of differential weathering in interbedded sandstones and marls. Vertical aerial photographs can be utilized most effectively in such areas to provide details of structural geology where cost and time requirements for conventional field mapping are prohibitive. (*Middle East. Hunting Aerosurveys Limited.*)

extent than in the schists; indeed, the development of gneissosity may result in the layering of a formerly massive rock such as granite. Variations in weathering tend to be slight over broad thicknesses, but the occasional band of soft-weathering material is common. Thus gneiss outcrops are usually rounded, and without their banding would be easily confused with granitic intrusives. The banding may be in the form of tone differences, rounded ridges, or deep erosion along parting planes. It may be highly contorted, and in many cases the gneissosity parallels the contacts of the parent body.

19-12. Modes of Occurrence of Igneous Rocks. In earlier sections of this chapter, reference is made to bedding with regard to sedimentary rocks and such features as gneissosity and schistosity in metamorphic rocks. In the matter of igneous rocks the "mode of occurrence is the general form and size of the eruptive body and its relations to adjacent rocks" (140). In many cases, a stereoscopic analysis of vertical aerial photographs will reveal a great deal of important data concerning the nature of an intrusive or extrusive rock: its attitude, method of emplacement, effect on the surrounding "country rock," including both frac-

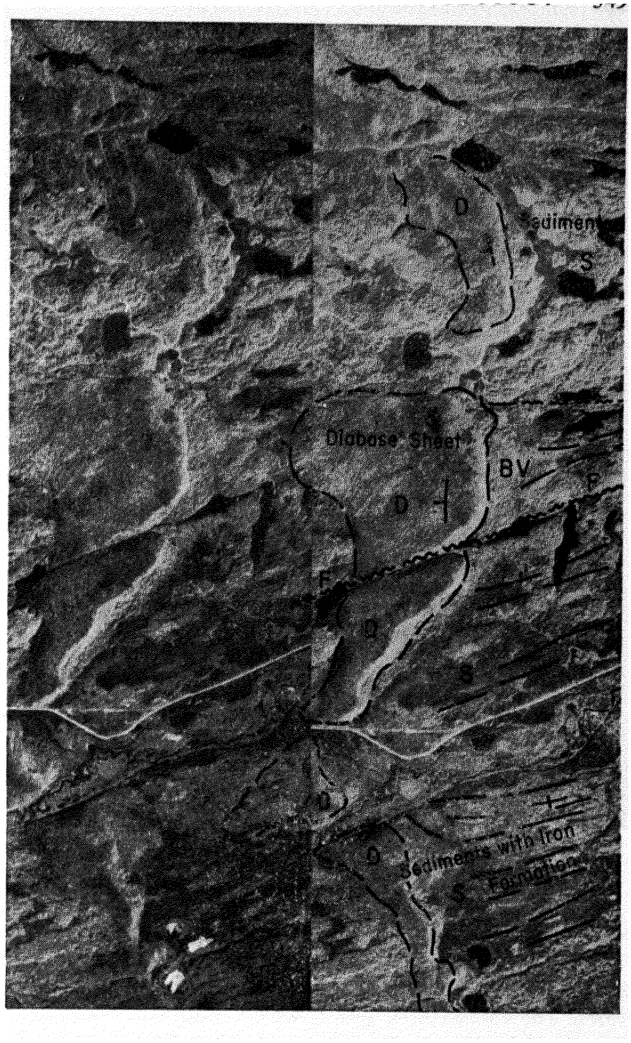


Fig. 19-10. A sheet of diabase *D*, some 200 feet thick and dipping at a low angle toward the left, intrudes old Keewatin basic volcanics *BV* and later Timiskaming sediments *S*. Bedding is evident in the near-vertical sediments to the south, while the volcanics, north of the fault contact *F-F*, have a more indefinite ropy appearance. (*Northwest Ontario. RCAF.*)

turing and folding and, to some extent, its composition.

There are many modes of occurrence of igneous rocks which can often be readily identified in aerial photographs. Intrusive plugs of granite or syenite are common everywhere and usually appear as rounded resistant mounds showing clearly in relief against the intruded formations. In some cases, the intrusive stock or plug may be largely eroded, leaving a depression in the earth's surface, possibly surrounded by concentric ridges formed by the intruded rocks as they were thrust aside at the time of intrusion.

Similarly, dikes and sheets of all types may be detected by differences in topography tone or texture (Fig. 19-10). The example in Fig. 19-11 shows not only an intrusive stock, but also dikes, with columnar jointing and *lit-par-lit* injection of pegmatite into the bedding planes of metamorphic schists.

Large batholithic masses of granite, which show no evidence of having a base and are discordant in their relations to invaded strata, present few problems to the experienced interpreter. All variations occur within the mass, from contorted gneisses to more homogeneous massive granites. Generally,

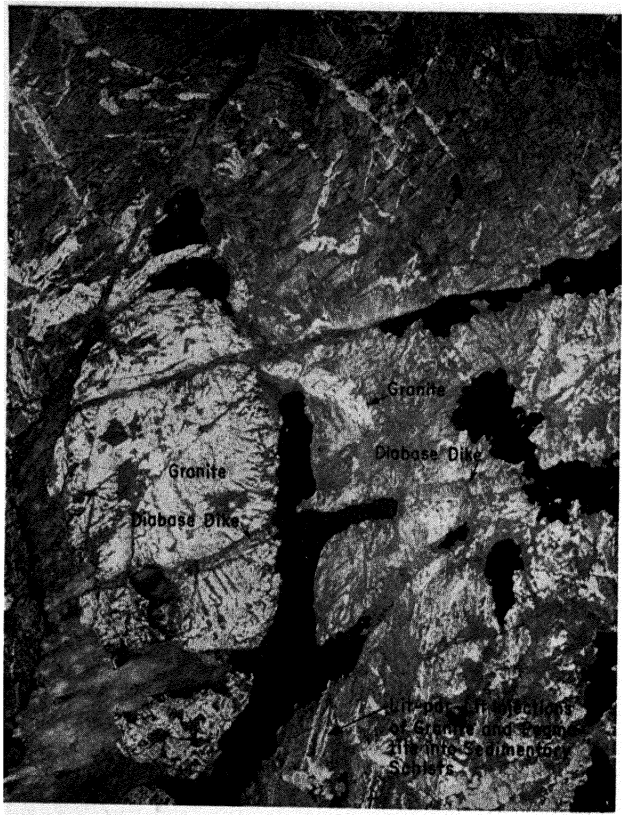


Fig. 19-11. This photograph illustrates various modes of occurrence of igneous intrusive rocks: a stock or plug of granite and pegmatite, irregular lenses and masses of pegmatite, dikes of diabase, and *lit-par-lit* injection of pegmatite into a schist developed from sedimentary rocks. (*Northwest Territories. RCAF.*)

the contacts of such large granitic masses can be detected by various means—tone, fracture pattern (drainage analysis incorporated), and textures. The contact of a granite with a basic volcanic rock is shown in Fig. 19-12. It is not difficult to distinguish between the characteristic modular ropy pattern of the volcanics and the relatively flat (in this case) granite topography.

Adjacent to the larger granite masses various types of contact effect can be noted. Small outliers of the intrusive can be observed, and under the best conditions, some assessment can be made as to the relative effects of contact metamorphism in the invaded strata.

The appearance of a stock of nepheline syenite is illustrated in Fig. 20-2*a*. This particular example occurs in South America, and it serves to indicate the necessity for creating a new set of identification criteria for rock types in each area in which the air-photo techniques are used.

19-13. General Basis for Application of Aerial-photographic Techniques to Study of Structural Geology. In the past few years, it has become routine procedure for most field geologists to make use of aerial photographs in some form or other, either prior to or during a field season. The extent to which aerial photography can be utilized depends upon several factors: the experience of the geologist in its application, the nature of the field investigation, the complexity of the geology, and the amount of rock outcrop to be expected.

In some cases, it is possible to employ single photographs, or composite photo mosaics, for location of traverse lines and plotting of field observations. However, in most areas a thorough stereoscopic analysis of vertical aerial photographs in conjunction with a field geological program will greatly improve the efficiency of the field work and substantially reduce the expense of such a program.

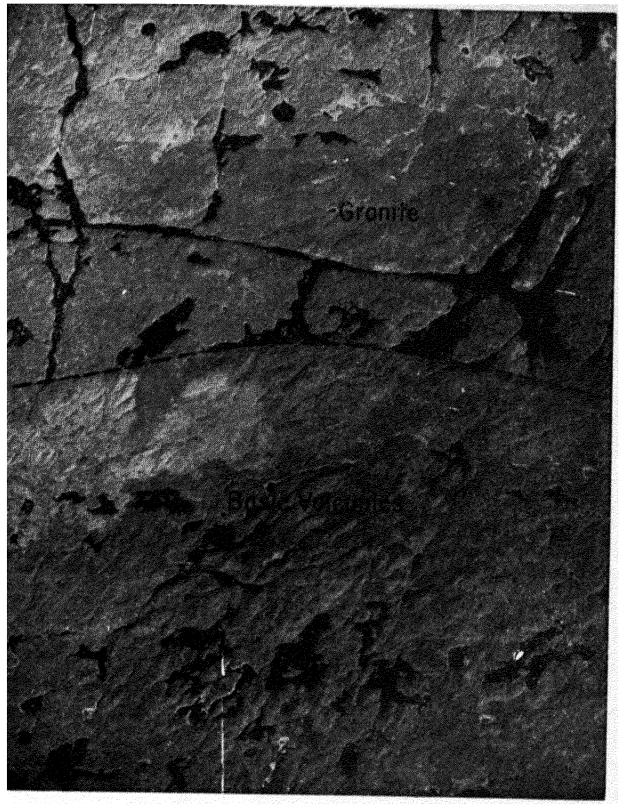


Fig. 19-12. A contact between granitic and basic volcanic rocks to illustrate the possibility of detecting and plotting such a contact by differences in fracture pattern, drainage pattern, tone, and texture. (*Northwest Ontario, RCAF.*)

In the analysis of air photos, the structural geologist is engaged largely in a study of topographic anomalies related to bedrock, and the exaggerated vertical scale (Sec. 24-10) provides him with an extremely useful tool, one which is not available to the field geologist on the ground.

It is by means of this exaggerated relief and the ability to view a large area at a time that the geologist is able to distinguish various rock types, establish continuity of certain formations, and detect, with some confidence, structural patterns which may be favorable for the formation of ore deposits.

It should be noted here that a great deal of useful and important geological information can be obtained by an experienced interpreter despite the presence of a reasonably heavy forest or soil cover and the lack of exposures of bare rock.

The intelligent use of aerial photography accelerates field work by showing convenient routes for travel, river hazards, swamps, forests, and outcrop areas.

Many geological features can definitely be identified in the aerial photos. Faults, joints, primary and secondary foliation, and contacts are commonly discernible.

Criticisms are frequently directed against the "indiscriminate" use of geological photo interpretation. The major objections are that such techniques tend to have limited usefulness for detailed problems with which the geologist is commonly involved; and second, that their substance is one step removed from actuality—in other words they must be interpreted.

While these limitations are real in most cases, the usefulness of the techniques is also very real, and it is desirable for every geologist to recognize what can and cannot be done, both from a detailed and a regional standpoint.

Although the criticism with regard to the detail



Fig. 19-13

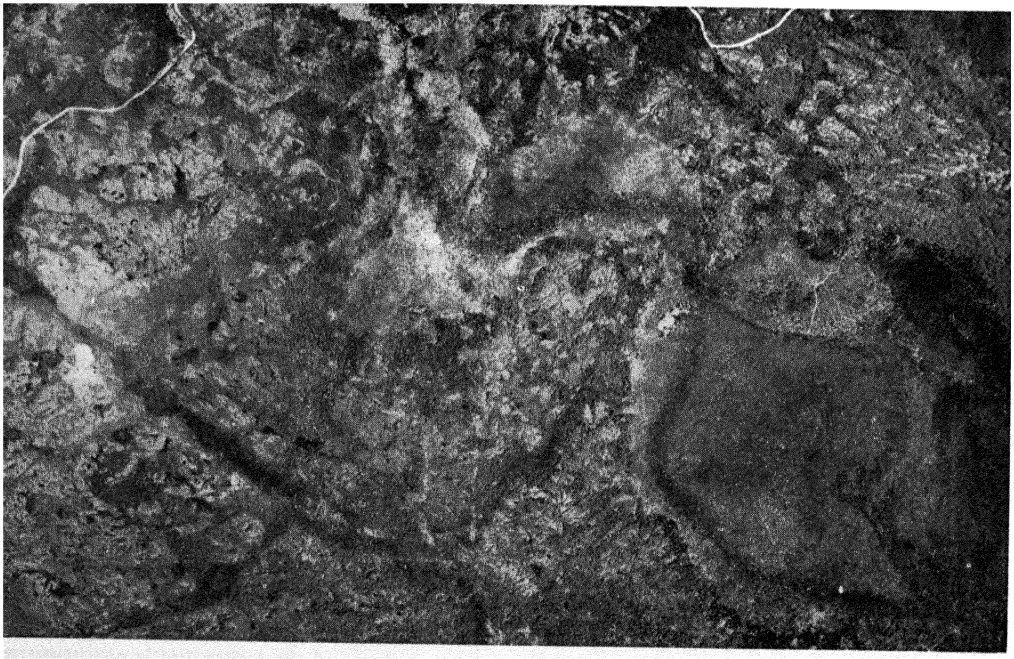


Fig. 19-14

Figs. 19-13 and 19-14. The effects of the state of tree foliage on the study of rock outcrops. In summer photography (Fig. 19-13) the deciduous trees and bushes (white) and the coniferous varieties (gray to black) mask most of the rock outcrop completely. Figure 19-14 illustrates spring photography, in which most of the rock exposures are clearly visible. (*Ontario. Photographic Survey Corporation.*)

of aerial methods is admitted, it is surprising how few practicing geologists realize the degree of detailed information which actually is available by these methods.

The other main objection to air-borne techniques is, as noted above, that they require interpretation and that no geological interpretation is as reliable as a genuine field observation made on bare rock. In reply to this it must be stated that *practically every geological map is an interpretation:* after every available outcrop has been visited, an interpretation of some kind must be made by the geologist if he is not to remain for life a mapper and recorder of outcrops.

Geological photo interpretation is not in itself an answer to all geological problems. It is not a labor saver and an easy substitute for the discomforts of field work. It is, instead, a tool which gives new and greater utility to conventional ground methods, as well as providing an entirely new means of expression of geological features.

19-14. Measurement Methods in Geological Interpretation of Air Photos. The results of a fairly recent questionnaire on photo geology distributed to a group of private and governmental geologists showed that only a small per cent used measuring devices in determining slopes, formational thicknesses, and angles of dip. Most rely entirely on visual estimation and assign a probable accuracy of ± 10 per cent.

In the mineral industry today a great deal of the geological photo interpretation is done for a rapid reconnaissance of a comparatively large area for a client who requires the information in a relatively short time in order to plan a season's field work efficiently and economically. The information required is inevitably related to structural anomalies and features of interest, and these are, in turn, dependent upon numerous determinations of strike and dip of sedimentary formations.

It is obvious, then, that for such reconnaissance studies it is not customary for the average photo geologist to employ one of the precise photogrammetric methods available. Such extreme accuracy must be sacrificed for a rapid evaluation of the regional structure and the pinpointing of areas of possible economic interest.

The accurate visual estimation of strikes and dips depends to a large extent on the experience of the interpreter. In an area of rugged topography with variable dips, the novice may estimate a dip at 65°, only to find in the next row of photos the same formation dipping in the opposite direction at 75°.

Generally, in such difficult areas, interpretation is confined to the central 25 per cent of the photograph, if possible, in order to avoid the inevitable distortion toward the photo edge (Sec. 24-2).

19-15. Instruments for Photogeological Measurements. In oil exploration and detailed mineral exploration, slope determinations and formational thicknesses are calculated by some form of stereometer based on the "floating-dot" principle, and there is no doubt that some relatively simple method of slope calculation will be evolved in the near future which will enable the photo interpreter to include more accurate estimations of dips and strikes in reconnaissance geological photo interpretation as well.

In the application of photogeological methods to the solution of complex structural problems and the study of gently dipping formations as encountered in petroleum exploration, a much more detailed quantitative analysis is required. The measurement of formational thickness is an essential for the preparation of structural contours or stratigraphic sections.

As noted by Fischer (58), "the accuracy requirements for geologic measurements are extremely variable. There is, therefore, need for many instruments so that the most economical procedure may be followed."

Measurements of the simplest type, i.e., those which are normally not related to a common datum, can be made with the stereometer-type instrument. These include such features as strike and dip of formations, the angle of inclination of a fault plane, and approximate thickness of individual rock formations. The measurement involved is that of vertical intervals between features which are usually close together in plan position, such as the top and bottom of a near-vertical cliff. The instruments commonly used for this type of work are the Abrams height finder, stereo elevation meter, Fairchild stereocomparagraph, Zeiss stereometer, and Wild stereometer.

Where greater accuracy in the measurement of relative elevations is required, as in the mapping of formational thicknesses over a wide area or in structure contouring, it is necessary to utilize a photogrammetric instrument of greater precision such as the Multiplex or Kelsh plotter.

An instrument recently developed by the U.S. Geological Survey is known as the Super Duper



Fig. 19-15. The amount of detail possible in geological photo interpretation varies with the scale of the available photography. Notice the difference in detail, particularly fracture patterns, between this example and Fig. 19-16, which covers the area outlined in white. (*Northern Ontario. Photographic Survey Corporation.*)

Dipper and is designed to find strike and dip of a slope on the stereoscopic model. The operation is based on two targets which are actually tilted in space and oriented along with the stereoscopic image of the aerial photographs. The targets employed are interchangeable, so that the size of target can be made to coincide with the size of the slope to be measured to increase the accuracy of the measurement.

There are numerous excellent articles dealing with the problem of geological measurements from aerial photographs, some of which are listed in the Bibliography (47, 49, 56, 215).

19-16. Special Problems of Structural Geology Inherent in Aerial Photographs. The major problem in the stereoscopic analysis and plotting of geologic structures is of course the inevitable distortion of photo image. Detailed analysis is usually confined to the center portion of each photograph, where this distortion is at a minimum. The amount of distortion varies directly as the ground clearance, i.e., the difference in elevation between the aircraft and the ground, so that in mountainous terrain the problem of interpreting and plotting details of structural geology is a major one.

The time of year and also the time of day at which the photography was taken may have a great effect on the efficiency of interpretation, in areas such as most of Canada with a considerable amount of summer foliage (Figs. 19-13 and 19-14). The optimum conditions for aerial photography used in geological interpretation are those existing in the early spring between snow and maximum foliage. Full summer foliage obscures a large percentage of rock outcrop and, to some extent, structural linears. Fall photography presents an added hazard in the form of irregular



Fig. 19-16. An example of detailed mapping accomplished by geological photo interpretation. While the actual rock types were identified by field checks, the faults, contacts, outcrop boundaries, and undefined "linears" were obtained from the aerial photograph. This photograph represents the block outlines in white in Fig. 19-15. (*Northern Ontario. Photographic Survey Corporation.*)

patches of light-colored autumn foliage, and even the presence of a blanket of fallen leaves in the late fall can cause the interpreter some difficulty. It is unfortunate that it is not always possible to have aerial photographs taken for a specific geological project, and the available photography, largely from governmental sources, is generally most used for lands and forests purposes and is therefore not the most suitable for geological interpretation.

The sun angle at the time of taking the photography is not usually a major problem in geological interpretation, but can definitely be a deciding factor in the amount of detail which can be obtained. Textural differences, which are a key to rock-type identification, can be reduced to a useless minimum or overexaggerated. Prominent linears can be obscured or distorted by heavy shadow, and in heavily forested areas a low sun angle produces long tree shadows and confusing false linears.

19-17. Special Problems Caused by Anomalous Terrain or Surface Conditions. Heavy soil cover, especially in clay-belt areas, can render geological interpretation extremely difficult, if not impossible. The structural clues may be reduced to abrupt changes in stream direction, long straight stretches of river, and similar drainage-system anomalies which give a hint of the rock type beneath the soil layer.

In mountainous and foothills terrain, the problems of distortion are always present, as noted above (Sec. 19-16), and are increased by the rapid changes in ground clearance.

The clearing of land for farming, plantations, and town sites may, in some cases, provide more rock exposures for the interpreter, but usually



Figs. 19-17 to 19-19. Fine examples of folded sedimentary formations. Ground geological surveys in such relatively inaccessible regions can be made economically and physically possible by the use of vertical aerial photographs in conjunction with field checks for the mapping of structure and lithology. (*Middle East. Hunting Aerosurveys.*)

Fig. 19-17

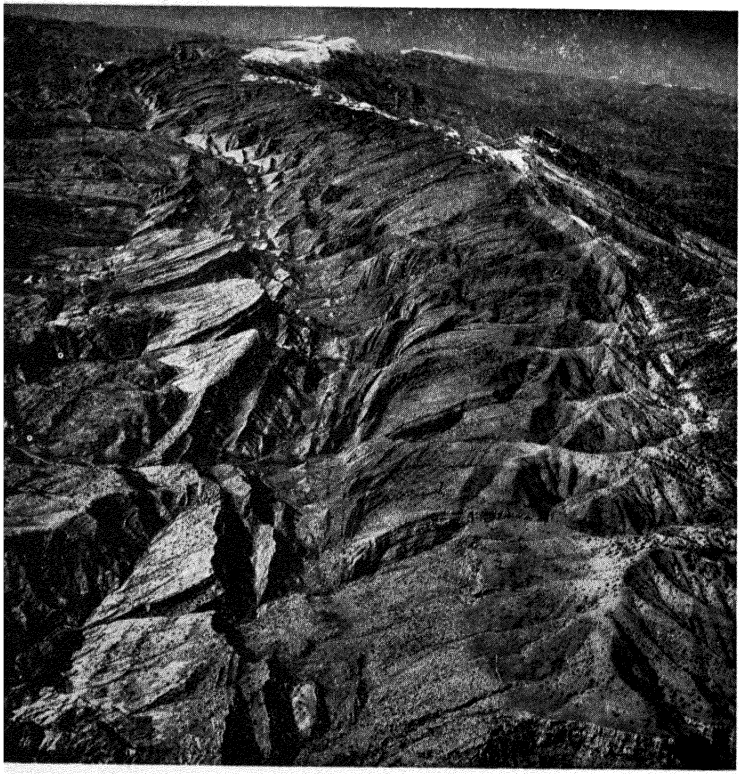


Fig. 19-18

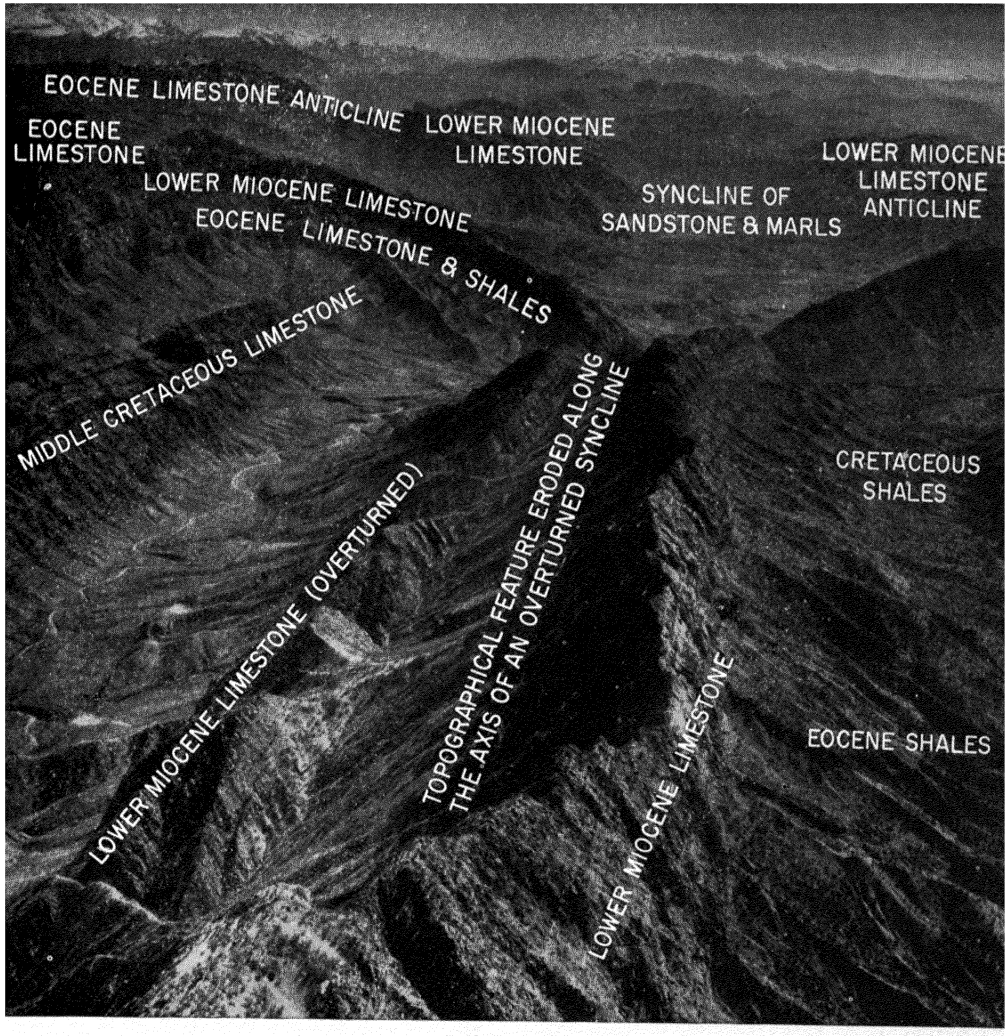


Fig. 19-19

tends to obscure a large percentage of valuable structural clues in the form of faint linears controlled by bedrock fractures and possible surface traces of bedding and gneissosity. On the other hand, in some cases the clearing and utilization of certain land areas, particularly in a region which is generally inhospitable to farming operations, may give a valuable clue to the presence of isolated patches of recent sedimentary formations which provide soil suitable for growing.

Where forest cover is present, logging operations can create the same difficulties. The necessary access and strip-logging roads are generally laid out in a more or less standard geometric pattern, which is most confusing. The scars of old logging trails can provide a series of patterns which are even more deceptive. Fortunately, however, these cause trouble mainly on photography of 1:15,000 scale or less, so that in reconnaissance work the problem is not so serious.

19-18. General Procedure for Geological Interpretation for a Reconnaissance Mineral Survey. Recent literature contains numerous references to "photogeologic procedures," and these generally include descriptions of stereoscopes, plotting in-

struments, methods of annotating aerial photographs, and similar mechanical steps in the stereoscopic analysis of aerial photography for various types of resources surveys.

Apart from the actual techniques of stereoscopic work, there are stages of planning and compilation which are equally important in the organization of an efficient and economical geological interpretation.

Phase 1 in this procedure is generally the compilation and study of existing data, in the form of maps and reports. Any advance information regarding rock types or structure will greatly facilitate the work of the interpreter. It is advisable to plot any available geological information on a suitable base map or mosaic of the area to aid in the interpretation. There is no single set of criteria for rock-type identification or for the detection of particular structural features which may be universally applied. With each new attempt in a different part of the world, the interpreter must be prepared to create a new set of standards from which to construct his picture of the geology.

For this reason, he will accept with deep gratitude any small clues as to the presence of a particular rock type or major fold axis and, after a relatively casual examination of all photos, will proceed carefully to construct his interpretation from the known to the unknown.

Phase 2 is the annotation of the air photos and preliminary analysis. In a preliminary examination, the geologist is interested primarily in two types of evidence: surface traces, of either bedding or gneissosity, and linears.

Surface traces, or structure traces, are best indicated by fine broken lines, and these, when transferred to a mosaic or map, give a fine regional view of the geological "grain" of the country. This is a substantial aid in the detection of folds, formational continuity, faulting, and in some cases rock-type identification.

Linears are generally straight or nearly straight lines and may represent the surface expression of a multitude of bedrock structures. Some of these may be identified as faults when evidence of movement is visible, such as displacement of a prominent dike or a resistant formation.

Other linears may be joints, shear zones, bedding, gneissosity, and schistosity and may possibly be identified and indicated as such by the interpreter. However, it is often found that some at least of these pronounced lineaments must be classified simply as "unidentified linears" and await identification in the field.

A further requirement of the preliminary analysis is the location and marking of areas of rock outcrop. Depending on the nature of the area, it may be necessary to indicate probable and possible outcrop in order to give encouragement to the field man who may be despairing of ever again seeing solid rock.

Phase 3 is the detailed or secondary analysis. As the interpreter becomes more familiar with the area, he begins to identify local masses of intrusive rock, granite, or gabbro, for example, by their distinctive angular fracture patterns, radial drainage, raised contact metamorphic zones. Here and there good exposures may permit the identification of a sedimentary band of quartzite or sandstone, and with scattered determinations of strike and dip of these formations a broad picture of the structural geology of the area is begun.

The amount of detailed interpretation possible will depend largely, of course, on the scale of available aerial photography (Figs. 19-15 and 19-16).

In the final stages, it is possible for an experienced interpreter with the aid of scattered field observations to detect and plot such refinements as local zones of *lit-par-lit* injection of granite into sediments, the fine distinction between uneconomic gabbro and diabase and asbestos-bearing serpentinized peridotites, and the degree of granitization of sedimentary and extrusive rocks (Fig. 19-16).

Phase 4 is the final geological interpretation. The final interpretation of the geology is best performed on a photo mosaic of the area, constructed, preferably on a semicontrolled basis, from a duplicate set of prints. The photo mosaic is preferred to a planimetric base map because of the ease of transfer of data from prints to mosaic and the obvious advantage of a composite picture of the entire area.

On this base, the linears, surface traces, and other scattered structural clues are plotted, and after further examination of selected photos, the final interpretation is made. At this time, broad regional features which can be observed on the composite mosaics or on the plot of the interpreted data take on more meaning as additional evidence in the form of minor structures, textures, and fracture patterns becomes available.

It is at this stage also that geophysical data can be related to geological structures, and a more

comprehensive interpretation of geophysical records and maps can very often be made.

Armed with this information, the field geologist is able to plan and execute an efficient and economical field program on a reconnaissance scale. This is accomplished by concentrating his efforts on those areas of interesting structure and by arranging traverses to visit the largest number of rock exposures with the minimum expenditure of time and energy (Figs. 19-17 to 19-19).

GEOMORPHOLOGY AND SEDIMENTATION

19-18. General. The applications of aerial-photographic techniques to these fields is based upon an intelligent analysis of landform. In so far as unconsolidated materials are concerned, Chaps. 2 and 9 to 15 provide a fairly comprehensive presentation of the value of air photos to such analysis. The analysis of the geomorphology and sedimentation of consolidated deposits is not covered in this book, except as implied, or as related to the subject matter of Chaps. 16 and 19.

APPLIED GEOLOGY

19-19. General. Applied geology (Sec. 7-3) covers the fields of mineral exploration, mining geology, and engineering geology, as well as applied geophysics, geochemistry, and geobotany (Sec. 7-22). The application of air-photo techniques to most of these fields has been covered elsewhere in this book.

Engineering geology is based upon an intelligent analysis of petrology, petrography, structural geology, and geomorphology in terms of engineering problems. The use of the aerial photograph in these fields is described in Chaps. 9 to 16 and in this chapter.

Applications to geophysical studies are discussed in Chap. 20.

Geobotanical investigations involve the coordination of botany with environment. The general study of environment is a primary capability of aerial-photographic interpretation, while remarks on botanical investigations appear in the latter part of Chap. 22.

Aerial-photographic techniques have little to offer mining geology except in a surficial way or in connection with engineering development (Chaps. 17 and 18).

There remain only mineral exploration and geochemistry. Comments on mineral exploration are included in the following section. Applications to geochemical study are briefly mentioned in Sec. 19-21.

19-20. Application of Aerial-photographic Techniques to Mineral Exploration. Mineral localization is a very complex phenomenon involving many factors, most of which are only imperfectly understood or not understood at all. There is no room for, or purpose in, their discussion in this book. An excellent summary relating mineral localization to structure in the Canadian Shield has been published by Gill (67).

The author, in 1953 (107), published some general opinions regarding the application of photographic techniques to mineral "reconnaissance":

What is mineral reconnaissance? It is simply a search for, examination of, and evaluation of features that may indicate mineral deposits. It is fairly general in scope, being followed, in favorable areas, by detailed rock study, sampling, assaying, and possibly development.

What are the features that indicate the possibility of mineralization? To review briefly, they are features that indicate the operation of mineralizing processes or that tend to facilitate, channel, or limit that operation. These features, which may be called "localizers" and "indicators," are reviewed briefly, in the following paragraphs, for the single process of hydrothermal mineralization.

Primarily, there is igneous activity. Hydrothermal deposits, according to economic geology, result from the movement and crystallization of fluids originating in bodies of igneous rock. Igneous rock bodies, therefore, are prime localizers.

Then there are "host" rocks—rocks whose physical and chemical characteristics affect mineralization. For example, it is reasonable to assume that hydrothermal fluid movement will be affected by rock permeability. Therefore, under usual conditions, relatively impervious rocks, such as shale and schist, do not favor mineralization, while porous rocks, such as breccia, soluble limestone, basalt, and sandstone, do favor it. This assumption has been borne out by field observation.

Next, there are structural controls. These may be features of mass warping, such as evidences of folding, uplift, and subsidence, that indicate igneous activity. Or they may be faults, fissures, joints, and cracks that bring different rock types into contact or provide channels for hydrothermal fluid movement.

Although not a localizer, color may be an indicator of mineral deposits. The color may be associated with an actual outcrop, an oxidation strain indicative of underlying minerals, or an alteration halo. In any case, the blacks, reds, greens, browns, and yellows asso-

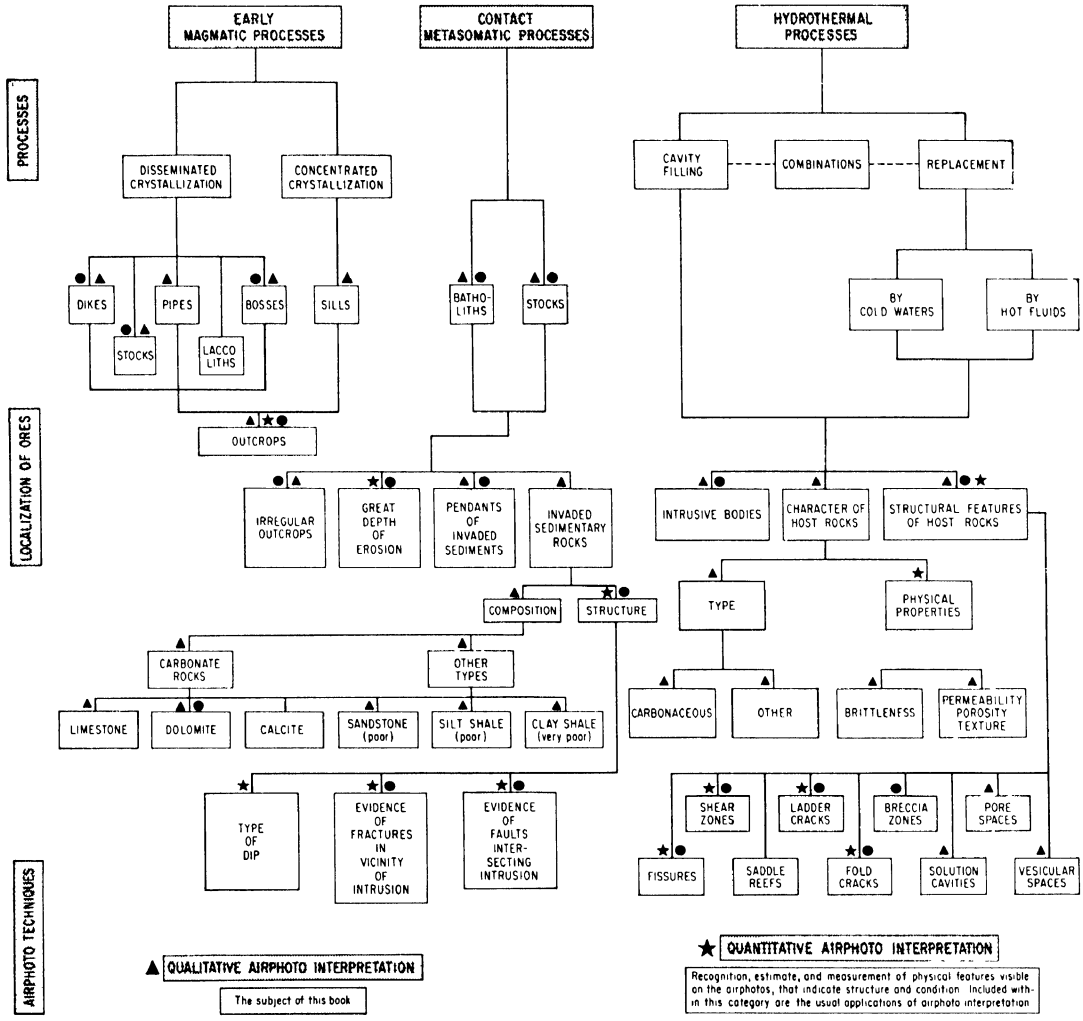


Fig. 19-20. A schematic presentation of the way in which aerial-photographic interpretation may be applied to mineral exploration. The various symbols beside printed entries refer to the particular technique that may be of value.

ciated with mineralization always bear investigation.[2]

Most of these localizers and indicators can be seen on air photos. In addition, recent work in air-photo interpretation facilitates the identification of many rock types in a manner described in the initial portion of this paper [and Chap. 16]. Therefore, by use of air photos, large areas can be covered rapidly. The origins, types, and general characteristics of the rocks can be determined. Stress signs, color, and vegetative features can be located and examined. Various locations can be rated according to the weight of favorable evidence. The most promising of these locations can be subjected to large-scale color photography, reinterpreted and possibly to aeromagnetic or airborne scintillometer surveys. Finally, detailed maps of these areas can be supplied to field geologists for use in ground investigation.

The general applicability of aerial-photographic techniques to mineral exploration is illustrated diagramatically by charts that the author prepared some years ago. One of these charts appears as Fig. 19-20.

Laylander (99) has been using color photography for mineral exploration with considerable success. Pertinent extracts are as follows.

[2] The matter of plant association, from the same paper, is extracted in Sec. 22-17.

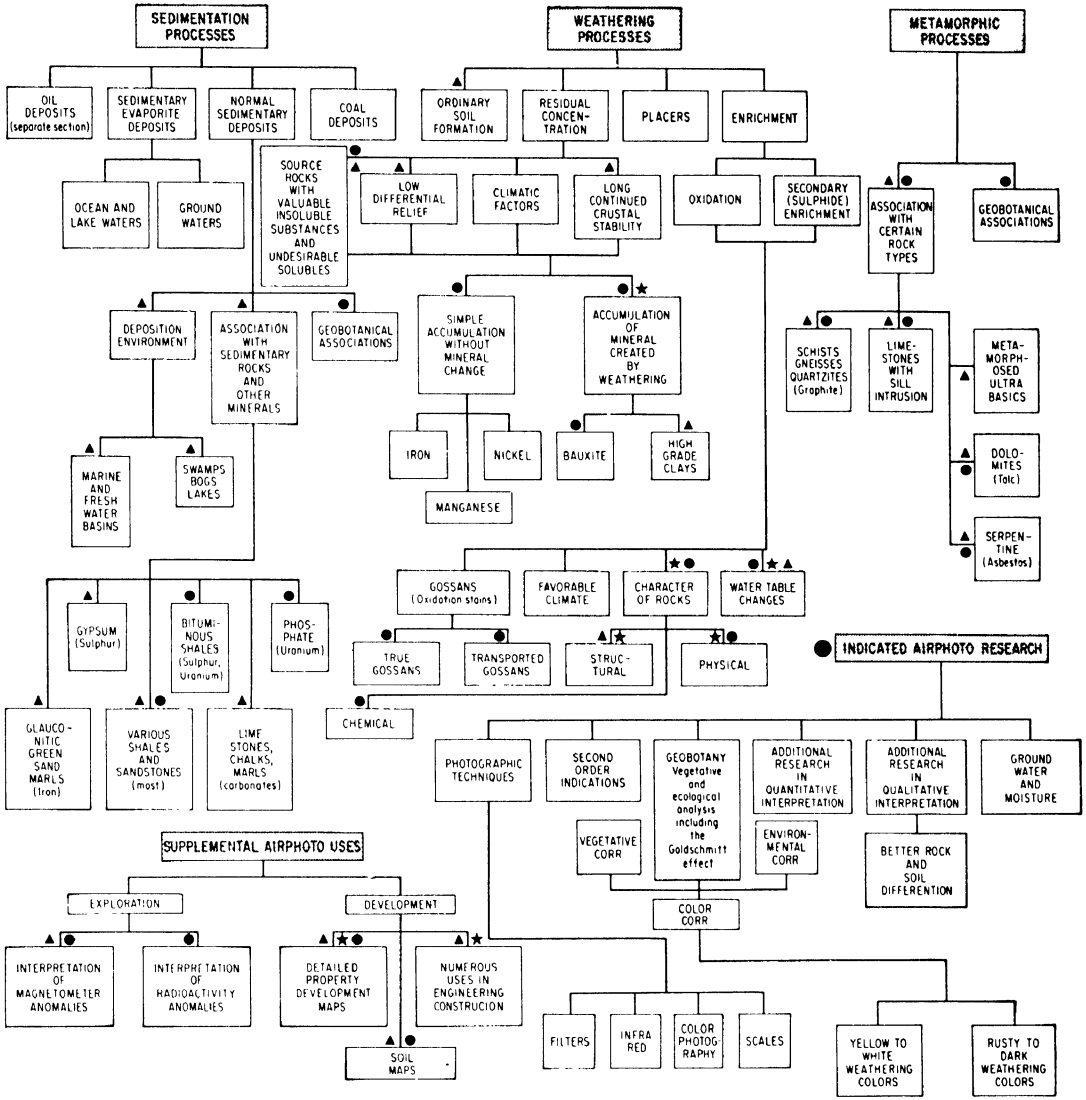


Fig. 19-20 (*Continued*)

The principal advantage of the color photographs for mineral exploration or general geologic mapping is that they allow a very detailed and complete pre-mapping of an area before field work. The concept of as thorough as posible pre-mapping of an area before ground studies has been slow in attaining general acceptance. This is probably due in part to the limitations of the black and white photographs, and perhaps to disinclination of the geologists to do the amount of "estimating" necessary in such work. But it provides much greater efficiency in the mapping work—particularly in remote and inaccessible areas.

In mineral exploration, it is possible to make a quite thorough analysis of an area and a selection of the critical spots—the situations in which ore can be expected. This is difficult for geologists to accept as being possible if their approach has been primarily a detailed ground and mineralogic study of areas as a basis of ore analysis. However, the advantages of the color photo-view have been demonstrated in many areas in which an opportunity for comparison has been possible. . . . In the study of dozens of mineralized areas it has been found that there are essentially none which do not have changes of color in the surrounding rocks reflecting the ore zones. For example, in the Pioche, Nevada, district which has important bedded lead-zinc deposits near the base of the Cambrian section, the color photographs show

areas of dark manganosiderite bloom and pyritic alteration along fractures 1,700 feet higher in the section. Those alterations are confined to the ore zones. Also, distinctive types of gossans reflecting copper porphyry deposits can be seen on the color photographs. In both types, the distinctive alterations and intensity of the zoning are very difficult to see by black and white photography, or by ground observation. The generalization can be made that there are essentially no important ore deposits which do not have both broad alterations and specific local alterations, fairly readily seen on the color photographs, which cannot be distinguished on the black and white photographs.

On the Colorado Plateau a color photogeologic study of about 2,000 sq. mi. of the uranium-producing areas indicated that there were usually subtle alterations of the rocks reflecting ore zones which were largely overlooked by ground studies. In the Big Indian area, for example, infrared color film with a special filter combination showed a change from a reddish to a yellowish color in the Chinle formation near ore zones which could not be seen either on black and white film or visually. There is a great field of potential research in study of areas by means of special color films and filter combinations, in determining non-visible changes in rock colors, related either to hydrothermal alteration or facies changes. . . . Plant patterns in many areas are quite sensitive to minor element concentrations, and such plant pattern anomalies are an aid in determining ore deposits at some distance below the surface of the ground. For example, within perhaps a mile radius of a lead-zinc deposit, where either hydrothermal or ground water has carried small amounts of zinc or manganese, there may be considerable change in the plant patterns. Those plant patterns may be picked up to some extent with the black and white photographs, but the infrared-color film will usually give much greater distinction. As far as has been observed there is little perceptible specific change in the colors of particular plants due to minor element concentrations.

The plant patterns also reflect the rock patterns. Considerable photogeological mapping can be done on that basis, where correlation between plant types and rocks on which they grow has been established. The correlation can be determined in less densely covered areas, and projected into heavily covered areas.

The interested reader should also refer to Secs. 5-22 to 5-26, 16-4, 16-6, 16-11, and 22-17.

19-21. Application of Aerial-photographic Techniques to Certain Geochemical and Geophysical Studies. Interpretation may be an important aid in the completion of certain investigations involving radioactivity and geochemical effects.

The texture of a soil provides a rough indication of its field density (gamma-ray interference); its specific area (amount of geochemical absorption); its permeability (amount of leaching, groundwater flow, and migration of radiation and/or absorption effects); its water retention (neutron and gamma-ray interference); and erodibility (susceptibility to surface-drainage formation and tracking of absorption trains). The influence of these factors on phenomena involving radioactivity and geochemistry is well established in both fact and theory.

Further, information on such items as natural moisture content, moisture retention and potential, and surface or shallow subsurface drainage are important aids to an investigator faced with the task of analyzing the vagaries exhibited by scintillometric and geochemical data.

Obviously, air-photo interpretation can be of great value in preparing effective soil and drainage maps and mosaics covering these items.

20 AERIAL PHOTOGRAPHY AND GEOPHYSICS

By H. S. Scott [1]

20-1. Scope of Chapter. The broad science of geophysics has a much longer history than has aerial photography. The latter has had considerable influence upon recent geophysical progress, particularly in the field of mineral exploration, and it is this aspect which forms the principal topic of the present chapter. A very general summary of geophysical exploration methods is given by way of an introduction to the subject. The chapter then goes on to show how the advent of aerial photography has added efficiency to old methods, permitted the development of air-borne techniques, and contributed much to the geological interpretation of geophysical results. It is contended that the value of aerial photography to geophysical interpretation is inadequately recognized and that in this field lies photography's greatest aid to geophysics. Only some general observations are made on the matter of interpretation, because this is actually geological photo interpretation as discussed in Chaps. 16 and 19.

Some brief comments are made on the use of aerial photography with respect to the execution of ground geophysical surveys for engineering purposes.

20-2. Relationship of Geophysics to Geology. Geophysics, as its name implies, is a very broad science. In many respects it has the attributes of an art. It is an important means through which geologists extend and add to their ordinary faculties of observation, for the purpose of investigating the composition and structure of the earth. The rock properties utilized by geophysical techniques are mainly magnetism, electric conductivity, density, seismic wave transmission, radioactivity, and thermal conductivity. There are other avenues of approach, and it is sometimes difficult to distinguish whether a technique is primarily geophysical or geological.

Most geophysicists (and surely all geologists) will agree that the role of geophysics is to supply basic data for the solution of geological problems and that it is therefore the handmaid of the geologist. This in no way relegates geophysics to a secondary function; on the contrary, it supplies an increasing proportion of the geological record for all purposes.

In this chapter the subject of geophysics is considered in two categories. These differ chiefly in the nature of their objectives and in the scale with which the corresponding techniques are applied. One category is termed exploration geophysics, and the other is earth physics.

EXPLORATION GEOPHYSICS

20-3. The Rise of Exploration Geophysics. Modern geophysical techniques play an important part in almost every present-day minerals-exploration program. This trend is to be expected as more and more rock outcrops come under the eye and hammer of the geologist and prospector. It is also related to the increasing need by the mineral industry for every available clue that may help in solving the complex problems of exploration.

From its first serious application toward the end of the last century, through periods of trial, disappointment, and general suspicion, geophysics finally won the confidence of the petroleum industry in the 1920s. Less enthusiastic recognition by the mining fraternity came more slowly, gaining its first foothold in the late 1920s, and still being withheld by a diminishing number of exploration men in 1957. The mining industry's skepticism is

[1] Technical Director, Hunting Technical and Exploration Services.

founded on the past performance of geophysics; early surveys for metalliferous deposits were rarely fruitful, and their results were frequently misleading. With postwar technological advances and improvements in interpretation, the record is improving, and geophysics is the key in an increasing number of important discoveries. Both the petroleum and mining industries now rely heavily upon this relatively young applied science for their future needs.

20-4. Résumé of Geophysical Methods. Geophysics plays two roles in mineral exploration. In one it is a direct method, whereby it measures the response to some physical characteristic of the desired mineral itself or of a closely associated mineral. A magnetite deposit, with its associated magnetic anomaly, is one of the few good examples. Others include electrically conductive sulfide bodies and radioactive deposits. In its other role, geophysics becomes a general aid to the geologist in helping to piece together the geological "picture."

Ideally, geophysics provides data for both objectives; it aids in the recognition and delineation of geologically favorable conditions, and then it points to promising geophysical indications within the vicinity. Thus a magnetic anomaly of relatively minute stature may, after careful assessment, point to an important body of base-metal sulfides. Unfortunately, the direct role of geophysics has rarely been demonstrated in the past, but discoveries by this means are being made with increasing frequency.

A very brief description of each of the principal methods of geophysical exploration is included here to acquaint the nongeophysicist reader with their application and scope. Each method is based upon well-established physical principles, but its success depends upon its proper application and the careful interpretation of the results.

Magnetic methods make use of the fact that geological substances have different and somewhat characteristic magnetic susceptibilities; these in turn lead to induced or remnant magnetism. If variations in the earth's magnetic field are measured and recorded at suitably spaced intervals on or near the surface, much information about the underlying formations can be deduced therefrom. The method may be used to distinguish granite from limestone, for example. Intrusive contacts may be further emphasized by the results of igneous metamorphism, which may include magnetite. Magnetic survey may reveal a body of pyrrhotite (a magnetic sulfide commonly associated with base-metal ores), or it may provide data from which the depth to magnetic formations through a thickness of relatively "nonmagnetic" sediments may be calculated.

Gravity methods have much in common with magnetic methods. A natural potential field, gravity in this case, is measured at suitable points in the survey area. Variations are related to changes in density of underlying formations, to the size and shape of the causative bodies, and to their distance from the plane of measurement. It is important that corrections be made for topography in the vicinity of each measurement; the effect of surface irregularities diminishes with distance, but large variations may influence a gravity measurement for a very considerable distance.

Electrical methods employed in geophysical exploration are very diverse. One of the oldest and simplest is the measurement of natural currents, which are generated by the oxidation of sulfide minerals.

The majority of electrical methods require that an electric field be applied to the ground, either by direct contact or by induction. Thus one important group determines variations in the resistivity of successive blocks of ground; an electric current, usually alternating current, is introduced through a pair of electrodes, and the voltage drop between another pair of electrodes is compared from place to place. The variations are interpreted in geological terms. Most sulfide bodies are good electric conductors, as are graphitic zones and wet shear zones. Many rock types have rather diagnostic resistivities in a given area.

A recent strong trend among electrical procedures is toward electromagnetic prospecting. There are many variations of equipment and technique, but the basic principles are the same. An alternating electromagnetic field is induced in the ground by means of a transmitting coil. Electric conductors in the ground are revealed by the generation of a secondary electromagnetic field, which is detected by means of a receiving coil. The method has been responsible for a considerable number of valuable direct discoveries.

Seismic methods require that a man-made shock, usually produced by an explosion of dynamite, act upon a series of portable seismographs (geophones). The time intervals required for the arrival of successive shock waves at the various geophones are recorded on a rapidly moving tape

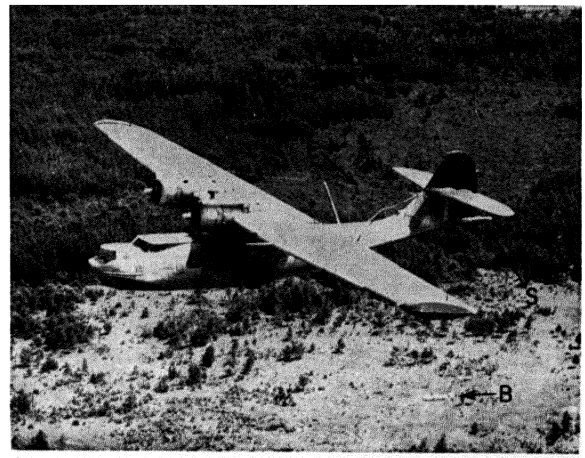


Fig. 20-1. Three geophysical methods in simultaneous operation over heavily drift- and forest-covered terrain. The aircraft is a Canso or PBY, carrying a total field magnetometer *B*, dual frequency electromagnetic equipment *E*, and a radioactivity counter *S*. There are also positioning cameras and a radio altimeter. All results are recorded continuously and automatically. (*Aeromagnetic Surveys, Limited*.)

With suitable equipment, and by planning the placing of geophones to suit the particular problem, the technique yields data on depths to reflecting stratigraphic horizons at various points, from which information the geological structure may be deduced. Another technique records time intervals required for shock waves to travel along formations and across adjacent beds by refraction; the results are interpreted in terms of depth and rock identity.

Radioactivity methods are employed mainly for the direct detection of deposits of uranium and thorium, in which application they have proved remarkably successful. However, radioactivity is a common and characteristic property of many rocks, and there is increasing interest in radioactivity surveys for their geological significance other than direct economic discovery. The most serious drawback to either application is that a few feet of soil, rock, or water is sufficient to mask gamma radiation, the energy measured in radioactivity surveys. Thus even a rich deposit must lie near the surface if it is to be detected; under these conditions outcrops are likely to be present also. Similarly, where the identification of rock formations can be aided by radioactivity patterns, there is probably sufficient outcrop to give preference to the use of more descriptive, normal, geological methods.

It is clear that the proper interpretation of radioactivity-survey results requires a knowledge of the distribution, type, and thickness of overburden (Sec. 19-21).

Other geophysical methods, and variations of those outlined above, are under constant test in the endeavor to improve the "finding ability" of geophysics. Recent work with thermal measurements offers promise, and the occurrence of increased radioactivity in some mineralized areas is being studied as a possible guide of wider applicability.

20-5. Air-borne Geophysics. During World War II, sensitive equipment for measuring changes in the strength of the earth's magnetic field from an aircraft was developed. Its purpose, in which it was successful, was submarine detection. After the war, no time was lost in applying the new technique to mineral exploration. Thus aeromagnetics became the first air-borne geophysical method, and it has since been widely adopted in many parts of the world. Several government surveys carry out aeromagnetic survey as a regular part of their geological programs, and a number of private contracting companies cover large areas each year.

The success of the air-borne magnetometer paved the way for the air-borne radioactivity detector. Banks of Geiger-Müller tubes were used initially, but these soon gave way to the much more efficient and compact scintillation counter equipment. The latter is now in universal use as an air-borne geophysical device.

The third geophysical method to sprout wings was the electromagnetic system, of which there are many varieties. It is the only common electrical method that does not require mechanical contact with the ground.

Recently an air-borne instrument has been developed which measures changes in the vertical gradient of gravity. Since the gradient can be re-

lated to variations in the earth's gravity field, the new equipment is ostensibly an air-borne gravimeter. Tests indicate that it will be a valuable geophysical aid.

Thus, four of the principal methods of geophysics have air-borne counterparts. The outstanding exception is seismics; perhaps a radio sounding technique will be developed which will be the closest approach to seismic survey possible from the air.

20-6. Relative Merits of Ground and Air-borne Geophysics. There is a popular notion that air-borne geophysical techniques have outmoded the older ground methods, particularly in the mining-exploration field. This idea may arise from the sensational and ingenious progress which the air-borne techniques have experienced. Certainly it has little basis in fact.

Air-borne geophysics should be regarded as neither an improvement nor a replacement of corresponding ground techniques. In several respects and under certain conditions it may be distinctly less desirable. In air-borne survey, measurements are made at a considerable and varying distance above ground, and in the case of conventional aircraft, at speeds which limit the recording of minute variations in the field under study. Nor do navigation and plotting problems permit an accuracy of location possible on the ground. It is interesting to note the increasing use of the helicopter for geophysical work; this tends to eliminate the objections stated here. With the helicopter, even very rugged terrain can be surveyed accurately, a great advantage over both conventional aircraft and ground-survey methods.

In favor of air-borne geophysics are the following factors. Profiles are recorded continuously, instead of at a succession of points, thus helping to compensate for the lower degree of resolution effected by the greater vertical distance involved. Air-borne surveys cover all the area of interest, unhampered by lakes, rivers, swamps, or other difficult conditions. Other important advantages are the rapidity with which surveys may be undertaken and completed, the elimination of difficult access as a factor, and cost. With aircraft operation, equipment design is not seriously limited by weight, and the most elaborate instrumentation may be employed. Ground instruments, of course, must be light, portable, and rugged.

The outstanding recommendation common to all air-borne geophysical methods is that they are readily applied over large, continuous areas. Small areas are usually uneconomical. It may be said, indeed, that aerial surveys are truly areal. Thus the geological interpreter is not tied to a few square miles or less, but is able to study details in their broader environment, first geophysically, and then, it is hoped, geologically.

20-7. Limitations of Geophysics. The chief shortcoming of geophysics in mineral exploration is that it rarely provides a unique answer. Results must be interpreted, and nearly always there are several interpretations possible. Basically, the problem is that of an equation in which too few of the variables are known to permit a unique solution. To arrive at the correct answers, one must either develop additional equations containing the same variables or obtain reasonable values for a sufficient number of unknown quantities. Geological mapping and deduction are the principal means of identifying the unknowns, and other geophysical methods commonly supply the additional equations.

A gravity anomaly, for example, may be caused by a change in density of the bedrock, by variation in depth to a formation of contrasting density, or by a combination of both factors. The correct solution hinges upon there being some evidence as to which situation exists. This may be determined by geological study, or by developing the results of another geophysical approach, such as magnetics, over the same area. Otherwise the geophysicist must depend upon an "educated guess" based on experience.

The foregoing remarks indicate why geophysics must not and cannot stand independent of geology. Geophysics is but another device in the geologist's kit. It does, however, require the guidance and full cooperation of the physicist to be fully effective.

It should be observed that the classical methods of geology itself are rarely entirely conclusive. Field data are commonly amenable to several interpretations, and here geophysics may supply the vital clue. Thus geology and geophysics should not be separated in minerals exploration, and as time goes by they should be brought even closer together.

APPLICATION OF AERIAL-PHOTOGRAPHIC INTERPRETATION TO EXPLORATION GEOPHYSICS

20-8. The Advent of Aerial Photography. The period of greatest development in exploration geo-

physics coincided generally with that during which aerial photography came into widespread acceptance by geologists and geophysicists. This fact is only partly coincidental. Any ground-survey technique is aided by photography for general mapping and for positioning and accessibility data. The rapid development of air-borne methods would not have been possible without aerial photography.

20-9. Aerial Photography in the Planning, Operation, and Plotting of Geophysical Surveys. For ground surveys, it is good practice to study the terrain and conditions upon it, in order to select the best locations for base lines, camps, access routes, and other field needs. This can be done conveniently and well by stereoscopic study of aerial photography before the field program commences. Presumably, in most cases, the geological trend is known, so that the direction of the transverse survey lines is fixed within reasonable limits. The difficulties to be encountered on each line can be anticipated and allowed for in time and cost estimates. Where survey lines are later found to wander from their intended course, it is generally possible to plot their actual positions with acceptable accuracy from aerial photography. Likewise, the length of each line as measured upon the ground can be checked for major error on the photography.

The need for topographic data in reducing the results of gravity surveys has been mentioned (Sec. 20-4). These data are generally in the form of a topographic map, which is so important that the costs of producing the map often exceed the other costs of a gravity survey. The use of aerial photography with adequate ground control reduces these costs very appreciably, in both time and money.

Radioactivity survey measurements are probably more at the mercy of unconsolidated overburden than of any other factor (Sec. 19-21). Moist, dense soils are particularly effective in blocking gamma radiation; several feet of thickness of any material is sufficient to reduce bedrock radiation to an insignificant amount. Stereoscopic air-photo interpretation showing the nature, probable thickness, and distribution of overburden in the survey area is therefore indispensable to the careful geological interpretation of radioactivity. Where the overburden is foreign to the underlying bedrock, it is regarded simply as a shield, and attention is concentrated in areas of outcrop and thin overburden. Where, however, the overburden is a residual soil still in place, the radiation results will be of greater significance; the soil may contain relatively insoluble thorium minerals derived from the parent rock, in their approximately original distribution.

Air-borne geophysics relies heavily upon aerial photography in all stages of planning, operation, and reduction of data. It is quite commonly required to survey a large area of which the regional geological strike is not known. Here the strike may be determined by means of geological photo-interpretation techniques. Survey lines are usually flown across the strike. The desired lines are drawn upon a photo mosaic, and this is used during survey flights by the navigator. A small, continuously operated camera records the actual path of the aircraft, and the film is linked by a series of numbered fiducial marks to the geophysical record. The geophysical results are plotted by relating the flight-path photography to the photographic mosaic, then tying in the geophysical record at frequent intervals. This technique not only assures that data are plotted along the actual path flown, but by allowing for variations in ground speed of the aircraft and variations in mosaic or map scale, it places the geophysical values in their correct positions along each line.

20-10. Aerial Photography and the Significance of Geophysical Data. Geophysical surveys are only as good as their geological interpretation. It is difficult to understand, in view of this fact, the indifference commonly shown by some mining-exploration people to the proper interpretation of their survey results. The function of geophysics is too often reduced to one of finding anomalies, which are then designated as prospects for the diamond drill. With few exceptions, the geophysical results of a survey should be converted to geological terms as completely as possible. Then it may be justified to appraise the economic possibilities of various anomalies, always bearing in mind that valuable mineral deposits within a survey area may produce no significant anomaly whatsoever.

Section 20-7 points to the need for facts or probabilities to substitute for unknowns in the geophysical equation. In the average ground survey, these may usually be derived from geological observation, from another geophysical source, or from both. In larger ground surveys and survey compilations and in most air-borne surveys, such



(a)

Fig. 20-2. (*a*) A cylindrical plug of magnetic, radioactive syenite, expressed in the topography and drainage. Little bedrock is to be seen, but the sharp relief near the center of the circular basin indicates shallow soil conditions and some outcrop. The extensive soil cover results from deep tropical weathering. (*b*) The total field aeromagnetic record obtained over the area shown in part *a*. A large central magnetic "low" is fringed by lesser "highs" to both north and south. This combination is normal for a steep, cylindrical, magnetic body at low magnetic latitudes. (*c*) Air-borne radioactivity results from the same area. The pattern conforms closely to the underlying structure despite thick overburden, because certain radioactive minerals have remained in the residual soil and may even have undergone some concentration during weathering.

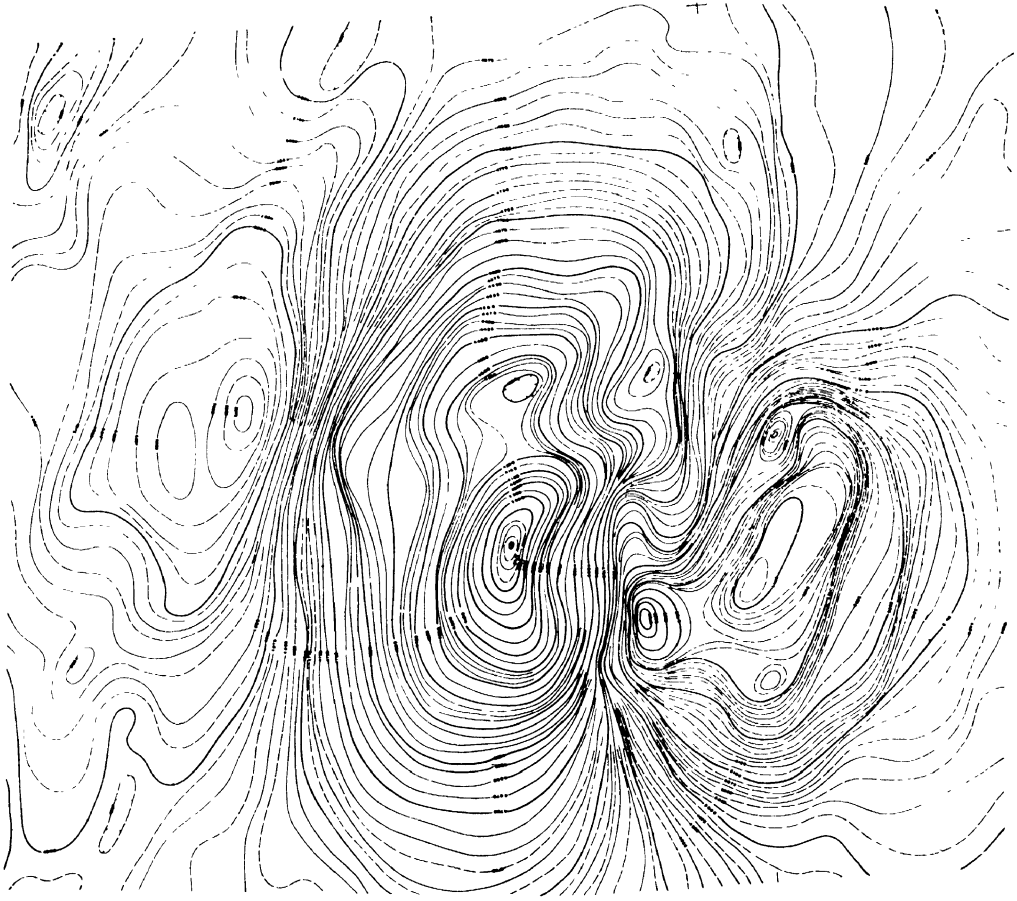
information is likely to be quite inadequate, because of the size of the area, and often because it is remote and little known. Here the tremendous value of geological photo interpretation as a support for the geophysical interpretation is evident.

The reader is referred to Chaps. 9 to 16 and 19 for a review of geological air-photo interpretation.

20-10a. Interpretation by Cooperation. The closest cooperation and mutual understanding between the geologist and geophysicist are essential if geophysics is to play its full part. In some cases a single interpreter may be responsible for both fields, and he must endeavor to avoid prejudice in weighing evidence from the two sources.

The geophysicist carries out his interpretation by mathematical treatment, rule of thumb, plain common sense, and experience, always taking into account any pertinent known geology. His preliminary interpretation should be in terms of structure and rock type if possible.

The geologist studies the photography, also in the light of known geology, with particular care in the vicinity of features interpreted by the geo-



(b)



(c)

Fig. 20-2 (*Continued*)

physicist. These may include contacts, faults, folds, stratification, and other features, and the study should indicate whether or not they have any surface expression. If evidence is found, all similar features in the photography should be interpreted and marked for reexamination on the geophysical records.

Similarly, the geophysicist must look over the shoulder of the geological photo interpreter and be guided by his clues. Constant checking between the two approaches helps to keep the interpretation closer to the truth as it progresses.

Several examples serve to illustrate the complementary nature of geophysical and aerial-photographic data.

In the area shown in Fig. 20-2*a*, radioactivity was discovered by ground observation at a point near the upper side of the photograph. Immediate identification and delineation of the source were desirable, but the geology of the surrounding area was too little known to suggest the zone of potential distribution. However, examination of the aerial photography revealed a large circular structure, consisting of a slightly raised rim, an internal basin, and both radial and concentric drainage outside the structure. The original discovery lies in a breach of the rim. With this interpreted unit in mind, subsequent investigation was planned to include the circular feature and a generous surrounding area.

Geophysical follow-up included two air-borne procedures, namely, aeromagnetic and radioactivity surveys, flown at the same time. The results for these over the area of immediate interest are shown in Figs. 20-2*b* and *c*, respectively. The magnetic result can be interpreted as a nearly vertical cylinder of relatively magnetic material, but whose exact horizontal outline cannot be defined precisely; it is believed to be a volcanic pipe. Study of the corresponding photography under the stereoscope enables an accurate position of the contact to be established. The radioactivity results confirm, and are confirmed by, both magnetic and photographic evidence.

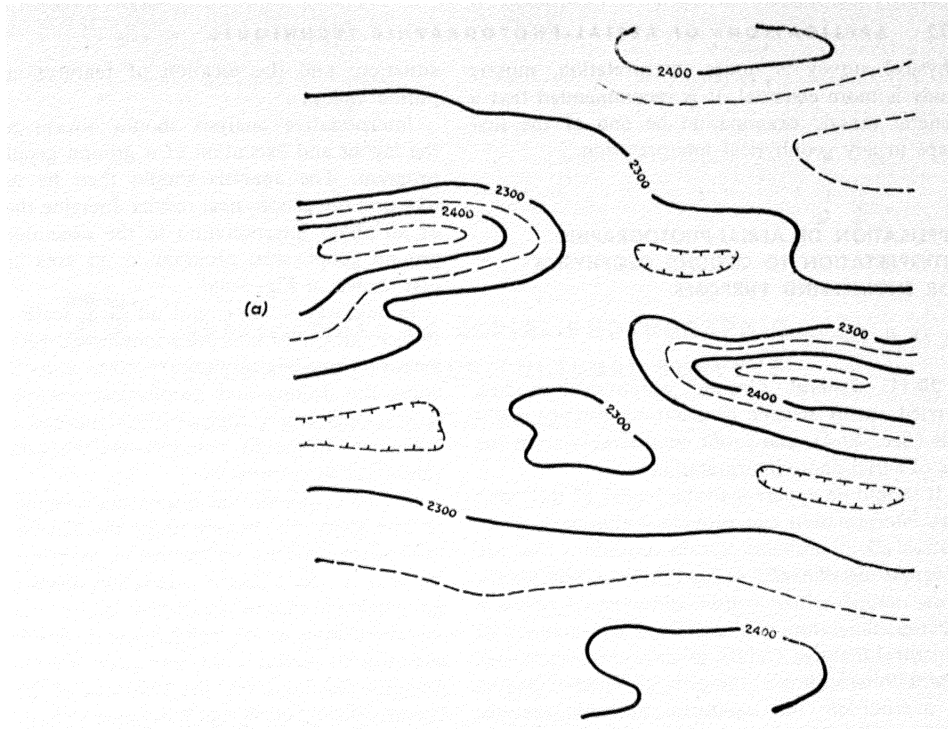
At this point a plan for detailed investigation on the ground was drawn up. This was strongly influenced by air-photo interpretation, which showed not only the broad structural configuration but major rock differences and the location of outcrop and shallow soil. A ground radioactivity survey added detail to the air-borne results, and the interpretation was compared carefully with the evidence of soil thickness and topographic relief. Geological mapping in conjunction with the geophysical interpretation revealed the nature of the structure. Finally, holes were drilled where they would yield the most significant information. All these phases derived benefit from air-photo interpretation.

Figure 20-3 illustrates a problem commonly encountered in the geological interpretation of aeromagnetic results. In part *a*, the magnetic contours suggest displacement of a magnetic formation by a fault or faults. However, this information by itself is insufficient to give the actual position and trend of the fault(s). The corresponding aerial photograph, part *b*, shows heavily drift- and forest-covered terrain. This is typical of much of the Canadian Shield where air-borne geophysics is relied upon to a great extent for geological enlightenment. It can be seen that a strong, if somewhat masked, linear feature crosses the photograph diagonally; it marks the termination of a general topographic lineation that appears at the top of the photograph and which may be related to folded, stratified rocks. The major diagonal linear is therefore almost certainly a fault.

In this case, both the magnetic and photographic evidence indicates a fault. The aeromagnetic data in this and many similar cases give strong support to the identity of the feature; the aerial photography adds location and direction, as well as supporting its interpretation as a fault.

Cooperative interpretation may turn up some surprising results, and one should be alert for unexpected correlations. For example, it was found by photo interpretation that some petroliferous reef structures in western Canada (previously outlined by geophysics and drilling) show up on the aerial photography, even though several major unconformities are present above the important structures. The surface expression evidently consists of a slight accumulation of late glacial sands, concentrating in areas where bedrock compaction and perhaps elevations in the Pre-Cambrian basement assisted in the earlier melting of ice. These shallow glacial lakes would act as loci for the accumulation of fine material in the adjacent ice (Chap. 11).

The importance of studying large areas on air-photo mosaics cannot be overstressed. Mosaics may impart new meaning even to a small geophysical survey area by estabishing a structural setting, for example. Where an air-borne geo-





(b)

Fig. 20-3. (*a*) Part of an aeromagnetic map showing a linear magnetic anomaly probably related to a band of folded volcanic rocks. The offset in this anomaly is strongly indicative of faulting. (*b*) An aerial photograph of the area shown in (*a*). Note the persistent linear which crosses the photograph from northeast to southwest. Broad north-south ridges to the north terminate at this line.

physical survey is under interpretation, mosaic study is more essential. It is recommended that a general mosaic examination be one of the first steps in any geophysical interpretation.

APPLICATION OF AERIAL-PHOTOGRAPHIC INTERPRETATION TO GROUND GEOPHYSICS FOR ENGINEERING PURPOSES

By D. R. Lueder

20-11. General. Ground geophysical studies, carried out by seismic or electric-resistivity methods (Sec. 20-4), can profit considerably from the use of aerial-photo interpretation.

It should be apparent to the reader of this book that interpretation can provide preliminary information about probable terrain conditions that are of great significance to geophysical operations. These include the location and type of bedrock outcrop; the nature of the geological structure and structural features (faults, joints), even when covered with overburden; the general range of depths of overburden; the landform, probable texture, and general uniformity and stratification condition of overburden; the nature of the ground-water situation; and the location of features such as buried valleys.

Interpretative analysis should always precede the layout and execution of a ground geophysical program. The analysis should then be used to interpret the geophysical results. Imagine the value of air-photo interpretation to the execution of a ground geophysical program in an area such as that shown in Fig. 3-4*a*!

In highway studies, and all large-scale terrain studies, air-photo interpretation should serve as a means of speeding up the subsurface study by confining the drilling and geophysical operations to those places where they are most needed and/or indicative. It should also increase the value and validity of the results.

In final comment, the author can remember one seismic study for an important foundation structure where bedrock was estimated as being x feet from the surface. Upon excavation, bedrock was not encountered until more than $2x$ feet had been traversed. Because of lack of observed indication and general geological information, the planned program did not reveal the existence of the small buried valley. The side of the valley was reflected, and interpreted, as being the bottom. This valley was detectable on the photographs.

21 APPLICATIONS OF AERIAL-PHOTOGRAPHIC TECHNIQUES TO AGRICULTURAL SURVEYS

By W. J. Creswick and W. H. Rockwell [1]

21-1. General. Today's world has an ever-increasing need for the foods, fats, and fibers that are required to maintain an ever-expanding population. In the proportion that these supplies are produced from the land, so the land must be wisely used to produce them. To achieve wise land use, it is necessary to appraise soil resources; estimate the capabilities of the land to produce; assess the measures necessary to reclaim wasteland; and ascertain the methods of ameliorating deficient soils and/or bringing new lands into use.

All these studies are based on agricultural surveys of soils, land use, land characteristics, and land capabilities.

This chapter is concerned solely with the means by which aerial-photographic techniques can increase the expedience, efficiency, economy, and dependability of such surveys. In doing this, allusion must be made to commonly accepted principles and practices of agricultural survey, and emphasis will be focused on certain problems of such surveys which can receive partial solution through the application of air-photo techniques. However, at the same time, it is not the purpose of the chapter to raise or dwell upon points of academic controversy, and it is trusted that the reader will save his queries on such points for the academic journals.

[1] Sections 21-3 to 21-5, 21-7 to 21-9, 21-11, and 21-25 to 21-27 were written by W. J. Creswick, Chief of Division of Land and Agricultural Sciences, Geotechnics and Resources, Incorporated. Sections 21-6, 21-10, and 21-12 to 21-24 were written by W. H. Rockwell. The author contributed certain editorial revisions.

21-2. Types of Agricultural Terrain Surveys and Maps. There are several more or less distinct types of "terrain surveys" that may be conducted for agricultural purposes, as well as maps that can be prepared therefrom. These are concerned with the following and other studies.

1. Agricultural soils
2. Agricultural land classification
   a. In terms of present use
   b. In terms of use capability
3. Special aspects of the soil-land complex
   a. Erosion and erosibility
   b. Salinity
   c. Potential for irrigation

Each of the above topics (and maps) may be studied or prepared at various levels of generalization, i.e., *reconnaissance, semidetailed,* and *detailed.*

In this chapter, the various types of studies, in so far as their primary subject is concerned, will be discussed in the same order as given in the above list. The last sections of the chapter will then consider their levels of generalization.

AGRICULTURAL SOILS

21-3. General—Definition of Terms. Agricultural soil studies involve the use of terms which, though they are common words or word combinations, have special connotations to agricultural science. Definitions of these terms, as used in this chapter, are given in the following paragraphs.

"Soil," for agricultural purposes, is the uncon-

solidated material on the surface of the earth's crust in which plants find anchorage and from which they draw nutrients in aqueous solution. Soil is a natural body whose physical, chemical, and biological properties are the result of the action of air, water, and living things, over a period of time, on mineral material.

"Pedology" is the study of the genesis and morphology of the various soils found on the earth and deals particularly with the bases for their classification (Sec. 7-9).

"Soil classification" is the process of assigning to categorical classes all the individual samples of soil that may be found.

"Soil survey" is the observation, identification, and classification of enough samples of soil in an area to assign all the land in the given area to one or more soil classes that have been established.

A "soil map" is a representation, on the plan or chart of an area, of all the different kinds and classes of soil that can be identified and delineated.

21-4. The Problem and Method of Soil Classification. Soil being a natural body, with morphological characteristics that reflect the combined effect of the infinitely variable, pedological, soil-formational factors (climate, parent material, topography, age, bioticism, Sec. 7-9), it can be seen that the number of possibly different soils is great indeed. If, to this initial variety, there are added all the permutations and combinations of descriptive factors such as color, texture, consistency, structure, chemical composition, chemical reaction, moisture-holding capacity, permeability, capillarity, etc., as well as profile differences due to the number, thickness, and arrangement of horizons, it can be seen that there *is an infinity of possible, individual soil separations.*

This infinity is responsible for the basic problem of soil clasification, i.e., *the difficulty—and perhaps the impossibility—of placing an infinite variety of soils in a finite series of classes that are practicable and meaningful to use.*

Regardless of this problem, soil classification must be, and is, carried out. How?

Individual samples, to be assigned to categorical classes, must be grouped so that any class is defined in terms of a "range of characteristics," grouped around a "modal type." It is easy to see that many samples may be obtained that may be difficult to fit into a class. In such cases, subjective judgments will have to be made, depending upon the individual survey, or some factors will have to be given greater weight than others, and *each determination will call for the strictest scientific discipline.*

On a morphological basis, individual samples may be assigned to categorical classes with relative ease. These categories may be presented in tabular form, and the categorization may be called a "taxonomic classification." Their presentation on a map, however, can be very difficult. Usually, the preparation of a map calls for a "cartographic classification," i.e., one which is consistent with the topography and planimetry of the land.

Although the ideal of the pedologist is to establish a classification of soils that would apply all over the world, in actual practice this ideal has not yet been attained. Not only are there infinite combinations of variables, but the fact that soil is an expression of site, as well as its other attributes, means that the soils in any area to be surveyed have to be classified on their own. In effect, any soil survey in a new area is an exercise in soil classification.

21-5. Soil Surveys and Soil Maps. A soil map is defined in the Soil Survey Manual of the U.S. Department of Agriculture (210) as "a representation on paper designed to portray the distribution of soil types and phases, as well as other selected cultural and physical features of the earth's surface necessary for convenience, in its use."

A soil map, the results of a soil survey, has two main purposes. Its primary purpose is "as a basis for classifying the results of experience and experiments regarding the characteristics and use-capabilities of soils in order that this information may be applied to each individual unit of operation. . . . The determination and mapping of soil types is an essential and integral part of any soil research program, particularly in its applied phases" (210). The second purpose, and in land-reclamation programs of equal importance to the first, is to serve as the basis for land classification in terms of use capability. Such a classification uses criteria beyond the physical attributes of the soil, e.g., spatial relations, engineering feasibility, and economic justification, but the first criterion is a physical classification of the soils expressed in the soil map.

The problem of reconciling a taxonomic or generic classification with a cartographic classification faces every soil surveyor who prepares a

soil map. It is fair to assume that the reader of a map should be able to find on the ground, at any point, that type of soil which the map indicates as being there. Furthermore, within any given area or areas of the soil map which include a particular category, four out of five, or eight out of ten, samples should conform to the description given the area(s) by the surveyor who made the map.

Many of the features which affect the taxonomic-cartographic reconciliation, and which also, according to the above definitions, must be portrayed on a soil map, are portrayed on aerial photographs. The problem of obtaining maximum value from photographs is one of using and recognizing these features and transferring them to maps accurately and consistently.

21-6. General Applications of Air-photo Interpretation to Soil Mapping. Probably the most useful key which can be established in using air-photo interpretation of soil surveys is the correlation between landforms and class of soil. This does not imply that any given landform will contain but a single class of soil, but that the soils within a landform will normally vary within a certain range. If landform mapping is done accurately, parent material will be similar throughout. The subsequent development of soil profiles will be determined by many factors, and only field checking can determine what effect these factors have had on soil formation.

While the identification of specific soil series and types can be established only with field work, the mapping of certain phases can be accomplished with a minimum of field checking. Phases are not differentiating characteristics of the soil profile, but are characteristics of the soil or landscape that are of importance in land use. The most common phase designations include variations within the soil type as to slope, erosion, stoniness, and drainage. Of these, slope and erosion are easily measured or identified by photogrammetry or photo interpretation. Drainage conditions can often be established by photo interpretation, particularly extremes of drainage. Stoniness can sometimes be identified, depending upon the scale of photography and the size of stones, and sometimes inferred by landform-soil associations.

Where the terms "deep phase" and "shallow phase" are used to indicate the thickness of the solum plus parent material over bedrock, photo interpretation can facilitate the mapping of such phases. Bedrock features such as fracture patterns and bedding are often visible on aerial photographs where the soil mantle is thin, although these features may not be visible on the ground.

Many of the miscellaneous land types which must be shown on soil maps can be identified and mapped directly on aerial photographs. Some of these are alluvial soils (undifferentiated), coastal beach, dune sand, made land, mines and dumps, peat, riverwash, rock outcrop, rough broken land, rough mountainous land, scabland, swamp, and tidal marsh.

A great many soil boundaries are coincident with such easily observable features of the landscape as the foot of a slope, the crest of a ridge, the margin of an escarpment, or changes in vegetation. When such boundaries have been established by ground traverses (Sec. 21-8), they can easily be extended by external observation only. While this can be done on the ground, it can usually be done more rapidly and accurately with aerial photographs. Tone changes observable on photographs may indicate changes in texture or drainage conditions which would be missed on the ground unless continuous sampling was carried out. There is a miscellany of additional photographic features that are coincident with changes in soil series and types, or the transitions between them.

21-7. Special Photographic Indicators of Value to Soil Mapping. In agricultural soil survey, three photographic elements of special significance may be stressed. One of these is *agricultural use and vigor of crops.* Especially in areas long under cultivation, cultivators have learned to adapt their crops to the soils most suitable for them. Where a rigid pattern of land use is maintained, crops are not always adjusted to the soils, and differences in soils are revealed in the response or vigor of the crop.

A second indicator may be seen in areas devoid of vegetation where the bare earth may have *surface microfeatures related to the structure of the soil,* which in turn may be related to significant physical and chemical properties. Surface microfeatures may be revealed in recognizable photo tones.

Thirdly, certain features may be determined by *factors remote from the area under survey.* This is particularly true of soils developed on transported materials, e.g., colluvial, alluvial, and glacial

depositions. Where petrographic and chemical composition are especially significant in separating soils, knowledge of the *source of origin* and *mode of deposition* is essential. Thus, in mapping soils of this kind, examination should be made of land beyond the area of survey, indeed as far away as the most remote point of origin of material. An interesting example of this was seen in central Iraq. In these soils, the relative proportion of calcium ions and sodium ions was critical. Materials derived and transported from highly gypsiferous formations tended to have a higher proportion of calcium. The problem was further compounded by the fact that these soils had been strongly influenced by the works of man and some of the material was transported by irrigation canals. Further, the development of the soil was influenced by the massive quantities of irrigation water applied through several centuries. The quality of this water was determined by the mineral composition of the land through which the river, the source of water, flowed.

By photographic techniques relations were established between calcium and sodium ion proportions in the soils and the geographic occurrence of these chemicals determined in relation to such remote factors as probable origin of various transported soils and the character of the country through which the river, and irrigation water, flowed.

When these relations were established, the mapping of the soils in the survey area was greatly assisted and was carried forward with a minimum of ground sampling. In this instance, the value of an aerial photograph covering the surrounding area was apparent and immeasurable. There is no reason to suspect that similar applications should be infrequent.

21-8. General Procedure in the Integration of Aerial-photographic Techniques with Soil Classification, Survey, and Mapping, The conduct of a soil survey and preparation of a soil map, or an exercise in any form of land classification, using aerial photographs, should follow a general sequence as follows.

In the *initial phase* of survey, all the available information and maps relating to the areas of interest, and adjacent areas, should be collected and studied. Photo mosaics and stereopairs should then be examined to see what different kinds of land are observable. If possible, random traverses should be made, to get a general idea of conditions to be met, relief, drainage and landform, vegetation crops, and accidental exposures of profiles in road cuts and excavations. One or more sample strips or traverses should next be selected on the basis of (1) casual observation in the field and (2) examination of the photos. These traverses should transect all the conditions that are likely to be found. Finally, based upon the same data, a tentative soil classification should be established. In this regard, maximum use should be made of any classifications that have been established for adjacent areas.

The *second phase* of survey involves the procurement of samples. It is usually wise to take as many samples along each traverse as are reasonably susceptible to analysis. This is detailed work which cannot be skimped or abbreviated. The soil profile should be examined on the face of prepared sample pits, and samples for laboratory analysis taken from recognizable horizons. Descriptions should be as full as possible. The auger should be used sparingly during this phase. When an auger hole reveals with certainty that a sample is similar to an adjacent one, a pit need not be dug. It is worthwhile, however, to make auger borings adjacent to pits so that at a later stage one can visualize a profile more completely from the meager evidence an augered sample gives.

Although these techniques of sampling are fairly standard, it must be emphasized that the location of samples is *selective*, largely because of the use of air photographs (Secs. 24-14 and 7-24). The ultimate result of this selectivity is a reduction in the total number of samples observed, as compared with the number observed on a ground survey without benefit of aerial-photographic techniques.

Where field observations and photo reading show more or less uniform conditions over some distances, sampling may be sparse (because a repetitive photo pattern indicates a repetitive profile, Sec. 7-13). Where conditions are indefinite, or transitional, sampling must be more dense. Samples taken for laboratory analysis should be taken from a cluster of samples on the ground, for a single sample may be anomalous and misleading.

From both field and photo observations, field descriptions, and laboratory analyses, a classification of the soils can now be firmly established. The problem, then, is to find to what extent features observable in the photographs can be related to the classes of soils established and to what extent boundaries, or, as is more likely, gradations, between classes are observable on the photographs.

As far as the photographs indicate differences found on the ground, techniques of interpretation can be used to delineate classes on the photos.

The *third phase* involves the actual delineation of soil classes on the photographs, using photo interpretation and interpolation between plotted samples. Where the photos do not reveal the whole story, further sampling must be done on the ground. At this stage the surveyor finds that the aerial photograph may assist him in making the reconciliation between generic and cartographic classes in a way that may not be possible by field examination alone. The pedologist must be careful not to give undue weight to very obvious photo features which are unrelated, or only weakly related, to factors of pedologic significance.

The *fourth phase* involves a validation of the mapping interpretation by further sampling in the field. When this checking reveals inconsistencies, the classification and the photo interpretation must be reviewed.

Only after field checking can all boundaries be confirmed and a closed legend applied to the map.

This sequence appears to put a heavy load on the laboratory in the initial stages of the survey. The work can be mitigated by dividing the area to be surveyed into apparently dissimilar regions and doing them one at a time. In this division, air-photo patterns are again of value.

Once indicators are established, much of the checking can be done by auger examination alone. Similarly, a few simple physical and chemical analyses which can be made in a field laboratory may be all that are required to identify a soil, much less than is necessary to describe it and classify it originally.

Accompanying the map which gives the results of the survey, there should be good descriptions of the soil. These can best be done after the map is prepared. Well-selected sites are chosen in truly representative areas, and at these sites pits are dug and laboratory analysis and descriptions made. The aerial photographs greatly assist in the selection of these sites (Sec. 24-14). The formal description of a typical soil can be taken from one or more of these pits, and the ranges of characteristics specified from the samples taken in the detailed phase.

AGRICULTURAL LAND CLASSIFICATION

21-9. General. Classification of land in terms of *present use* serves three very useful purposes in agriculture. First, in areas where research into performance capability is yet to be done, an indication (although not a precise determination) of capability can be found in the use to which the land is put, in so far as this represents the accumulated experience and preferences of the operators. Secondly, where reclamation, conservation practices, or amelioration of land by engineering and introduction of amendments are to be instituted, it is necessary to know how the land is used prior to the changes contemplated. Thirdly, in some areas competition, or indeed conflict, between various uses may have arisen. Before any resolution of the competition, or regulation of use, can be effected, a map of present use must be prepared.

In addition to agricultural purposes served, a present land-use map may be required for institution of an equitable and just system of assessment for taxation or redistribution of holdings.

"Use-capability classification," or "land classification," as it is commonly called, is carried out for soil-conservation programs, reclamation of land, especially by means of irrigation and drainage, as well as for the opening to new agricultural settlement of virgin lands in the tropics or in the northern areas of the temperate lands.

Classification of land in terms of use capability is based upon the inherent characteristics of the soil (as shown in the soil-survey report and on the soil map), geographic and economic characteristics of the area, spatial relations, and engineering feasibility where engineering works are required.

Classification of land must follow scientific method and should not be simple description. Given certain physical, geographic, economic, and spatial conditions, there are many ways in which land can be classified. The method used depends upon the purpose that the classification is to serve.

For soil-conservational purposes a system of classification devised by the Soil Conservation Service of the U.S. Department of Agriculture has been widely applied elsewhere, e.g., in North and South America and in Africa. For reclamation by irrigation a similar classification devised by the U.S. Bureau of Reclamation has been used, with modifications to meet local needs and conditions, in Africa and the Middle East.

Both of these systems assign lands to numbered classes, and there is an implied rigidity to them that is not entirely satisfactory. Many other systems have been evolved, sometimes more flexible than the two widely used ones quoted above or suited more specifically to local conditions.

It can be argued that land classification should not be undertaken until a soil classification, as thorough as is possible, has been made. However, in practice, land classification is sometimes carried out to serve a special purpose without a soil survey being conducted.

21-10. General Application of Aerial-photographic Techniques to Land Classification. Aerial photographs have been widely and extensively used by land classifiers. This has been particularly true when only present land use is of interest, or where use capability must be studied without the prior completion of a detailed soil survey.

Without aerial photographs an accurate survey of present use is a tedious and time-consuming job. Every farm and sometimes every field must be observed, and the information recorded. If such a survey were conducted over a very large area, much of this information might become obsolete before the results could be published. With aerial photographs, such a survey can usually be conducted rapidly and accurately, depending upon the degree of detail and the nature of the information required.

Usually, specific crops cannot be recognized but similar crops can be grouped, and after their air-photo pattern has been established by ground checking, these groups can be mapped by interpretation. Thus, a survey which maps small grains, row crops, hay, permanent pasture, orchards, and woodlots as separate units, but does not differentiate within each unit, can be conducted rapidly with a minimum of field checking.

It must be remembered that the photographs only show conditions at the instant they were taken. Rotation of various units such as hay and small grains can be established only by inquiry. Also, the season of the year in which the photography was taken will determine the air-photo pattern of any particular land use. Grain stubble will appear very different from growing grain. While correlating ground conditions and land-use patterns as they appear on aerial photographs, the surveyor should always be aware of the season of the photography.

Besides their direct application, it can be seen that the use-capability classifier who has not got a soil classification at his disposal, but must nevertheless provide a general picture of his subject, has the distinct advantage of doing a fair job of soil classifying on his own when he uses aerial photographs.

The fullest use of aerial photographs in surveying and mapping, whether present land-use or a use-capability classification, should follow the same general sequence as that described for a soil survey, with the exception that sampling and testing may be largely omitted if only present use is being studied.

21-11. Examples of Application of Aerial-photographic Techniques to Soil Mapping and Land Classification. Detailed maps for planning the operations of farms, particularly for soil conservation by the U.S. Department of Agriculture, Soil Conservation Service, have been made for large areas in the United States and by provincial agriculture departments, for the same purpose, in many parts of Canada (Fig. 21-1). This map shows the soil type, slope, and erosion on the land of a farm in southwestern Ontario. From this map there is derived a map of land-use capability, according to the system established by the U.S. Soil Conservation Service. The farm planner, employed by the Service, using this map, then draws up a plan of management for the farm designed to bring every acre into a high state of productivity and keep it there. Similar use of aerial photographs is made in the soil-conservation programs in Australia and in many of the countries of Africa and South America.

Semidetailed maps have been made for considerable areas of Africa and the Middle East for reclamation programs of arid and semiarid areas. Both soil maps and land-classification, or more precisely use-capability, maps have been prepared. These have been done by survey companies under contract, by government departments, and, in less well developed countries, by government officers assisted by experts from United Nations assistance agencies, International Cooperation Administration, and Colombo Plan. In the past, aerial photographs have not always been available and mapping has been done slowly, and not entirely satisfactorily, on the ground, by the use of bases prepared by the soil surveyors themselves, or by topographers assisting them, with compass or plane table. Good topographic maps, even on a large scale, are not always available. However, aerial photographs are almost universally available when required now, and this very important work is proceeding, making optimum use of them. The land-classification system used in projects for land reclamation by irrigation works is commonly that devised by the U.S. Bureau of Reclamation of the Department of the Interior for use in the arid southwest of the United States.

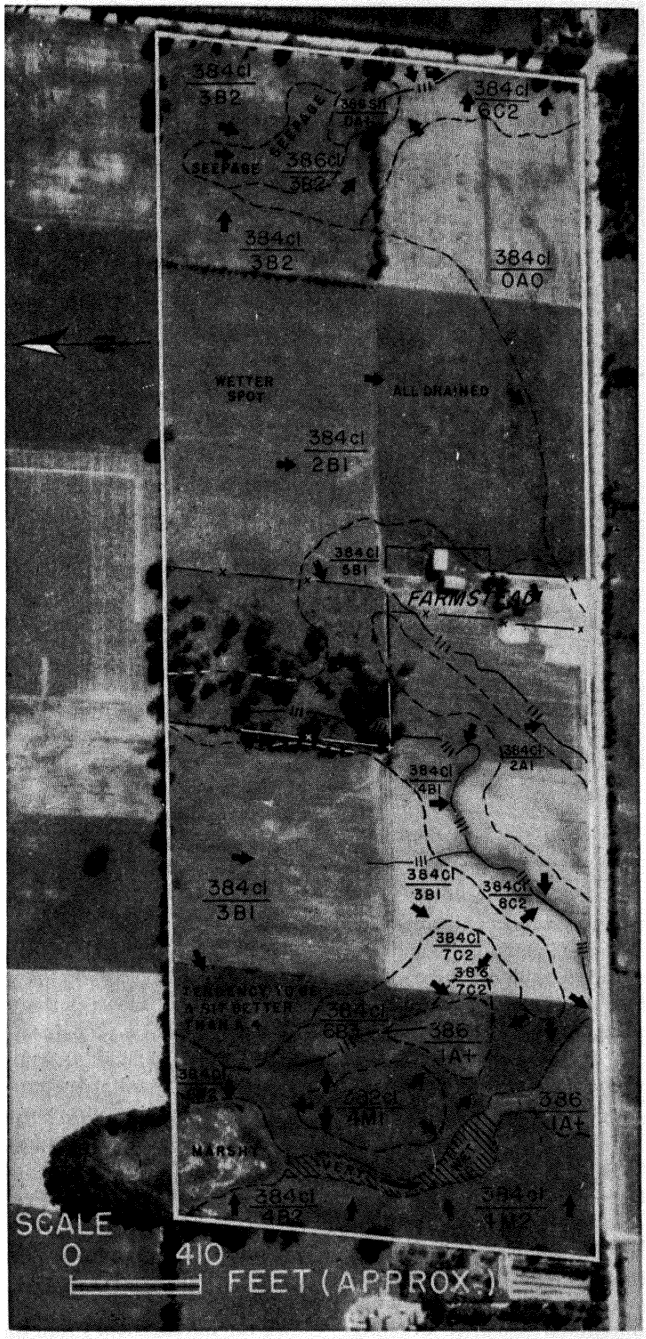


Fig. 21-1. A detailed map of a farm in southwestern Ontario to show soil type, slope, and erosion for the preparation of a soil-conservation plan. The figures in the numerators designate soil series. The denominators designate slope and erosion according to the conventions of the U.S. Soil Conservation Service. (*Ontario Agricultural College, Ontario Department of Lands and Forests.*)



(a)

Fig. 21-2. Reconnaissance mapping of land in Jordan to determine grazing potential and management requirements of nonarable land. The vertical air photograph (a) illustrates strikingly the distinctive patterns of the various land classes.

Semidetailed- or detailed-reconnaissance soil maps have been produced, county by county, of most of the fully settled agricultural land of the provinces of Canada and for most of the United States. Although in the past aerial photographs were not always used, or were used to a limited extent merely as bases on which to plot field data, they are now in almost universal use in North America to more or less advantage, according to the skill and convictions of the soil surveyors.

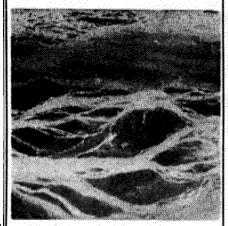
Although aerial photographs have as much application to semidetailed mapping, they have perhaps been more widely used in general or general-reconnaissance maps. A general map of the soils of Newfoundland was prepared by photo interpretation with a minimum of field examination and reconnaissance maps of northern Ontario, and the pioneer fringes of the other provinces are being mapped, making optimum use of photos.

In Asia, Africa, and South America, a great deal of smaller-scale mapping is being done. An example of a "range" survey of a Middle East country, on a reconnaissance scale, is shown in Fig. 21-2. This shows particularly well how land classes, separated on a natural basis but defined in terms of use capability, can be recognized and delineated on aerial photographs.

One of the largest projects in soil and land-use mapping ever undertaken was done under the Colombo Plan in West Pakistan. Two series of maps were drawn. One was a generalized soil map, and the other is a map of land use at the time of the survey (Sec. 23-14).

SPECIAL SURVEYS

21-12. Introduction. From time to time the need for special agricultural surveys may arise. Such surveys usually deal with a particular phase or limiting factor which is of prime importance in a particular area. Because such surveys are restricted

Type	*Key*	*Landform*	*Aspect*	*Vegetation*	*Drainage pattern*	*Photo characteristics*
4A		Brush Type. Bottoms of wadis, level ground often broken by small hummocks and ridges formed by water flow	Perennial vegetation with relatively little bare ground	Mainly perennial herbs and woody shrubs	Braided channels	Light tone, dotted, reticulate, or mottled with medium grey indicating presence of vegetation
4B		Brush Type. (Level areas without definite drainage lines.) Depressions or large areas formed by the confluence of several wadis	Perennial vegetation with considerable areas of bare ground	Mainly perennial herbs and woody shrubs	Arcs and lines of vegetation developing *across* general trend of drainage	Light tone; often distinctive reticulation of dark grey (vegetation) possibly due to seeds germinating at edges of successive flood levels
8B		Rock Type. (Lava stones.) Usually undulating, rarely level	Bare stony ground, usually entirely covered with stones up to 12 inches in diameter, seldom smaller than 3 to 4 inches	Very sparse and mainly annual herbs	Interrupted drainage with many local 'mud-pan' drainage basins	Very dark grey; coarsely mottled appearance. Lighter where (*a*) stones are small and (*b*) higher rainfall results in growth of lichens on the stones

Field work for a study of 30,000 square miles was completed in 10 weeks. Part of the range-interpretation key is reproduced in (*b*). [*Hunting Technical Services (London)*.] *(b)*

in scope, and usually map conditions which may change fairly rapidly, it is desirable that they be conducted as economically as possible in a short period of time.

Erosion and salinity are conditions which can usually be mapped rapidly and accurately when air-photo interpretation is employed in conjunction with selected field work. Applications of air-photo interpretation to surveys of the conditions are described briefly in the following paragraphs. Preliminary planning for irrigation developments can also be expedited by proper use of aerial photography, although the information required for such planning encompasses many aspects of agriculture.

EROSION SURVEYS

21-13. General. As stated previously, a survey dealing with only a single condition or phase of the soil or agriculture might seem uneconomic. Under certain circumstances, however, a survey dealing only with the problem of soil erosion can be most useful and economical. Such circumstances would exist in an area where certain conditions of the land, of management, or of climate are contributing to disastrous, accelerated soil erosion and where the need for planning control measures is urgent.

21-14. The Nature of Soil Erosion. Soil erosion should not be confused with geological erosion. The latter is the normal process of rock weathering in a natural environment which forms new soil from parent material at about the same rate as soil is removed by wind, water, and gravitational movement. Soil erosion, on the other hand, is an accelerated process under which soil is bodily displaced much faster than it can be formed (Chap. 4).

Wind and water are the active forces of soil erosion. While differing in the nature of their action, they both accomplish the end result of removing and transporting surface soil. The effects of both can be easily identified and mapped on aerial photographs with a minimum of field work.

21-15. Erosion by Water. Water running over exposed land surfaces affects the movement of soil to a greater or lesser extent, depending on factors of slope, land use, volume of water, and type of soil. The general category of water erosion may be further subdivided into sheet erosion, rill erosion, and gully erosion. These three types are by no means separate and unrelated, as they may all occur in the same small area and one may develop into another. They are convenient subdivisions, however, for purposes of description and illustration.

21-16. Sheet Erosion. Sheet erosion is the more or less even removal of thin layers of soil over an extended area of sloping land. The removal of dark-colored topsoil often exposes light-colored subsoil which is deficient in humus. This color change is often the key to the detection and mapping of this insidious type of erosion on aerial photographs. Because there is no striking change in relief effected by sheet erosion, as there is by gully erosion, it is often overlooked on aerial photographs and often ignored on the ground. However, one who is looking for this specific type of erosion will find tangible clues on aerial photographs by which it can be identified. In addition to changes in color tones, its effect on productivity of the land results in patchy, uneven crop or grass growth which can usually be detected on the photographs.

21-17. Rill Erosion. Water running over sloping land generally tends to collect and concentrate in small streamlets. When the volume and velocity of these streamlets are sufficient to generate cutting power, numerous small incisions are cut in the surface of the land. These incisions are usually too small to be observed individually on aerial photographs, but collectively their effect and photo pattern are often quite similar to sheet erosion. Changes in color tones on the photos may be more uneven and appear as a "feather" pattern. Land dissected by rill erosion is usually smoothed out by operations of tillage, and small incisions obliterated. Eventually, however, the net effect on soil fertility is the same as that of sheet erosion, and low productivity is reflected in crop yields.

21-18. Gully Erosion. Usually gullies follow sheet or rill erosion where volume and velocity of runoff are sufficient or where concentrated water continues cutting over a long period of time. Gullies may start in natural depressions and drainageways or along man-made depressions. The size, shape, and density of gullies and the speed of their formation are governed by many aspects of the soil and the nature of volume of runoff. These are treated in Chap. 4. The agriculturists are primarily interested in the impact of erosion on agriculture, its extent, possible future expansion, and control.

The extent of gully erosion can be mapped easily on aerial photographs with a minimum of field work. Once this is done, air-photo interpretation can aid in arriving at reasonable estimates of its possible future growth. Conditions of lands toward which gullies are advancing such as the slope, vegetative cover, and the nature of the soil can be ascertained. These all have direct bearing on the rate of erosion. If aerial photographs of an eroded area flown at different times are available, an accurate measurement of past gully advance can be made. Illustrations of gully erosion appear in Chap. 4.

21-19. Wind Erosion. The movement of soil by wind is most common in arid and semiarid regions, but occurs to some extent in humid climates as well. Wind erosion can be a serious problem on level as well as sloping land and is a threat wherever the original stability of the soil is greatly reduced.

Wind erosion is not ordinarily divided into subtypes as is water erosion, but is classified on the basis of intensity. However, its manifestations on the ground surface vary with soil type, climate, and vegetative cover, and these variations are often evident on aerial photographs.

Lowering the stability of sandy soils to a point where wind action can move soil particles often results in the formation of dunes, with complete removal of fine materials from the surface soils. Such dunes may eventually become stabilized by vegetation, but the fertility of the soil has been reduced and the resulting surface may be too rough for cultivation.

Finer soils are more cohesive than sand, but are still subject to wind erosion under certain conditions. Wind erosion on such soils generally

does not form dunes, but results in the wholesale removal of surface soils. This condition may be restricted to a single field or farm, or may be severe over large areas.

21-20. Planning Erosion Control. Planning of erosion control can be aided immeasurably by the proper use of aerial photographs. Topographic mapping by photogrammetric methods is becoming more economical, accurate, and widespread in the planning of control structures and practices. Contour tillage, strip cropping, terraces, diversion channels, and check dams are all measures which can be planned rapidly and economically where good topographic mapping is available. Air-photo interpretation can be combined with photogrammetry to determine runoff, vegetative cover, erodibility of soil, slope, and the boundaries of watersheds. The ability to compile this basic information rapidly and inexpensively is a valuable asset to anyone engaged in control planning.

SALINITY SURVEYS

21-21. General. In many arid regions of the world saline or alkaline soils present a serious problem to agricultural development. Whether these conditions exist prior to agricultural development or whether they develop subsequently, the effect of reducing crop production in a region can be considerable, sometimes disastrous. The planning of effective reclamation or control measures must be preceded by a thorough investigation of conditions as they exist.

21-22. Applications of Air-photo Interpretation to Salinity Surveys. In areas where high salt concentrations (saline or alkaline) are damaging crops, such damage can be measured and mapped in detail by the use of aerial photographs. Any increase or decrease in areas affected can be measured where aerial photography is secured periodically. In places salt concentrations become so high that no vegetation, or only the most salt-tolerant plants, can exist. Air-photo patterns of such areas can be interpreted accurately and rapidly.

In undeveloped areas the problem of mapping salinity by means of air-photo interpretation is more difficult. Unless there is some surface expression such as a white encrustation, the only key may be the effects on natural vegetation. In very arid regions such vegetation may be extremely sparse or nonexistent or may be composed largely of halophytic plants.

Determination of the chemical composition and pH values of salt-impregnated soils is largely the work of field tests, but occasionally some indication of the nature of salts and their toxic effects can be derived from air-photo patterns. The terms "white alkali" and "black alkali" are often used to describe different surface manifestations of salts which can sometimes be related roughly to specific salts or pH values.

IRRIGATION SURVEYS

21-23. General. Before any irrigation project can be initiated, a great deal of preliminary investigation and planning must precede construction. Such planning involves problems of land use and water use as well as of economics. The work required in such planning increases with the size of the project, and large projects may require the services of land and soil specialists, hydrologists, agricultural economists, engineering geologists, and engineers.

Preliminary planning should resolve the problems concerning major features of the land, soil, water supply, and economics. It is in these planning stages that air-photo interpretation and photogrammetry can be most useful.

21-24. Applications of Aerial Methods in Irrigation Planning. Most of the applications of air-photo interpretation to irrigation surveys have been discussed indirectly under other headings in this chapter or in other chapters of this book. A rapid reconnaissance survey of soils, use capability, or present land use is usually necessary before a feasibility study can be completed. Air-photo interpretation is a valuable adjunct to conventional survey methods in the conduct of such surveys. The reconnaissance soil survey would probably stress soil permeability, while the use-capability survey would consider slope as an important factor. In the first case skillful interpretation reduces field work, time, and expense to a minimum, while photogrammetric methods are invaluable in determining elevations and slopes of large areas of land. Delineation of surface drainage and determination at watershed boundaries can be accomplished rapidly and accurately on aerial photographs, thereby aiding in the determination at runoff. Engineering soil studies necessary in the

planning of structures can be facilitated through air-photo interpretation. These and many other factors which must be considered in feasibility studies and planning can be studied more economically and accurately when air-photo interpretation and photogrammetry are utilized properly.

SOME PRACTICAL CONSIDERATIONS

21-25. Levels of Generalization, Preferred Scales, Dates of Flight. As was mentioned in Sec. 21-2, there are three rough levels of generalization in agricultural mapping. These are the reconnaissance, semidetailed, and detailed levels.

In a *reconnaissance survey* the separation of kinds of soil and delineation of boundaries is done in a general way only. Boundaries between kinds of soil are not traced on the ground, and their representation on a map is only approximate. The results of a reconnaissance survey are used for an inventory of soil resources of the area mapped and as a guide to the selection of areas to be studied in more detail.

A *semidetailed survey* separates all the kinds of soil that may be identified, but boundaries are not necessarily traced on the ground. The results are used in the design of programs of research into the characteristics and management of soils. They are also used in planning land-use programs, in the subdivision of land into agricultural holdings, and in the planning of irrigation, drainage, or other works to serve the area.

A *detailed survey* requires the tracing of boundaries in the ground, and the results are expressed in sufficient detail so that the operations of an individual holding can be planned from them.

The above levels of generalization cannot be specifically defined in terms of scales of maps, but do conform, very roughly, to the following:

For reconnaissance mapping, scales of 1:30,000 to 1:60,000 are commonly used. However, scales smaller than 1:50,000 have limited value. If they are available, photos of an even larger scale, for subsequent sampling in the field, with mosaics on a smaller scale for plotting, are preferable. For semidetailed mapping, scales between 1:12,000 and 1:20,000 are suitable. For detailed mapping, plotting must be done on larger-scaled bases, but as aerial photographs have their minimum use in detailed soil mapping, it is usually not worthwhile to have flights made to obtain contact prints at a scale greater than 1:10,000. From this or from other photographs at a semidetailed scale enlargements will suffice.

Of all the factors considered in soil mapping, the moisture regime is the most important. Moisture conditions either in bare soil or reflected in vegetative response are very apparent in aerial photographs. For purposes of agricultural soil survey, photography exposed after wet soil has begun to dry out is most suitable. If land-use maps are being made, that season when all the crops are in but not yet harvested is the best time for photography. In temperate and semiarid regions there is likely to be a short period when both these conditions can be met. Unfortunately, photographs for other and more common purposes should be taken at other seasons, e.g., when the land is bare (for geologists or for photogrammetry) or when trees are in full leaf (for forest inventory).

21-26. The Soil-mapping Base. Soil maps drawn on bases provided by good planimetric and topographic maps are, of course, the most useful. In practice, such base maps are not always available. Indeed, in much of the world where soil maps are urgently required, they are entirely lacking. However, plotting a soil map on mosaics, or as an overlay to mosaics, is quite satisfactory. Mosaics commonly serve as the maps on which much of the development plans are worked out, and the engineer, agronomist, or soil researcher can make full use of the results of a survey presented in this way.

Soil boundaries may sometimes correspond to easily recognized topographic features such as the break in a slope, edge of a forest, a geological feature, or margin of a wet area. Sometimes they do not. In any case, they bear some relation to identifiable topographic features. Points on boundaries established in the field can be identified by distance and bearing from fixed, permanent features, and boundaries drawn by interpretation necessarily lie at some determinable distance and bearing. Thus, the user can identify soil boundaries presented to him in the photo map. When, at a later date, planimetric maps are prepared, soil boundaries (or the location of sample sites identified on the map) can be rectified in the same way as topographic features. Any error in this process is likely to be smaller than the inherent possible error in the location of the soil boundary. It has been said that every soil boundary on a map is the result of a subjective observation, and with few exceptions, this is true.

For additional, more detailed discussion of mapping bases, see Sec. 24-9.

21-27. General Economics of Applying Aerial-photographic Techniques to Agricultural Surveys. Seldom, if ever, has an area been surveyed for the same soil or land classification both with and without aerial-photographic techniques. Nevertheless, some general observations can be made from the large amount of work that has already been done separately in these lines.

Mention can be made of the relative value of these techniques at the various degrees of detail. In reconnaissance mapping the effort is probably one-tenth, or less, that required in doing the work on the ground without aerial photographs. In detailed mapping, say, for the preparation of a farm plan, aerial-photographic techniques barely save one-tenth of the work. In semidetailed mapping the work saved is somewhere between the calculated 10 and 90 per cent.

When the work is done in the proper order—reconnaissance, semidetailed, then detailed—the aerial photographs are usually available, anyway, by the time the more detailed mapping is done.

This comparison does not tell the whole story. No matter what the economic saving in using aerial-photographic techniques, no assessment can be made of the greater precision made possible by their use. Not only are boundaries more accurately delineated, but separations of classes may be made by use of the aerial view that might have been overlooked by ground inspection alone.

The author estimates from an experience in a Middle East country that on a project that combined soil and use capability, semidetailed surveys of a 50,000-hectare tract, together with a training exercise in the use of aerial-photographic techniques, the maps were prepared in about half the time that the same number of men had spent in equal areas of similar terrain without aerial photographs.

In another Middle East country a 6,000-square-kilometer tract was surveyed in semidetail for soils and use capability by eight surveyors in 3 months. This project was carried out under a contract which specified a certain number and density of field examinations and laboratory samples. Experience showed that with full and effective use of aerial-photographic techniques this time might have been cut in half, and subsequent work undertaken by the same firm is being done at the faster rate.

22 APPLICATIONS OF AERIAL-PHOTOGRAPHIC TECHNIQUES TO FORESTRY, BOTANY, AND ECOLOGY

By V. Merritt, J. F. Cunningham, and D. R. Lueder

22-1. Scope of Chapter. This chapter has to do with the applications of aerial-photographic techniques to the fields of forestry (temperate and tropical), botany, ecology, and geobotany.

Because of the previous work of people like Spurr, Losee, Woods, Seely, et al. (see Bibliography), the application of aerial-photographic techniques to forestry, at least in the temperate zones, has become both standard practice and fairly well disseminated knowledge. The problem of today is not one of discussing how they may be applied, but rather one of keeping pace with the new applications as they are developed.

Because of this it was decided to survey *briefly* the already well-developed field of temperate-zone forestry, in terms of major techniques and methods, ancillary applications, and possible future applications. Tropical forestry, not so well developed, was to be given similar treatment. A survey of recent topics being discussed was to complete the treatment.

The final portion of the chapter consists of brief expository treatments regarding the applications of air-photo methods to botany, geobotany, and ecology. These sections are confined to literature surveys, supplemented by the author's slight experience and somewhat greater enthusiastic feelings about possibilities.

APPLICATIONS TO TEMPERATE-ZONE FORESTRY

By J. F. Cunningham [1]

22-2. General Background. The position of aerial photography in the field of forestry has gained increased importance as its application has been developed and its technique perfected. Tremendous advances have been made, and continue to be made, in this comparatively new science, which was introduced shortly following the close of World War I. The pattern of development progressed from the aerial sketching of forest types to oblique aerial photography, and finally to the vertical aerial photography which we know today.

Early research and development were directed toward a need for base mapping of remote forest lands in Canada and the United States. Forest typing or classification was then compiled on this base, either by aerial sketching or ground-strip cruise methods. The search for economy in forest surveys led to much research into the possibility of extracting descriptive forest-stand data through stereoscopic analysis of vertical and oblique aerial photographs. In this respect the Forest Inventories Section, Forestry Branch, Department of Northern Affairs and National Resources, Canada, and the Forest Experimental Stations of the U.S. Forest Service pioneered in the investigations relating to the measurement of tree height and stand density on aerial photographs. A great deal of research is now in progress, and much more is needed. The training of foresters in the techniques of air-photo interpretation is of prime importance in this program of continuing research.

22-3. General Specifications for Forestry Photography. Until very recently, little information was available concerning the type of aerial photography best suited to forestry. The needs of the forester differ significantly from those of the photogrammetrist. The forester must not only distinguish the various stands of timber, he must also measure and evaluate them. He requires superior qualities of resolution and tone. The photographs

[1] Formerly Acting Chief, Forestry Division, Hunting Technical and Exploration Services.

must be recent to obtain a current analysis, since old photography is frequently out of date because of the growth increment accumulated, logging, fire, insect attack, or any of the various changes in forest cover that man may have brought about over the intervening period.

To obtain the maximum information from the stereoscopic analysis of aerial photographs, an interpreter requires large-scale prints of good definition and quality, printed on glossy paper, with no harshly contrasting black-and-white tones. Another problem, until very recently, was the confusion which existed in some quarters regarding the scale of photographs required for forestry purposes. Mapping personnel are often content with a relatively small scale of photography; but the forester requires large-scale photography in order to carry out the detailed interpretation required of him. As a result, a compromise scale of 1:15,840, or 20 chains to 1 inch, has become the recognized standard for forestry purposes. However, with the advent of more efficient and economical methods of air photography, it is now practical to obtain photography of a scale and type specifically required for the use which it is to fill.

Air photography is normally exposed on panchromatic film, 9- by 9-inch format, incorporating a minus blue filter. This film-filter combination has produced the most satisfactory results in tone differentiation (a factor of prime importance in forest-type classification) and in individual tree-species identification. The 6-inch focal-length lens is now generally accepted for forestry photography. This focal length has the advantage of producing an exaggerated third dimension, thus facilitating the delineation of forest types from a height-classification standpoint and producing a larger image for individual tree measurement.

22-4. Application of Aerial-photographic Techniques to Forest Inventory. The forestry profession, requiring the solution of the many and varied problems attending woods operations, was quick to recognize the economic significance of the air survey, and indeed has contributed immeasurably to the general acceptance accorded the technique today, through its policy of research and development.

The most important development in this regard has been the evolution of the "forest inventory survey" based upon the interpretation of air photos. Prior to the advent of this technique, it was common practice in forest surveys to carry out what is termed a "strip cruise." Strips of varying widths were run on the ground with compass and chain at regular spacing and interval, with previously cut base lines serving as control. By varying the spacing and width of the strips and tallying the trees by species and stem diameter, a suitable sample of the acreage was obtained. As the tally was taken, the cruiser mapped various topographic feature such as rivers, creeks, lakes, swamps, rock outcrops, etc., and also noted the points on his strip where significant changes in forest type occurred. Upon return to the office, the surveyors plotted these strips on the available base maps. The spacing of strips was usually 10 or 20 chains so that the forest-type boundaries were accurate only for the distance which the cruiser could see on either side of his strip. This led to obvious errors in the construction of the forest-type map. All forest-type boundaries could be joined only by a straight line between their occurrence on adjacent strips. It can readily be seen that, while the mensurational data taken were more than adequate, the accuracy of the volume estimate was destroyed through the application of inaccurate forest-type areas.

Efficient stratification in forest inventory today is based largely upon stand classification from air photographs. The proper use of good air photographs for this purpose may well reduce from one-half to two-thirds the number of plots or samples to be measured in the field for a given standard of precision. Stratification by use of air photographs is the basic sampling method used today in forest-inventory survey.

Foresters experienced in the field and in the art of air-photo interpretation—for the two are inseparable—are able to accurately stratify forest conditions on the basis of the several visible features, as follows:

Many of our temperate *tree species* are readily recognized by an experienced photo interpreter when they constitute a minimum of 25 per cent of the stand volume. Generally speaking, however, a much broader classification of species composition is employed in extensive inventory surveys. This classification usually rates the various areas according to volume of softwoods, in increments of 25 per cent.

Normally, *stand height* is classified in 10-foot intervals and is weighted by volume.

There are several schools of thought regarding the estimation and classification of the *stand-*

density factor by air-photo interpretation. They all are dependent upon the one feature which can be seen and measured on an aerial photograph, namely, crown closure. "Crown closure" is defined as that percentage of the area of a given forest type which would be covered by the hypothetical downward projection of the visible tree crowns contained within that type. It is normally estimated in 10, 20, or 25 per cent classes, depending on the intensity of the survey.

Estimates of crown closure vary directly as the resolution quality of the photographs. Superior qualities of resolution reveal the many small openings in the stand which would not be discernible on fuzzy, poor-quality photographs.

It is most important that no attempt be made to employ a stratification which requires the interpreter to make disinctions that cannot be secured with a suitable degree of accuracy. The technique calls for consistency in the interpretation, and thus demands the best possible approach to relative, rather than absolute, accuracy. Accordingly, it will be found that stereograms of typical stands whose forest type, height, and crown density have been established and agreed upon by one or more experienced interpreters and confirmed by field observation will be most useful as standards to maintain consistency. It is important also for the sake of consistency to limit, as far as possible, the number of interpreters employed on a single survey.

The initial photo interpretation must be done as carefully as possible to provide a stratification, which, because of its dependability, will require the minimum number of field plots. This importance is emphasized when one considers that field costs contribute approximately 50 per cent to the expense of any forest survey.

22-5. Mensurational Techniques and Instruments for Measurement of Tree Heights. A number of techniques and instruments have been developed for the measurement of tree heights on air photos of both the vertical and oblique type. These may be considered as belonging to one of three main classes: the parallax method, the shadow method, and direct-image measurement.

The *parallax method* uses measurement of the parallax difference of the third-dimensional tree image on vertical air photos followed by a use of the parallax formula to compute tree height in feet. This method is dependent upon crown-cover conditions which allow the interpreter an unobstructed view of ground level at the base of the tree or stand to be measured. The parallax bar (stereometer), Abrams height finder, and Fairchild stereocomparagraph are all instruments of satisfactory precision when employed by competent photo interpreters. The Harvard parallax wedge, while not of the same order of precision, is of considerable utility when employed as a rapid check on the interpreter's estimation of stand-height class.

The *shadow method* has been successfully applied to height measurement on both vertical and oblique air photography. However, its main value is achieved on the former. The governing factors affecting the accuracy of measurements by the shadow method are the conditions of level ground and sharply defined shadows such as are cast by conifers on a snow background during the late winter. A correction must be applied to the reading to account for the average depth of snow. Under the conditions described, the shadow method is the most accurate means of obtaining tree heights from air photographs. Space will not permit presentation of the mathematical theory and calculations, but reference will be found in Seely (163).

When conditions do not obtain for the efficient measurement of tree shadows because of hilly or broken topography, or lack of shadow clarity, *direct measurement of the tree image* provides an accurate means of estimate. This method is most effectively employed when the angle of view is approximately 45°, a condition normally fulfilled in the foreground of an ordinary aerial oblique or near the edges of a vertical photograph. Image measurement is effected with either the pole scale (164) on verticals and obliques or the tree-height grid on obliques only. A disadvantage of the pole scale is its requirement for a converting factor in order to determine actual tree height, since it does not take into account the varying scales of the tree images. The tree-height grid, however, is scale-corrected and gives a true reading.

22-6. Miscellaneous Applications of Aerial-photographic Techniques in the Field of Forestry. In addition to the stratification and mapping of forest types (forest inventory), there are a number of aerial-photographic techniques that find supplemental use. These include supplemental studies (cutover, burn, entomological, regeneration, site studies) and special exploitative surveys for roads, materials, rivers, etc.



Fig. 22-1. Aerial view of cutover area. Note the logging patterns. (*Ontario. Photographic Survey Corporation.*)

22-7. Supplemental Forest Surveys. Government regulations normally require plans to be submitted annually showing the location and extent of the past year's logging operations, i.e., cutover surveys. For many years it was general practice to run ground traverse around cutover boundaries to determine the area of each cut. This was a difficult and time-consuming task because of the inherent irregularity of the boundaries.

The air photograph presents in plan view the exact shape and area of each cut which can be readily and accurately measured by area-grid overlay or polar planimeter in a fraction of the time formerly required (Fig. 22-1).

Accurate delineation is required of any stands of timber which have been lost by fire, since the resulting disruption of the growing-stock normality necessitates an immediate revision of the sustained-yield management plan. *Burn areas* can be easily delineated and measured on aerial photographs.

The technique of air-photo interpretation has been successfully applied in mapping the location and extent of *forest insect attacks*. This, of course, is possible only in the case of those insects which cause a significant tonal characteristic to become evident in the dead and dying foliage. The damage caused by the spruce budworm (*Choristoneura fumiferana* Clem.) is of this type. In mid-August, the stands which have suffered heavy attack present a rusty red foliage, which persists for several weeks before the dead needles fall.

Large-scale air photography has recently been demonstrated to resolve the *regeneration* of conifer seedlings. In addition, the relative degree of successful regeneration may be quickly estimated from the air.

Some additional applications are mentioned in Sec. 22-15.

22-8. Special Studies for Exploitation. The efficient design of *haul-road and strip-road layout* prior to logging operations can quickly be achieved through the preliminary photo analysis of topographic and drainage conditions. Economy of operation is provided in the shortened turnaround time of logging trucks and sleighs. In addition, the camp foreman may study his entire

operation at a glance. The process of road location is identical with the early stages of route survey described in Sec. 17-7.

The transportation of pulpwood or saw logs by water, or "river drive," as it is termed, necessitates the placing of guide booms across blind channels and back eddies and the clearing of shallow rapids. The logs may then float freely to the mill with a minimum of manual labor and wood loss. Control dams are usually required to store sufficient water prior to the "drive" to flush the wood down small rivers and creeks during the spring freshet.

It can be readily appreciated that air photography can play a large part in studying the course of a river and planning the improvements necessary to transform it into an efficient carrier (Chap. 18).

Materials for road and dam building are also required for effective logging operations. The part that aerial-photographic techniques can play in materials survey (Chap. 17) thus becomes a factor in good forest management.

22-9. Some Recent Developments of Particular Interest. Among recent developments in air-photo interpretation for forestry purposes are two which hold exceptional promise for the future.

The technique of obtaining timber estimates from large-scale sampling photographs as developed by Losee (104) is revolutionary in its approach to the problem of forest-survey economy. Subsequent to the obtaining of vertical photography at a scale of 1:7,200 (6-inch lens), strips spaced 1 mile apart are flown at a scale of 1:1,200 (with a 24-inch lens).

Normal aerial cameras are limited to scales smaller than 1:2,400 because of image movement on the film during exposure. For this reason some form of image-movement compensation is required. The P.S.C. Panning Camera [2] was tested and found to eliminate 66 per cent of the distortion due to image motion. The technique employed rotates the camera on its horizontal axis in the direction of the line of flight, thus keeping the camera focused at the same place on the ground during each exposure. While the shutter is closed, the mechanism rotates forward to its original position, ready for the next exposure.

Estimates made from measurements on the large-scale photographs (Fig. 22-2) of tree height and crown diameter related to stem diameter, following regular statistical-sampling procedures, are applied to type areas designated on the 1:7,200-scale photographs (see also Figs. 22-8 and 22-9). It is entirely possible that as this technique becomes perfected, operational pulpwood surveys may be estimated entirely from the photographs, without the customary field survey, once the basic data for stand-volume tables are obtained.

Aerial photographs not only present a complete picture of the surface of the earth on which physical detail may be quickly and accurately mapped, but they reveal characteristics of the land which may not be apparent on the ground. In recent years much emphasis has been placed upon the evaluation of the productive capacity of forest stands, or forest site, as it is termed by foresters. Through the efforts of Hills and Brown (74 to 76) a technique has been developed to produce basic forest site type mapping from air photographs.

The interpretation of landforms by persons having a knowledge of local glacial geology, and local ecology, forms the basis of this technique. A landform embraces a specific parent soil material and a pattern of topography, depth to bedrock, drainage, and soil profile. Specific topographic positions on a given landform are characterized largely by differences in drainage and are called land-type "components," or "sites." Within the framework of land types, relationships between the forest and its environment may then be observed and recorded. Major land types based on texture, fabric, and petrographical nature of geological materials are broken down into components based on soil moisture, soil nutrients, local climate, relief, shallowness over bedrock, and geological origin of materials.

APPLICATIONS TO TROPICAL-ZONE FORESTRY

By V. G. Merritt [3]

22-10. General. The applications of aerial photography to forestry have been pioneered in the temperate forests, and a great many of the initial difficulties associated with such applications have been overcome. The successful use of the method in the northern climate is related to the following factors:

1. The relatively simpler nature of the forests as compared with those of the tropics

[2] A development of the Photographic Survey Corporation.

[3] Chief Forester, Canadian Colombo Plan Survey of Ceylon.

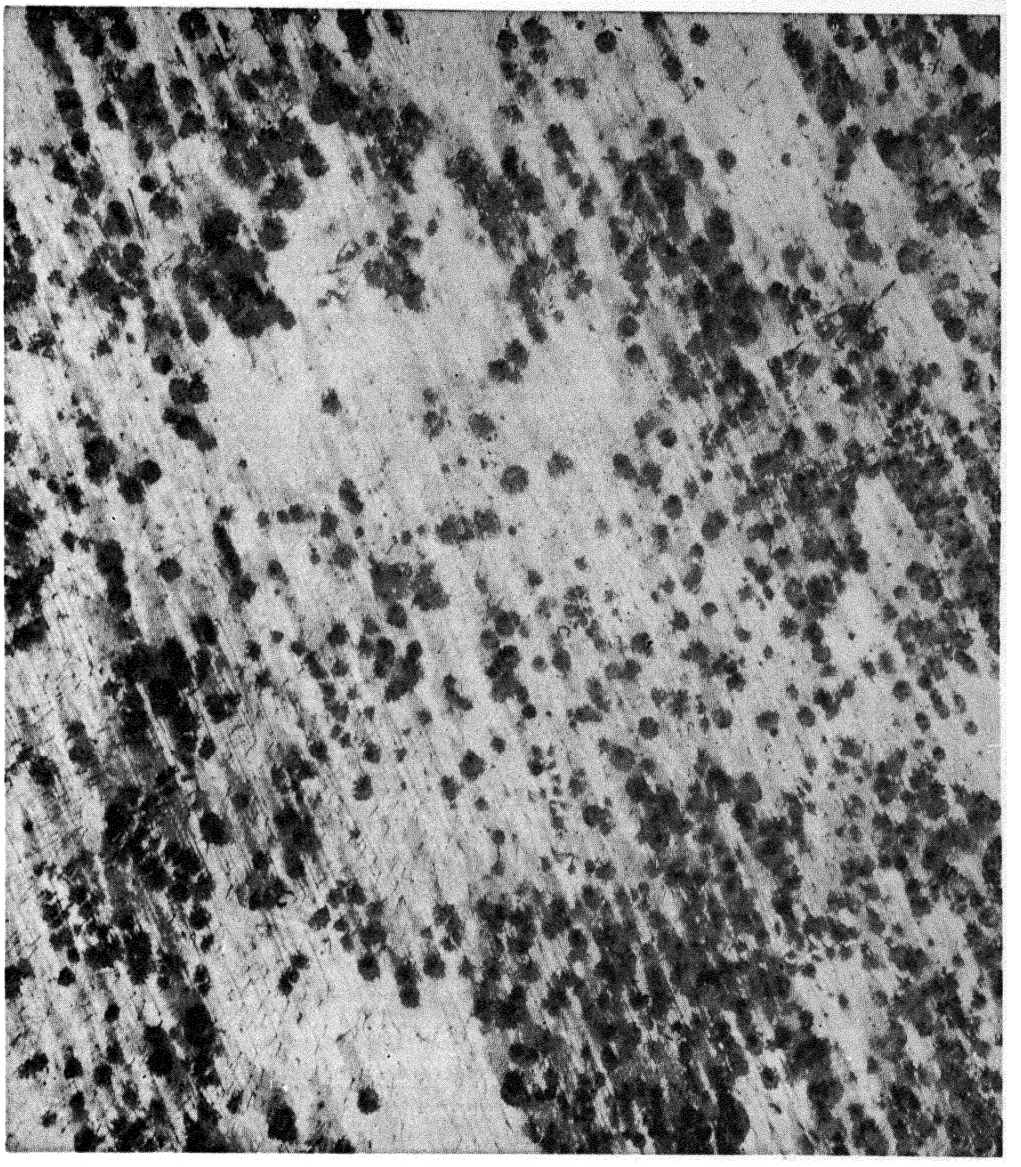


Fig. 22-2. Large-scale vertical with camera having image-motion compensation. Scale at 1:1,200, 24-inch lens. (*Ontario. Photographic Survey Corporation.*)

2. The existence of pure stands of even age, e.g., pure pine stands or pure spruce stands

3. The existence of reliable volume tables, adaptable to the photo technique, for practically all species

4. The comparative ease with which species can be recognized in the field, and the relatively few species involved.

5. The economic factors which have given incentive, and borne the cost of research, in the search for techniques

In the tropics the situation becomes far more complex:

1. The forest, in practically every case, is very



Fig. 22-3. An oblique view of a tropical forest, giving some idea of its variety. (*New Guinea.*)

complex and is composed of a large number of species.

2. Pure stands are rare, as are even-age stands.

3. Volume tables exist for desirable species only, and these comprise an extremely small proportion of the whole forest population.

4. One-hundred per cent recognition and identification of species is difficult, making field work slow and laborious.

5. Economic pressure is not great, as tropical forests have not given the quantitative yield of desirable species that the temperate forests have. Tropical extraction is highly selective, yielding one to five or six trees per acre.

If these adverse conditions and the associated limitations are kept in mind, a great deal can be done with the interpretation of air photos in tropical forests.

This interpretation can be considered in two divisions: (1) vegetational mapping and (2) mensurational techniques.

22-11. Vegetational Mapping. In the mapping of broad vegetational types, very accurate work can be done. Many varieties of tropical forests can be recognized by the patterns apparent from the aerial photos. Mangrove forest, Moist Evergreen forest, Dry Zone forest, Deciduous forest,

Thorn-Scrub, Parklands, and Montane forest types can nearly always be mapped accurately. Subdivisions within these forest types can often be recognized after a study of conditions on the ground. The subdivision of main types can best be accomplished by correlating the photographic patterns to a knowledge of conditions on the broader site areas such as would correspond to valley bottoms, ridges, medium slopes, alluvial soils, river banks, and moist and dry plains. It should also be borne in mind that although very broad classification may be made a standard over most tropical areas (Mangrove, Moist Evergreen, Deciduous forest), the subdivision will vary greatly for geographical units since they are more dependent on species. Species themselves are of course the most variable and uncertain factor and may vary most widely within relatively small geographical units (Fig. 22-3). This means that lessons learned about species and forest types at the subdivision level in one country will have to be learned all over again in another.

Recognition of individual species or trees is generally not possible because of the large number of species per acre in tropical forests. However, when a species does form a pure stand (a rarity), it is very often recognizable on air photos. If a species has a tendency to occur in small groups, but not *too* small, such groups can be recognized.

Sometimes, in special cases, color air photography will pick up individual species, particularly if a tree flushes a particular color at a certain time of the year. The difficulty in this case, however, is one of timing, as the availability of the aircraft, together with suitable flying and photographic weather, must coincide with the leaf flush (Secs. 5-25 and 22-15).

The possibilities of color photography in the tropics have not been fully explored, no doubt because of costs and the uncertainty of results (Chap. 5). Color photographs also offer certain difficulties in mapping and in stereoscopic interpretation. These are not serious, but should be considered when undertaking a color-photographic project. Perhaps a point to consider in color is that for photo interpretation true color rendition may not be too important, but color contrast is most important. Modified color work therefore may be of value for the selection of individual species.

In summary, if a classification is carefully thought out, aerial-photographic interpretation provides a reliable and accurate method of mapping the broader classes, and often the major subdivisions, of tropical forests. Individual species are very difficult to identify. When the form of a particular tree can be recognized, it is often not of commercial value but may serve as the site indicator of a forest division.

22-12. The Measurement of Tropical Forests and Mensurational Techniques. The measurement of forest stands in temperate forests, through the medium of aerial photos, has achieved sufficient precision and accuracy to make the method of great value in the surveying and inventory of forest land. The great success of the work in temperate zones has encouraged tropical foresters to try the methods on tropical forests. This has been done, and to a large extent has been successful, in certain tropical forests, but many difficulties remain.

Again, the classification and degree of information required are most important. If a forest type or subdivision is recognized on the photos, then we can ask whether or not it has a commercial possibility. This question (not considering accessibility) can generally be answered on the photos. Forest quality can be classed as good, medium, or poor. However, the precision with which height and density (a correlation of basal area and crown closure) can be determined from air photos leaves a lot to be desired. This is often difficult in the temperate-zone forests, particularly in the uneven-aged Deciduous or Mixed forests. In the tropics, the difficulties of the northern deciduous forests are greatly increased. Estimation of density of basal areas through crown closure may well be impossible at the degree of accuracy required for successful volume determination. Tropical forests are generally dense, and even a simple density classification such as sparse, medium, or dense becomes difficult.

Height estimation and measurement from air photos may be fairly precise in the temperate forests, but become difficult in the tropics because of the various layers of the vegetation that obscure the forest floor. Average heights of many forest types can be determined, but there is likely to be a wide range of divergences of individual trees from the average for the stand.

In tropical forests, the problem of height and density may be overcome to a great extent by considering the dominant layer only. In this case, fairly reliable crown counts may be made on suitable-scale photos (1:10,000 to 1:16,000). As



Fig. 22-4. This very large scale photo (1:650 approximately) illustrates the detail that is obtainable for botanical and ecological studies. The trees and man (the author) are easily discernible.

these dominants are generally the commercial timber, then crown counts may be a reliable index of commercial density if the proportion of the commercial species can be determined from ground-plot enumeration. Density can also be estimated (sparse, medium, or dense) on crown closure of dominants.

This method may be successful in the reconnaissance or over-all stock survey, but where a more detailed knowledge of the lower layer is required, height and density problems from air photos are very difficult.

22-13. Field Work. Field work to back up the air-photo work with reliable volume and species figures presents grave difficulties, particularly in the field of species recognition. In a country where a good forest department exists, 10 per cent species recognition and enumeration may be attempted, but even here difficulties emerge. The men capable of recognizing all the species are generally fully employed with executive duties and are in the top ranks of the department. They just do not have the time for cruising. Local men such as forest rangers or farmers may know the local names for a large number of trees, but this method is not too reliable. Specimen collecting and examination by botanists are time-consuming, and then the number of plots required for statistical precision is difficult to achieve.

In virgin forest areas 100 per cent species recognition is very difficult. Actually, the services of a top-rate forest botanist would be required for cruising. However, a compromise can be worked out. Most foresters can learn the main commercial species and pick up several more in a preliminary

reconnaissance. These could be recognized and recorded as such, while all other unrecognized species may be classified as such, and the diameter noted. In this way, a total basal can be worked out, of which the recognized species would form a percentage. As percentage of basal areas bears a relationship to volume, fairly reliable figures could be obtained, revealing a stand to be composed of a certain percentage of desirable species, both by stem count and diameter classes and volume.

This partial enumeration is criticized on the basis that if a survey is to be made, a knowledge of all species should be obtained, since in the future, some species hitherto unused or neglected may become highly valuable, and if not recorded, the survey would have to be done again to obtain the information necessary for its exploitation.

Undoubtedly this is true, but in view of the difficulties of a 100 per cent enumeration, particularly in unknown and virgin areas of the tropics, the forester may have to make a decision considering the cost and the immediate practical use and precision of the survey. Partial enumeration may allow a much larger number of plots to be put in, and then the knowledge of all recognizable species will be more accurate.

On the other hand, the cost and time for a 100 per cent enumeration may allow only a few plots, and then the knowledge both for commercial and noncommercial species is far from satisfactory.

Another difficulty in tropical forestry is the lack of volume tables. Where forest departments are established, these can be obtained for some of the commercial species. They can be localized by interpolation through height or bole length and diameter curves from information taken on the



Fig. 22-5. This very large scale photo (1:650 approximately) is another example of the detail that is obtainable for botanical and ecological studies. The trees and various plant colonies are easily discernible.



Fig. 22-6. Stereopair showing interesting geobotanical and ecological effects in a semiarid climate. Note the associations between certain formations and certain vegetation. The fractures are accentuated by vegetation (probably because of moisture retention). Also note the significant tonal patterns. (*Western United States. U.S. Department of Agriculture.*)

plots. Another method may be considered where the relation of diameter, bole length, and form factors, regardless of species, can be worked out and applied to all trees (regardless of species), thus yielding the total volume of the forest. If volume tables of a few local species are obtainable, these could serve as a corrective factor in the estimate for that species.

The fundamental technique in air-photo forest mensuration is one of isolating or classifying similar areas of forest vegetation, then sampling a sufficient number of these areas to such a degree as to obtain average reliable figures of stem count, diameter, basal area, and volumes in species and diameter classes. This figure is then multiplied by the acreages of the classified areas.

This method can be applied to tropical forests, although difficulties will be encountered and modification of the techniques used in the temperate-zone forests may have to be adopted to suit local conditions.

The following paragraphs suggest a method for inventory of tropical forests:

The broad classes and subdivisions of the forest vegetation should be investigated and typed on the photos; i.e., the patterns which show on the photos should be classified as to the forest type they represent.

If possible, broad timber-quality classes (poor, medium, good) with their subdivisions should be typed. Height and number of dominants per acre should be a reliable guide.

If concentrations of a particular species can be recognized, this can be noted, and even form another subdivision. A broad site or topographic factor can be introduced such as valley bottoms, alluvial flats along rivers, dry and moist planes, medium slopes, ridges. These may help in correlation of particular species to site conditions. The measurement of height and density, and particularly density (relating crown closure, basal area, and stem count), is very difficult to estimate on

aerial pictures of tropical forests. In some types of tropical forest, however, it can be applied with accuracy, and this should be investigated. Stem counts and basal areas do vary a great deal, but this variation in most cases cannot be reliably determined from air photos. Having set up a classification system, sample plots can be placed in as many areas representing such classes as accessibility and cost will allow. Plots may be taken in the manner to which the forester doing the work is accustomed, but it is the author's preference to use line plots of ⅕ acre, about 10 plots to a line. These lines should be as widely scattered as possible so as to give a fair representation of forest population for the forest type.

If the photos have been carefully typed and interpreted, strong correlation should soon be apparent as the results from the plots are brought together and averaged. The plots will give reliable figures on species which were unrecognizable on the air photos but which can now be applied to the forest type.

Once the air-photos method is started in a given country or geographical unit area, a wealth of experience is soon gained, and further survey can be undertaken that relies more on the photos and less on ground work.

The greatest difficulties and costs are encountered at the beginning or on the first survey. Subsequent surveys should cost much less and gain in accuracy.

Where aerial photos have been used and properly understood, tropical forest departments soon begin to rely on them as an important tool. However, the danger of introducing air photos into the tropics without trained personnel may tend to discredit the air-photo method.

The temperate-zone forester thoroughly trained in air-photo techniques can very profitably work with the local tropical forester. The tropical forester supplies his knowledge of forest types, species, and site conditions, the temperate-zone forester interpreting these through the medium of air photography. This method will work to mutual advantage. The temperate-zone forester need not be afraid of the complexity of tropical forests if he has a local man to guide him through the maze of species. On the other hand, the tropical forester, who, through necessity, is generally well educated in botany and trained to consider the detailed ecological relationship of the forest, will gain in the broader concept of forest relationship as required by air-photo work, as well as in a knowledge of air-photo mapping and interpretation.



Fig. 22-7. Another illustration of interesting geobotanical and ecological effects in a semiarid climate. Note again the associations between certain vegetation and the significant tonal pattern. The fractures again are accented by vegetation (probably because of moisture retention). (*Western United States. U.S. Department of Agriculture.*)

SOME MISCELLANY CONCERNING FORESTRY

By D. R. Lueder

22-14. General. The following section is concerned with mention of a few recent papers that consider the applications of aerial-photographic techniques to forestry. The use of aerial-photographic methods can become rather detailed when they are seriously and intelligently applied to a field of terrain analysis, usually under stimulus of commercial necessity.

22-15. Recent Topics Being Considered in Forestry. Wood (225) in 1953 presented a tentative outline for a report on the use of air-photo techniques in forestry. This is a representative list and should be examined by all those interested in the applications of aerial techniques to forestry.

In 1956, Coleman and Rogers (37) reported on current developments. Major recent developments included land-use and hydrologic studies (Chap. 18), insect damage, forest-fire control, reforestation, and wildlife census.

A very interesting subject is that involving the uses of CD film (Chap. 5) in forestry. Bennett (16) has commented on this as follows:

> From the above it can be seen that a knowledge of the infrared reflectivity of the various subjects would be helpful when interpreting results. For example, it is well known that certain types of trees give high reflectivity in the infrared and that other trees do not. The intensity of these radiations is controlled, to some extent, by the chlorophyll content of the leaves, or needles, on the trees, and also by their cell structure. The leaves of hardwood trees usually give high reflectivity in the infrared, especially during the Spring and Summer months, when the leaves are green. The degree of infrared reflectivity usually decreases in the Fall, when the leaves change colour, and virtually disappears when the leaves turn brown and fall off the trees. On the other hand, the infrared reflectivity of the needles of most softwood trees is nearly always considerably less than that of the leaves of hardwood trees, unless a comparison is made with hardwood trees in the Fall when the leaves of the hardwoods are dying. In any case, if the comparison is made in the Spring and Summer, it can be stated that the healthy hardwoods have a much higher infrared reflectivity than healthy softwoods. The significance of this is that, in spite of their near-similarity in actual colour, hardwoods can easily be distinguished from softwoods on Camouflage Detection Film due to the distinct differences in their colours as seen with this film. In general it can be said that healthy hardwoods, in Spring and Summer, appear magenta (reddish) and that healthy softwoods appear bluish-purple in colour with the Camouflage Detection Film.
>
> In addition to the two above mentioned broad distinctions, another useful property of the film is that hardwood leaves or softwood needles that are dead or dying usually photograph as a bright green with this Film. This is due to the fact that such leaves or needles have lost their infrared reflectivity and also that they have turned prematurely red or brown. The combination of both these conditions causes the green rendition of such leaves or needles. This is different from the effect obtained with healthy hardwood trees whose leaves have simply turned red or yellow in the Autumn. Such leaves still retain some of their infrared reflectivity and photograph as yellow in the case of the red leaves and white in the case of the yellow leaves.

Bennett summarized the color effects applicable to various types of trees. These are presented in Table 22-1. There are several papers describing the photographic registration of various types of foliage on various types of film. Prominent among these is one by Bäckström and Welander (4), which includes reflectance-wavelength curves for six types of trees at three different periods from mid-spring to early summer. Infrared film is also discussed in Chap. 5. Illustrations of infrared and panchromatic effects are shown in the last three illustrations of Chap. 5.

SOME COMMENTS ON THE APPLICATION OF AERIAL-PHOTOGRAPHIC METHODS TO BOTANY, GEOBOTANY, AND ECOLOGY

By D. R. Lueder

22-16. General. It should be emphasized that the author is far from being either botanist, geobotanist, or ecologist. Consequently, this part of the chapter must be brief, general, and largely confined to a consideration of references. It is included mainly as a stimulus to further efforts on the part of botanists, ecologists, etc. (Sec. 7-21).

22-17. Possibilities and Recent Topics of Study. It should be obvious to the reader of this book that photographic techniques have much to offer botany, geobotany, and ecology.

Botany and plant ecology are, in many essential ways, closely tied to forestry (Sec. 22-13). However, botanical species (excluding forest types) generally are smaller, more complex, of infinitely greater variety, etc. Yet they occur in characteristic environments, have characteristic associations, display various colors, shapes, etc. With color.

Table 22-1. Colors in Which Various Forest Subjects Are Recorded by Camouflage Detection Film (From Bennett)

Subject	As recorded on Camouflage Detection Film
Healthy hardwoods in spring, summer, and early autumn	Magenta (reddish)
Healthy softwoods	Generally blue to purple although new growth in some types may have some reflectivity in the infrared and thus be recorded as a dark red
Healthy hardwoods in autumn when leaves are red	Yellow
Healthy hardwoods in autumn when leaves are yellow	White
Unhealthy trees, either hardwood or softwood, whose leaves or needles have died and turned reddish brown in color	Green
Hardwood leaves that have turned color and fallen from the trees	Green
Roads of all types	Green
Sandy beaches, cutover areas, and logging trails	Green
Clear water	Brownish black
Shallow, dirty water	Variable

infrared, camouflage, and panchromatic films, scale and filter variables, and qualitative interpretative methods, there is no reason why botany, and particularly plant ecology, cannot be advanced by a technique for systematic and efficient regional study.

Some applications to botany and plant ecology are suggested or discussed in Chap. 15. The Forestry Section of the Report of Commission VII by Coleman and Rogers (37) includes references to many botanical and plant-ecological investigations being conducted by various people and organizations throughout the world. This is very interesting reading and has an extensive bibliography. Truesdell (206) reports on several applications of the air-photo method to ecological and botanical studies. He mentions papers by Churchill and Stitt (34) and Witenstein (224), as well as a study of diseased and healthy cereal crops instituted by the Committee on Plant and Crop Ecology of the United States National Research Council. The use of air-photo interpretation in seaweed surveys has been described by Cameron. The author, while surveying tidal marshes some years ago, had encouraging discussions with ecologists regarding the correlations that could be established between the distinctive patterns of such areas (Sec. 15-10) and the location of organisms upon which oysters feed. Finally, it would seem evident that interpretation could be used to delineate wet malarial mosquito-breeding areas in relatively inaccessible regions such as New Guinea. These delineations could then be used to plan malaria-control measures.

Geobotany, and its closely allied subject, geochemistry, can be well served by aerial-photographic techniques. An extract from a 1953 paper of the author (107) briefly summarizes the value of geobotany to mineral reconnaissance:

> Plant association may be an indicator. Practically no scientific information was available on plant-mineral associations until Goldschmidt published the results of some tests in 1934, describing what has since been called the Goldschmidt enrichment principle.
>
> According to this principle, minerals are dissolved in soil water and absorbed by plant-root systems. In the plant they ultimately migrate to the foliage. When the foliage withers and falls, and eventually decays on the ground, some of the minerals remain, enriching the soil. Concentrations of minerals results.
>
> Since about 1940, the Finns, Swedes, Norwegians,



Fig. 22-8. Geobotanical anomalies G possibly related to hydrothermal activity. These vegetative and tonal features occur on the top of a topographic dome. There is no true orientation with respect to sun exposure. Fractures are faint but discernible and intersect the area. Note the streams that are the only ones in the area showing vegetative-tonal character. This area might be very interesting from the standpoint of mineral exploration. (*Western United States.*)

and Russians, together with some Canadians, have found that mineral concentrations may affect plants in several ways:

1. They may change the appearance of foliage.
2. They may cause certain tolerant (or indicator) plants to thrive while stunting or killing all others.
3. The minerals may be concentrated selectively in the foliage of certain plants.

Many plant-mineral associations have been found. For example, zinc may be indicated by luxuriant ragweed in the presence of other stunted growth; the so-called zinc pansy is often a luxuriant grower in the vicinity of zinc dumps; the 2-foot brilliant-red campion has been found to thrive in a soil having a copper concentration of 14 pounds per ton, while other plants die. Douglas fir, larch, and the lodgepole pine may concentrate copper and zinc selectively in their foliage. If space permitted, many similar associations could be described.

Most of these localizers and indicators can be seen on air photos. . . . Filters provide a promising field, particularly in determining rock and vegetative types. Filters utilizing actual vegetable and mineral pigments can be constructed. It is possible, therefore, to look for given indicator plants, rock types, and mineralization colors by taking photographs and examining prints and negatives through filters that will emphasize the particular plant or rock colors desired. This technique would be of great value in arid areas. It might well be of tremendous value in forest-covered areas where prospecting by any means is difficult.

The field of plant-mineral associations in general is interesting. Little has been done to date. Air-photo research provides a rare tool for investigation on a large scale. Again, the results might be of particular value in forested areas [Figs. 22-4 to 22-8].

It should be apparent that the photo perspective, supplemented by color camouflage, infrared film (Secs. 5-25 to 5-27), and special filters, with the aid of interpretative theory and techniques, can be of great assistance to geobotanical research and mapping. There is no real reason why it should not be applied to a maximum.

23 APPLICATIONS OF AERIAL-PHOTOGRAPHIC TECHNIQUES TO URBAN, REGIONAL, AND MILITARY STUDIES

23-1. Scope of Chapter. This chapter will consider the many ways in which aerial-photographic techniques may be applied to urban planning and development. Then, because "areas" and regions are in many ways similar to municipalities, if they are not simply their extension, there is a brief discussion of the part that can and should be played by air-photo techniques in their study. Finally, because they are so frequently concerned with cities and regions, but also because there does not seem to be any other convenient place, military applications are discussed. Each of these topics is considered under a separate heading.

In a way, this chapter is a difficult one to write. The difficulty is not related to a lack of subject matter; rather, it is associated with either the danger of belaboring what would seem to be obvious points or the apparent necessity of repeating material that has been included in previous chapters. In the latter case, of course, proper cross references can be included. This does not make for interesting reading, nor does it promote ease of study. In fact, it can be annoying if carried too far. An attempt has therefore been made, in the following pages, to use as few cross references as are consistent with an adequate presentation.

URBAN PLANNING, DEVELOPMENT, AND OPERATION

23-2. General. An urban area is one within which a relatively great *concentration* of people live, or are intended to live; the inhabitants are serviced as a group with certain of their utilitarian and community needs; the major portion of the land is directly occupied by the inhabitants and their service facilities; and there is a relatively great justification for community of interest and operation.

23-3. The Mapping Base—A Fundamental Item. For any terrain study, large, small, specific, or general, an adequate mapping base is essential. Such a base is required for any of the applications discussed in Chaps. 17 to 22. However, it is a particularly important requirement for urban studies because of the usual high land values in urban areas and the proportionate significance that accrues to any given map unit or boundary. As will be brought out by subsequent sections, the preparation of an adequate base also happens to represent a large part of the contribution that aerial-photographic methods can make to urban studies.

The entire subject of mapping bases, their characteristics, method of preparation, etc., is covered, for convenience, in the first part of Chap. 24. However, one aspect, that of *obsolescence*, is so important to urban studies that it is mentioned here.

An obsolescent map, in so far as any study is concerned, is one including details that no longer bear a reasonable approximation to reality. For terrain maps whose general emphasis is on geology, soils, forestry, and certain types of engineering, obsolescence is not a particularly important consideration. Most of these maps are concerned with details of the terrain. In terms of human life, features of terrain are static. Further, although man is incessantly engaged in changing the terrain, the results are usually insignificant compared with the landscape as a whole. As a consequence, once a terrain mapping base is available, it may be used for a considerable length of time with a certain confidence, and those cultural changes that do occur can be easily incorporated.

The situation in urban areas is different. Here the major emphasis lies with cultural details, either in terms of their changes in previous cultured areas

or in terms of their encroachment upon previously undeveloped land. In both of these instances, obsolescence becomes a factor of major importance and mapping methods or bases must be of such a nature that they can be brought up to date, with reasonable frequency.

Fortunately, aerial-photographic methods provide relatively simple and economical techniques both for preparing initial detailed maps (Secs. 24-5 to 24-9) of urban areas or for revising and modernizing existent ones (Secs. 24-6, 24-7, and 24-9). This insurance against obsolescence is one of the great assets that a proper air-photo approach offers to urban studies.

23-4. Classification of Urban Studies. It is somewhat difficult to classify urban studies because of their numerous overlaps. However, it seems proper to make an initial differentiation between studies that are primarily concerned with planning and development and studies concerned with the operation of urban units and facilities. This basic differentiation is shown in the following list:

1. Planning and developmental studies
   a. General (terrain, culture)
   b. Specific (water resources, engineering, subdivisional development, zoning, development of service facilities)
2. Operational studies
   a. General (population and service patterns)
   b. Specific (tax-assessment maps, base and legal maps, traffic studies, service operation, defense, and disaster)

The following pages discuss most of these studies to some extent.

23-5. Nature of Planning and Developmental Studies. Planning and developmental studies are undertaken primarily to determine the best way(s) to provide or develop *new* areas, services, facilities, and policies for the ultimate benefit of the urban-suburban community.

The first requisite of a proper planning or developmental study, like most other studies, is the procurement of adequate, dependable information that is basically pertinent to the objective of the investigation.

In some cases, the pertinent information may be desired over a large area and/or have a high level of generalization. In other cases, it may be required for a relatively small area and/or be quite detailed along certain lines. The first type of study may be called "general," and the second "specific."

General studies are usually concerned with two basic classes of information: one concerns the nature of the terrain within the area of interest; the other concerns the nature of the culture. The nature of the terrain embraces data on the topography, soils, depth of overburden, rock, surface drainage, and subsurface water conditions. Cultural data cover the existing land usage and occupancy, transportation network, location of existing urban services and facilities of all types, etc. For the usual general study most of the information *is* generalized. However, even if it is detailed, as it sometimes must be, it will generally be found that all items of desired information receive approximately equal emphasis. No separate items are selected for special regard and concentration.

The specific study, though it may require some data on all the aforementioned items, usually is primarily concerned with only two or three of them and, accordingly, must give these a much more detailed look, to the usual detriment of the others.

Both general and specific planning and developmental studies can be well served by aerial-photographic techniques, but the approaches, costs, and times involved are different.

23-6. Application of Aerial-photographic Techniques to the General Study of Terrain. To one who has read this book, the application of aerial-photographic techniques to the study of soils, unconsolidated materials, rocks, and organic deposits (Parts I and II), surface drainage (Chaps. 3 and 4 and Secs. 18-17 and 18-20), subsurface water conditions (Chap. 4 and Sec. 18-7), vegetation (Chaps. 6 and 22), and land use (Chaps. 6 and 21) should be apparent.

Suffice it to say that the proper application of qualitative air-photo methods, including the usual selective field check, to the terrain mapping of any appreciable area (greater than 500 acres) is quicker, cheaper, and usually more dependable than any other method of producing equivalent information.

For purposes of general urban planning, because of the variety of complex factors that is involved, it is doubtful whether any other method should be used at all. For purposes of detailed urban land use, building-condition and occupancy surveys, and specific urban planning and development, the aerial techniques will usually require more ground check than is implied by the term "selective."

23-7. Application of Aerial-photographic Techniques to the General Study of Culture. Aerial-photographic techniques, properly applied, are usually the *best* means for completing *most* general studies of culture. This positive statement may seem strong to some, but it is true, and there does not seem to be any reason to hide the fact.

What alternative ways of completing general cultural studies are there? If maps are unavailable or nonexistent, one may study the culture by covering and mapping it upon the ground—an archaic procedure in *most* cases. If maps are available, one may examine them. However, in this latter situation, several questions are important. Is the map *sufficiently up to date* to be effective in realizing the objectives of the study? Is the map *positively inclusive* in identifying *all* the cultural occurrences that are of interest to the study? Is the map *completely accurate* in locating and identifying the pertinent cultural features? [1] If the answer to any one of these question is negative, as it usually must be,[2] then the photographic approach is better.

The photographic approach is based upon the truth that an aerial photograph is a factual depiction, through the photo perspective and medium, of everything exposed to the sky upon the earth's surface. Among other things, it is a complete picture of general culture. If a properly exposed and processed photograph is taken at the correct scale, is effectively read and analyzed (Secs. 1-6 and 1-7), and is supplemented by selective field check where necessary, and if the developed information is plotted upon a suitable mapping base, a rapid, economical and dependable cultural survey may be completed to any reasonable degree of detail.

Of course, there are the inevitable exceptions. Maps may be sufficiently current, inclusive, and dependable for the purposes of study. Photographic restrictions due to climate, seasonal foliage, or aircraft unavailability may be incompatible with the time for completion of the study. In some cases, the area may be too small to justify new flying costs. This latter objective should be rare, since even a small area (2 to 10 square miles) may be photographed for a few hundred dollars if aircraft mobilization is not excessive. The costs of surveying such small areas on the ground would usually be more.

The following features may be definitely, and usually easily, identified upon properly exposed aerial photography at various scales. Of course, the effectiveness of identification varies for different items, and there are usually optimum scales, or ranges of scales, for each.

1. Transportation details
   - *a.* Railways, marshaling yards, roundhouses, stations, bridges, etc.[3]
   - *b.* Roads (concrete, bituminous, dirt), trails, culvert locations, intersections, street geometrics, bridges of various types, cracks in concrete pavements, etc.
   - *c.* Surface pipelines, pumping stations, tanks, feeder pipes, etc.
   - *d.* Transmission lines, towers, types of towers, etc.
   - *e.* Old road beds, abandoned race tracks, road allowances, etc.
2. Building details
   - *a.* Houses of all types, barns, sheds, garages, fences, driveways, and to a certain extent, the style and class of house (by size, roof shape, chimneys, and other details)
   - *b.* Buildings, factories, and churches, similarly with some factories identifiable as to type of activity, ventilators, skylights, chimneys, loading docks, exterior facilities, etc.
3. Special urban details including gas stations, storage tanks, transmission towers, water towers, airport facilities, parking lots, telephone poles, sidewalks, cracks in concrete pavements, lumber yards, backyard gardens, billboards, refuse heaps, junkyards, individual cars, docks, etc.

Many of these details appear in Figs. 23-1 and 24-1.

It might be mentioned that the identification of many of these details is best done from photos that show some shadow patterns. Such patterns, for example, would appear on photos taken between 10 and 11 A.M. or 1 and 2 P.M., presuming that atmospheric conditions permitted adequate photography and resolution (Chap. 5).

Maynard (119) has presented a paper on the use and effectiveness of photo-interpretative "keys" (Sec. 24-23) in the analysis of industry. This in-

[1] Anyone who has dealt extensively with urban and other cultural maps is acquainted with the fantastic array of misinformation that can be accumulated thereon—paper streets, triangular trapezoids, submerged highways, ethereal buildings, etc.

[2] Even if a map is prepared by photogrammetric means, these defects may exist and should be checked photographically.

[3] These items are indicative only. Theoretically, it should be possible to "see" all items having horizontal dimensions that are greater than the resolving power of the photograph, and in some cases, items that are smaller.

dicates how "automatic" urban photo reading and analysis can become.

23-8. Application of Aerial-photographic Techniques to Specific Planning and Developmental Studies—Miscellaneous. Zoning studies are concerned both with the delineation of zones in existing areas and the layout of new zones for areas susceptible to future development. Probably no single aspect of urban planning affects so many people in so many ways for so long a time as a zoning ordinance. Consequently, it behooves the zoning committee to take special pains to secure adequate and accurate information on those aspects of the city-suburban complex that are pertinent to zoning differentiation. With the exception of existing tax assessment, practically every one of the items that affect such differentiation can be directly or indirectly investigated on a proper aerial mosaic.

The location of ground water and exploitation of surface water supply may be aided by aerial-photographic techniques in a manner discussed in Chap. 18. Pipeline-location and -foundation conditions may be partially advanced in the manner described in Chap. 17. Cultural studies may aid location and routing of water lines. The applications have either been previously discussed or are obvious.

Engineering projects for new areas or old may be materially aided by the use of proper air-photo techniques. The techniques vary both in type and combination. Reference should be made to Chaps. 17 and 18, as well as to Secs. 24-7 to 24-9 for further details.

Land acquisition is usually an important, and often dominant factor in urban-engineering studies. Land-acquisition maps and plans may be prepared and developed with discretion, speed, and economy, through the proper application of air-photo methods.

Subdivisional and real-estate studies are aided immeasurably by the application of techniques discussed in Chaps. 17 and 18. Such application, by aiding the evaluation of natural beauty, individual trees, and natural drainage, actually pays for itself by increasing the value of the developed land. Proper qualitative interpretation also cuts the costs of construction for sewers, culverts, bedrock excavation, etc.

23-9. Nature of Operational Studies. An urban operational study is one made to secure better operations of the community unit.

Like planning and developmental studies, operational studies have as a prime requisite the procurement of adequate, dependable data that are pertinent to the objectives of the investigation and consistent with its finances.

Also like planning and developmental studies, some operational investigations may cover large areas and tend toward a fairly high level of generalization, while others will cover relatively small areas and/or be rather detailed in nature. The first may be called general studies, and the second specific studies.

General operational studies are primarily concerned with the existing population patterns and service patterns.

A population pattern is the arrangement of classifiable population areas. The classification may be made upon almost any basis—size of house, size of lot, type of house, type of working activity, economic grouping, sociological grouping, etc.

A service pattern is the arrangement of existing urban service centers and facilities. These include a host of items such as fire stations, fire hydrants, fire alarms, water mains, schools, parks, playgrounds, swimming pools, police stations, call boxes, telephone facilities, gas stations, electrical poles, substations, storm and sanitary mains, manholes and inlets, telephone cables, bridges, culverts, streets, roads, etc.

Specific operational studies are largely concerned with special aspects of existing population, service, and utilities, which must accordingly be emphasized.

23-10. Application of Aerial-photographic Techniques to General Operational Studies. Air-photo methods can contribute to general urban operational studies in two ways. The first is related to the provision of an adequate mapping base. The second is the provision of techniques for efficiently and dependably securing much of the data that is desired for annotation thereon.

The subject of mapping bases—for all types of studies, including urban ones—is covered in Sec. 24-9.

The subject of general cultural studies has been

Fig. 23-1. A fine large scale view showing the multiplicity of detail visible on proper aerial photographs. Even such things as tarred cracks in concrete roads, rows of vegetables in truck garden, telephone poles, etc., are discernible. See Fig. 24-1 for another urban view. (*Ontario. Photographic Survey Corporation.*)



discussed in Sec. 23-7. A rereading of this section, and the lists included therein, will show that many of the cultural items desired for general operational investigations of existing service patterns (Sec. 23-9) can be obtained directly from the photography.

Section 23-7 also shows that houses of various general types, churches, schools, lot sizes, layouts, commercial and industrial activity, parks, etc., can be located and delineated on the air photo. This simply means that the effective study of population patterns may be given a tremendous forward impetus. The basic data become easily available. Initial tentative classifications can be blocked out on almost any basis. These classifications can be field-checked, revised, etc., according to standard sampling methods, with the added advantage that the sampling is founded upon a realistic appraisal of the true population complexes and activities.

Witenstein (224) has presented a brief discussion of the manner in which photo analysis can be used to investigate population patterns, service patterns, and their associations in terms of logistics, urban activity, and socioeconomics. This is here quoted to some extent:

> Urban patterns everywhere are the physical manifestations of complex cultural and economic sequences of events, as well as the result of specific adjustments to climate and terrain. Within the patterns of urban units are observable differences in land-use—industrial, commercial, residential, port, railway or military areas which occupy large sections and are the basic components of urban areas. They are a result of the degree of industrialization, ease of access to and from other areas, particular site features, availability of construction materials, and the economic levels of the population.
>
> The characteristics of these fundamental areas tend to remain consistently uniform throughout large geographic or political regions and are easily recognizable in the photography because urban land-use dictates specific types of construction; types of construction found in industrial, port or railway areas reflect the needs and capacity of the transport media or the industrial production. The construction in various residential areas reflects the ability of different classes of people to command specific types of housing and space. As a result, the recognizable functional area provides a common denominator for the understanding of a variety of related urban features. The study of these interrelated quantitative features can be so organized that we can ascribe quantitative values whose extent can be measured in the aerial photograph by delineation of the functional areas. . . . These features are reducible to a system of recognition standards or criteria which become working tools. . . . The assembly of such keys is possible because the characteristics of various functional areas tend individually to remain uniform. These uniform features are recognizable in city after city, and they will differ between cities only with respect to size and relative position. . . .
>
> Beyond the recognition and delineation of functional areas, each key becomes a symbol around which a whole series of related concepts are studied. To each of these concepts quantitative values can be assigned much as a mathematician assigns values to his "X's" and "Y's."
>
> For example, in a given foreign country a particular type of residential area has the following predetermined average values per square mile: population of about 100,000, a daily requirement of about 28 gallons of water per head, complete lack of plumbing, the daily use of 120 cars for removal of night soil and rubbish. Pursued further in this sample area, the average annual income ranges between $50 and $200 per year, the life span averages 27 years, a typical family averages 7 persons, and occupies 1½ rooms. It is even possible to determine social and psychological reactions in this area to a variety of stimuli, such as politics, economic depression, fire, bombing, or propaganda.
>
> From such an examination of each of the functional parts of a city to whatever detail we wish to explore, an evaluation of a town's facilities and capacities with respect to transportation, industry, electric power, and other urban utilities, as well as housing and hospital facilities, and capacity for storage and distribution of supplies can be made. Additional estimates can be made for such logistic problems as the amount and type of food, clothing, sanitation, and shelter which might be required in order to supply the local population in even military occupation.

23-11. Application of Aerial-photographic Techniques to Specific Operational Studies—Tax Maps. Probably one of the most useful and financially productive applications of aerial-photographic methods to urban operational studies is that related to the preparation of tax-assessment maps. Everyone who has lived in a town is familiar with sporadic revelations of unrecorded and untaxed properties, inequitable and obsolete tax assessment and the general state of confused delay that attends any surveys and inquiries regarding taxation of single or group properties.

These taxation maladies are caused by many things: rapid urban and suburban expansion without corresponding increases in the staff and facilities assigned to handle taxation records; obso-

lescence of methods; sheer corruption; frequent changes in municipal government; insufficient salaries; etc. While everyone agrees upon the causes and results, everyone also agrees that while taxation is annoying, if it must be, let it be efficient, correct, and equitable.

Aerial-photographic methods, properly supplemented by field and legal checking, provide a means of reaching this tripartite objective. Moreover, it is the author's opinion that these same methods can be used to reach the objective at no cost, or even at a profit! The tax reassessment that should result from a proper study should increase revenues by at least the discovery of untaxed properties, thereby defraying a portion of costs. The incidental benefits, in terms of a base map, street plan, etc., should add further economies by reducing municipal costs that result from lack of adequate data.

Essentially, the production of a tax-assessment map begins with an accurate analysis base; is followed by a combination of air-photo analysis, selective legal checking, and field survey; and ends with completely drafted maps, mosaics, and keyed index cards. These latter may even be keyed, filed, sorted, and located electronically and may include a host of items in addition to ownership and location.

King (95) has presented an interesting and factual history of one typical case in which photographic methods were used to aid tax reassessment.

23-12. Application of Aerial-photographic Techniques to Other Specific Operational Studies. It should be obvious to the reader that there are many facets of city management and operation that could conceivably benefit from a planned use of aerial photographs and photographic methods.

These even include traffic analysis. To the best of the author's knowledge, aerial photography has not been used extensively to aid traffic analysis, but there is no real reason that it should not. The application to parking analysis is obvious. That to origin-and-destination studies, based upon population patterns, would seem intriguing. There is even some possible justification for sequential aerial photography during the rush and nonrush hours to aid in the analysis of traffic flow, obstacles, etc. One aerial photograph, at a scale of 1:20,000, covers approximately 9 square miles. At this scale, automobiles and trucks can be recognized. It should be possible to conduct a sequence of photographic missions throughout any given day, and on a series of days, that could be statistically planned and analyzed to provide much valuable information about a given city's traffic characteristics.

At this conclusion of the discussion of the application of air-photo techniques to urban studies, an extract from King's (95) interesting summary of an actual case history is in place:

> It was during this period of using aerial photography as a means to the rapid production of maps for purposes of taxation, that aerial photogrammetry as a municipal tool was born in this area. Because the tax revaluation project was financed by the citizens and directly affected nearly all pocketbooks, interest ran high and many people stopped to observe the operations and were curious as to the over-all progress of the revaluation work and the general approach to such a task. The aerial photography became the center of attraction—at least until the new tax values were made public—and needless to say, found many proposing its use, especially representatives of various municipal offices. The water department, having made a close study of the photographs, in a study of its facility extension, was the first to request use of the photos. The city engineer's office followed in turn and was quite happy with the ease with which drainage areas could be estimated for the design of storm drain facilities, and also in the recognition of "paper streets"—streets which had long existed according to the official city map hanging in the engineering office, but which did not exist on the ground.
>
> The project was gaining widespread publicity; anyone in the planning stage of a construction project seemed to learn about the photographs. The local utility company had its engineering staff inspect the photos; it was the answer to a problem which has plagued many utilities in recent years—the problem of acquisition and maintenance of complete, up-to-date maps for use in company planning and construction projects. Real estate men, title lawyers and representatives from a pipe line company found the maps very helpful in their work. The photographs were quite highly praised by a visiting committee appointed by Congress for the purpose of investigating and studying prospective sites for the National Air Academy.
>
> From the city administration's point of view, it, like many others, was faced with serious problems of city growth. In such situations, the photographs help in planning new subdivisions and layouts; they give the over-all view necessary for the selection of new recreational sites and schools; they provide needed data for studies of industrial land, storage facilities, traffic flow, parking and transportation problems. For detailed engineering planning, the photographs are useful to the city engineer for street relocation work

and in laying out by-passes or over-passes to break traffic-flow bottlenecks. Boulevard approaches and exits can be better designed and located. In road development, the photographs indicate the location of property to be served, and what property will be least disturbed by various alignments of the proposed road. In addition, they can be almost constantly referred to in connection with grade and alignment determination on proposed streets and in preparing estimates.

REGIONAL PLANNING, DEVELOPMENT, AND OPERATION

23-13. General. A region is any portion of the earth's surface that can be treated as a unit for any purpose and on any basis whatever. It may consist of a geographic area, a geomorphic area, a physiographic unit, a geological subdivision, etc.

The application of aerial-photographic techniques to the planning, development, and operation of such a unit is simply the intelligent use of the techniques described throughout this book. Any urban areas are analyzed according to the general methods described in this chapter. The various technical aspects of planning, mapping, etc., are accomplished in accordance with the discussions of Chaps. 17 to 22 and 24.

The important things about regional studies are their requirements for both adequate information and effective coordination. Because regions are usually large and complex, the procurement of adequate information is slow and costly if old-fashioned methods are used. Air-photo methods, contrarily, can provide dependable data rapidly and economically. Effective coordination depends upon an early knowledge of the major regional characteristics and their *significant* ramifications, both with regard to place and type. Only with such a knowledge can the proper further studies be assigned their correct priority and inclusiveness. Air photos are almost the only medium through which these early characteristics can be efficiently determined and to which they can be referred.

23-14. Examples of the Use of Aerial-photographic Techniques for Regional Studies. A number of regions have been—or are being—studied primarily by aerial-photographic methods. Projects with which the author is familiar are the Canadian Colombo Plan surveys of West Pakistan and Ceylon,[4] the Engineering Soil Survey of New Jersey,[5] and the current Overthrust operation in the United States and Canada. Other projects have included the Hunting Group Surveys in Iraq,[6] the survey of the Federal District of Brazil,[7] the geological surveys of Newfoundland [4] and part of Angola,[4] engineering surveys in Maine [8] and Indiana,[9] and Operation Tectonic in Canada,[1] as well as various specialized efforts by various governmental agencies in North America and abroad.

The Canadian Colombo Plan surveys were designed to stimulate proper future planning for, and development of, natural resources in certain "have-not" or severely underdeveloped countries. The objective was the rapid provision of adequate, dependable information. The methods chosen were the various aerial-photographic techniques.

The survey of Pakistan included the following:

1. Aerial photography (1:40,000) and uncontrolled mosaics (1:40,000, 1:253,440) of some 300,000 square miles
2. Reconnaissance geological and agricultural soils and land-use mapping of some 165,000 and 110,000 square miles, respectively (including 18 and 4 man-years of selective field check, respectively)
3. Preparation of multicolored, fully printed, and scribed map sheets
4. Preparation of reports on geology, land use, and soils
5. Completion of some 40,000 square miles of mosaics and 1,350 miles of planimetric maps

The entire result, although a deliberate attempt was made to keep it at a proper level of generalization, ended by providing an amount of detail greatly in excess of the original anticipation and far beyond the usual ideas of reconnaissance.

The Colombo Plan Survey of Ceylon involved:

1. Aerial photography and mosaics at 1:25,000, covering the entire island
2. Preparation of a reconnaissance tectonic map of the entire island, including broad rock differentiations
3. Execution of certain forestry surveys and the establishment of proper air-photo survey procedures
4. Preparation of certain factual reconnaissance

[4] Contractor for all these was The Photographic Survey Corporation.

[5] Undertaken by the Joint Highway Research project sponsored by the U.S. Bureau of Public Roads, State Highway Department of New Jersey, and Rutgers University.

[6] Contractor was Hunting Aerosurveys Limited.

[7] Contractor was D. J. Belcher and Associates, Incorporated.

[8] For the Maine State Highway Department.

[9] Undertaken under the auspices of the Joint Highway Research Project sponsored by Purdue University and the Indiana State Highway Department.

and preliminary studies on selected river basins, such studies to involve mapping of land use, agriculture, geology, drainage, ground water, forestry, damsites, reservoirs, topography, etc.

5. The preparation of reports on the river basins

The Engineering Soil Survey of New Jersey, probably the first *detailed* air-photo soil survey ever undertaken, covering 7,000 square miles, was described by the author (106) in 1951. Certain of its aspects are covered in Secs. 24-17 and 24-18. Holman and Nikola (79) have also reported on the survey.

The Overthrust program, undertaken in Canada and the United States for the benefit of a number of mining companies, comprises some 405,000 square miles of structural, petrological, and drainage mapping, as well as mosaicking and overlaying.

The Hunting group program was described by Coleman and Rogers (37).

The survey for the Federal District of Brazil covered approximately 25,000 square kilometers and included numerous considerations of terrain.

The geological surveys of Newfoundland (1952), Operation Tectonic (1955–1956), and Angola (1954) were merely smaller versions of Overthrust.

MILITARY PLANNING, DEVELOPMENT, AND OPERATIONS

23-15. General. Military-planning, developmental, and operational studies find exceptionally valuable tools in the various aerial-photographic approaches.

Generally, wartime military operations are relatively brief, as well as preoccupied with the necessity for realizing their varied and shifting objectives in a minimum of time. After military operations have ceased, there is generally a withdrawal to the home bases, a rehabilitation and refurbishment period, and finally a resumption of study for the future.

In both wartime and postwar situations, aerial-photographic methods are of exceptional value.

During wartime, air-photo techniques—*properly applied and efficiently organized*—supply the speed that is essential to effective military defense and offense. Perhaps this attribute was responsible for the broad and varied application of all aerial-photographic methods during World War II and the Korean War. Indeed, as has so often happened in the past, the ill wind of war wafted some good—in the case of the aerial-photographic field, a remarkable stimulus to the entire theory, application, and development of aerotechniques.

In postwar periods, aerial photographs often provide the *only* approach. Areas of interest are no longer accessible at will, if at all. Discretion of study, planning, intentions, emphasis, etc., is of paramount importance. In areas previously mapped and investigated, the items of interest or direction of study may have changed, or the area itself may have different characteristics. The aerial-photographic approach is inherently discreet, and it requires no access.[10] Further, it has the advantages of speed and accuracy and, even for poor photographs, a measure of dependability and accuracy.

23-16. Classification of Military Studies. Military studies *that deal with terrain as a major factor* may be divided into two broad types, logistical and operational, depending upon their basic emphasis. Another division of military studies is the old stand-by "miscellaneous," to cover that class which proves the value of any system by being its exception.

All the major classes may be divided upon the basis of their primary interests, subinterests, objectives, etc. A tentative classification follows:

1. Logistical studies
   - *a.* Terrain appreciation
     - (1) Integrated and general
     - (2) Specific (siting; transport and trafficability; military resources and materials; landing and loading; vegetation)
   - *b.* Cultural appreciation
     - (1) Integrated and general
     - (2) Specific (service and transport facilities; resources; socioeconomic)
2. Operational studies
   - *a.* Terrain appreciation
     - (1) Integrated and general
     - (2) Specific (armored trafficability; defense; offense)
   - *b.* Evaluative and intelligence (enemy intentions, capabilities, dispositions; offensive results; camouflage)

[10] The air-photo approach obviously requires air photos. For inaccessible areas, the author assumes that some type of photographic cover exists, and is available, as it so often is. If no photographs are available, the approach is impossible, or at best loses its discretion.

23-17. Nature of Logistical Studies. Logistical studies are concerned only with the efficient supply of modern military forces. "Only" is, perhaps, a poor word, for the efficient supply of modern military forces—ground, naval, and air in all their heterogeneity—is an unbelievably complex proposition. An effective logistical system must not only support the direct fighting forces, it must also support the "supporters," the captured, the wounded, the sick, the civilian communities under its control, the replacements, etc. It must order, transport, record, stock, and supply, at numerous levels and shifting points, all that infinity of items required by the military-civilian complex. These include, broadly, fuel, oil, and lubricants, spare parts (from aircraft engines to jeep lights), personal equipment, weapons, tools, ammunition, medicines, special supplies, special equipment (ordnance, signal, medical, etc.), recreational items, rations, water, clothing, etc. A logistical system must also encompass all the services and service facilities that are ancillary to the supply of these items: maintenance and repair centers (ordnance, engineer, signal, quartermaster, aircraft, ship), supply-distribution centers of all types, port and harbor facilities, and transport systems. Finally it must provide for the rehabilitation of towns, villages, factories, and populace, as well as for housing of replacements, burial of the dead, establishment and maintenance of sanitation, etc., *ad nauseam*.

Indeed, when one views the activities that properly fall within the scope of a logistical system, one wonders why there are any men left to fight or, since it requires such trouble for their support, why there is any time to do so.

With such a variety of concerns and such a complex of applications, logistical study should cover all the factors that might conceivably affect its operations to a significant degree. Included among such factors are two—terrain and culture—which can be partially studied by air-photo methods.

23-18. Application of Aerial-photographic Techniques to Studies of Terrain and Culture as Logistical Factors. A discourse on the applications of aerial-photographic techniques to studies of terrain and culture as logistical factors would merely be a repetition and belaboring of previously presented information (Sec. 23-1). To one who has read this book, and in particular this chapter, the applications should be clear. Essentially, the applications are similar to those of urban analysis. The emphasis has merely changed and, as mentioned in Sec. 23-15, what other ways are there besides air photos in many areas of the world, and what faster and more discreet methods anywhere?

Of course, it is not permissible to discuss such projects as may be currently under way regarding the use of air photos for terrain and cultural military studies. However, it may be interesting to quote from a research proposal for a trial project that the author once submitted to a division of the Armed Services of the United States.

1. *Designation and Title.* Rapid preparation of operational and logistical terrain maps from uncontrolled aerial photographs.

2. *Objective.* Evaluation of qualitative air-photo interpretation as a means of rapidly preparing maps containing the essential elements of operational and logistical information (except detailed topography).

3. *Military Application.* In many areas, terrain intelligence is meager or altogether lacking. It is possible, in many of these areas, to procure limited uncontrolled aerial photography before the commencement of operations. (Much is already available.) From these photographs, using qualitative air-photo interpretation, simple terrain (not topographical) maps can be prepared for a variety of purposes and issued to combat units in advance of movement. It is conceivable that such maps can be prepared (to various degrees of detail) within periods ranging from 12 to 72 hours. Sample types of information might be the following:

a. Areas of definite hard standing and/or good drainage
b. Areas of poor drainage (permanent or seasonal)
c. Definite sources of construction material (sand, gravel, clay, quarry rock)
d. Location and evaluation of sites for airfields, depots, routes, and bivouacs
e. Definite location and evaluation of engineering problems associated with such sites
f. Road-network evaluation
g. Tank trafficability
h. General geology
i. General soils (texture, ground-water table, and depth to rock)
j. Beach-landing conditions
k. Salient terrain features

It is emphasized that this information is to be derived from aerial photographs *alone* and with no other reference material.

It would be odd indeed if any military organization worthy of the name neglected the manifold opportunities for creating complete, integrated,

and standardized terrain and cultural logistical maps that air-photo methods have put in its hands. Some might ask where one gets the photos. The answer is that most of the photographs already exist and are available. While scales, qualities, and capabilities vary, they are all usable to a degree.

23-19. Nature of Operational Studies. Military operational studies are intended to facilitate the planning and execution of military offensive and defensive maneuvers; the estimation and prevention of equivalent enemy operations; and the evaluation of enemy intentions and capabilities as well as the results of one's own offensive.

In so far as air-photo techniques are concerned, they may be concentrated either upon appreciation of the terrain as a medium for offensive and defensive maneuver or upon an evaluation and analysis of human activity.

As with all other similar studies, terrain appreciation may be integrated or specific. For example, the terrain mapping might be done from the sole standpoint of trafficability for armor, trafficability on beaches, topographic fields of fire, possibilities for shelter, visually commanded areas, location having defensive possibilities, etc.

Evaluative and intelligence studies are concerned with the analyses of features, objects, and revisions of the terrain that, properly analyzed, give clues to the intentions, dispositions, strength, capabilities, supply points and routes, and material resources. Such studies may be considered of a "semi-general" nature. Other more specific evaluative studies are concerned with the results of bombing missions, air strikes, shelling programs, or naval attack carried on either by one's own or by enemy forces. Or, alternatively, the emphasis may be placed upon some very specialized thing such as camouflage detection, long-range photography, etc.

23-20. Application of Aerial-photographic Techniques to Military Operational Studies. The applications of air-photo methods to military operational studies have been, and are, so numerous, variable, and interesting, that it would be quite easy to devote a chapter, or even a book, to their discussion and illustration. The military uses were the first uses of aerial photography, dating from balloon photography during the Civil War era to the massive and complex programs of today.

Unfortunately, space and the general nature of this book do not permit such a discussion. In fact, these considerations, combined with the fact that many of the current and past studies are classified information, limit this section to such references as the author knows are more or less available to the general reader and of particular current interest or pertinence.

Captain Ragnar Thoren, in the Report of Commission VII, of the American Society of Photogrammetry, has presented a 23-page summary of photo interpretation in military intelligence (197). In this article, Thoren covers aerial-photo reconnaissance, ground-photo reconnaissance, and photo interpretation, together with their strategic and tactical applications. Equipment and teaching are also discussed. It is a well-written and interesting general article of special interest for its treatment of long-range photography with cameras of 100- to 240-inch focal lengths, one of Thoren's particular specialties. However, Thoren mentions only long-range photographs that provide exceptional detail (belt loops on a man's trousers) at a distance of 1 mile. Military photographs need not be so concerned with such minute details, and the author is personally acquainted with long-range photographs of militarily significant and identifiable objects having dimensions of 2 to 25 feet that were taken from distances of 5 to 30 miles away.

Truesdell (206) has reported on some military studies in ecology.

O'Neill and Nagel (142) have discussed the use of a special variable high-intensity-light table that can be used with dyes constructed with actual vegetable and mineral pigments to investigate camouflage.

Brock (27) gives a fair amount of attention to the physical aspects of aerial photographs as they are related to military interpretation.

The Cornell group (43) has completed a comprehensive nine-volume set of completely illustrated air-photo terrain patterns.

The author has completed some reports on the relations between air-photo patterns of beaches and the trafficability thereon (13, 14, 43).

The various military agencies of the United States, Canada, Great Britain, and other countries have published many other manuals and papers on aspects of military operational interpretation.

Doubtless, these cited publications represent only a small fraction of the investigated applications that are, or shall some day be, available to the general reader.

24 SOME PRACTICAL CONSIDERATIONS AND MISCELLANY

24-1. Scope of Chapter. This chapter is concerned with a variety of topics, some of which have practical significance and others that have either current interest or important supplemental value to the body of this book.

In general, the material of the chapter is grouped under three subject headings: (1) some aspects of photogrammetry, (2) some practical considerations associated with qualitative techniques, and (3) some matters of current interest.

Much of the material that appears under the last two headings represents the opinions of the author. Like most opinions, these are not irrevocably solidified. Rather, they are subject to change in the light of further and better discussion.

The material on photogrammetry is not intended as anything more than a general familiarization with certain important elements, plus a few miscellaneous practical comments. Since it is, to a degree, extraneous to the purpose of the book, it is presented in smaller type. For detailed treatment, the reader is referred to other references.

SOME ASPECTS OF PHOTOGRAMMETRY

★ 24-2. Aerial Photographs Are Perspective Pictures. It should be evident that a vertical aerial photograph does not depict the land in its true shape, scale, etc. Instead, it provides a distorted picture of the land, the amount and nature of distortion depending upon the geometric position of the camera lens-plate combination at the instant of exposure; factors inherent in the aerial-photographic method; and the nature of the terrain being photographed.

The distortions related to the geometric position of the lens-plate combination are commonly described as distortions due to "tilt" in the x and y directions; i.e., the airplane and/or camera are not moving in a plane perpendicular to a radius from the earth's center. Although much advance has been made in the reduction of tilt, it is practically impossible to eliminate it completely. However, there are ways of eliminating or compensating for its effects, as well as techniques that can afford to ignore small amounts.

The distortion due to factors inherent in the aerial-photographic method are related to (1) variations created by the instability of photographic paper and film, (2) optical properties of the camera lens, and (3) the inevitable radial distortion involved when an area is viewed from a point. The first two causes of distortions are extremely complex, and bothersome to all photogrammetrists; they are being reduced by research. The third cannot be reduced, but it is often an aid rather than a hindrance (Fig. 24-1 and Sec. 24-5).

The distortions due to the nature of the terrain being photographed are related to the variations in distance below the airplane that are created by uneven terrain, together with the additional effects that such uneven terrain has upon radial distortion (Fig. 24-2).

The successful preparation of accurate topographic or planimetric maps from aerial photographs depends upon the elimination of, or compensation for, these distortions. This brings up the matter of the stereo model.

★ 24-3. Creation of the Stereo Model. Stereoscopic photographs were discussed and illustrated in Sec. 1-9. There it was stated that they were essential for effective photographic interpretation. They are also essential for effective topographic mapping.

Assuming that two pictures (a "stereopair") are taken (Fig. 1-4) so that a certain portion of ground is photographed twice, it is possible to substitute a plate-lens combination for the position of the photographic plane at the instant of exposing each of the pictures. Further, it is possible to recreate the terrain as it appears on each picture. This is illustrated in Fig. 24-3.

There are various types of apparatus in current use that recreate the general situation illustrated in Fig. 24-3. These may be generally classified as "optical-projection" types and "mechanical-projection" types. Hunting Aerosurveys (82) describes the basic principles of their operation in a rather clear manner. For the optical projectors, they say,

"Our problem is to obtain a true-scale plan from the information given in the pictures. In the stereoscopic

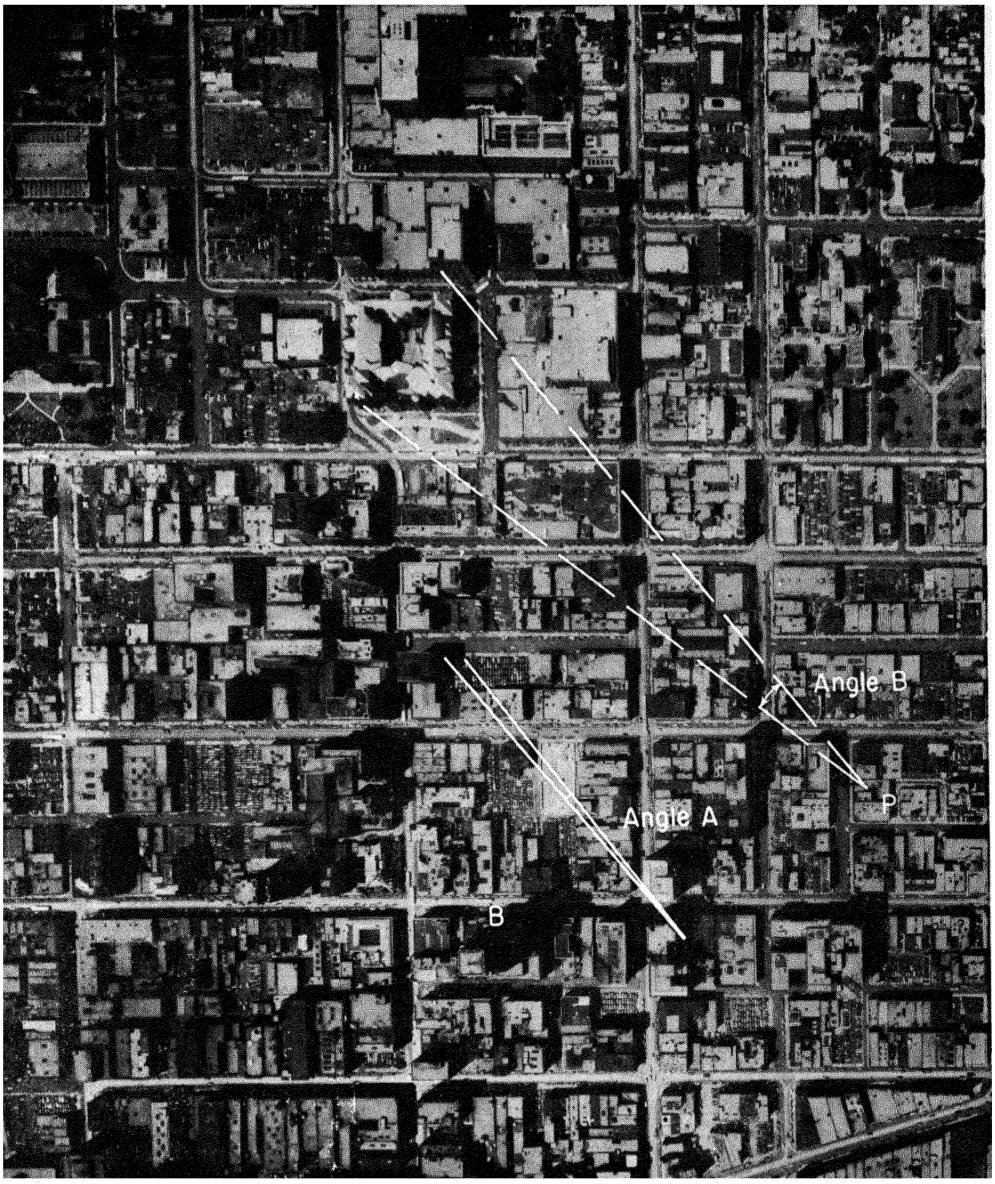


Fig. 24-1. This picture illustrates the radial distortion that is inherent in vertical aerial photography. Note the outward lean of the buildings (such as *B*). This lean increases progressively in all directions from the plumb point of the air photo *P*, near the lower right edge of this figure, the other half of the photo having been cropped. Figure 24-2 illustrates the reason for this distortion by showing that *AB* appears as a line on any photo that is not exactly centered over it. This figure also illustrates the use of a photo as a plane table (Sec. 24-2). Angles measured from the plumb point *P* are true angles, while those measured from any other point *A* are not, since the top and bottom of the building showing an angular separation from *A* are obviously in the same plane.

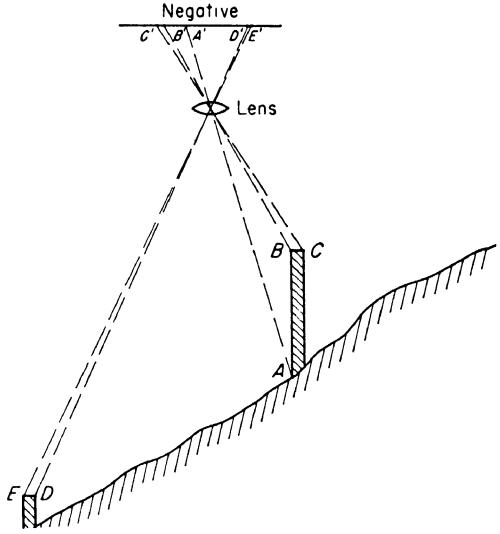


Fig. 24-2. This diagram illustrates the cause of radial distortion (see Fig. 24-1) and the distortion caused by the nature of the terrain being photographed. Note the scale change on the negative of *BC* compared to *ED*.

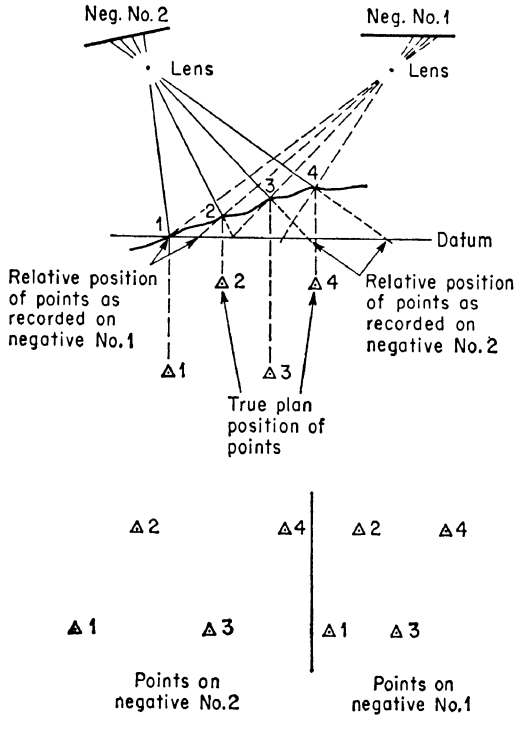


Fig. 24-3. Recreating the terrain as it appears on each picture. [*After Hunting* (82).]

plotting method, this is done by putting the two pictures back in the same relative positions as they occupied in the air and reprojecting the light rays back through suitable lenses. It is not necessary to have the pictures the same distance apart as they were in the air; so long as the directions of the re-projecting light rays remain the same we can successfully reproduce in miniature conditions identical to those occurring in the air.

"[Figure 24-4] shows how this can be done; the pictures are printed on transparent plates like lantern slides, a source of light is placed behind each and a lens of suitable focal length is put in front so that rays from points 1, 2, 3, and 4 emerge at the same angles as the original rays which entered the air camera to form the picture.

"[Figure 24-4] also shows that if the two projectors are set at exactly the same angles of tilt as the air cameras had, then the rays from the left projector will intersect those from the right so that points 1, 2, 3, and 4 occur in the same relative position in space as they did in nature (but to a much smaller scale).

"Referring back to [Fig. 24-3], it will be realized that every point on the ground (in addition to our chosen points 1, 2, 3, and 4) will be photographed and represented by a pair of intersecting rays when we re-project the photographs under the conditions of [Fig. 24-4].

"In an optical projection apparatus one projector is fitted with a red filter and the other with a blue filter, so that the coloured rays shown in [Fig. 24-4] are actually made use of in practice. The person operating the apparatus wears spectacles of the same complementary colours so designed that his left eye sees only the rays from the left-hand projector, and his right eye sees only those from the right-hand projector. This arrangement gives the operator a stereoscopic (i.e., 'solid') impression from the two projected pictures, enabling him to see the position of points 1, 2, 3, and 4 actually occurring in space. The resected picture which the operator sees and works on is referred to as a stereoscopic model."

The various types of apparatus that employ optical projection to create the stereoscopic model are equipped with controls and devices that enable the operator to both alter the scale of the model and measure the relative heights (to scale) of any points within the model (Fig. 24-4).

Mechanical plotters utilize metal rods, instead of light rays, to recreate the proper situations existing at the time of photography (Fig. 24-7).

★ 24-4. Necessity for Ground Control. After a photogrammetric operator has recreated the photographic situation at the instant of exposure for two successive overlapping pictures, i.e., after he has created the stereoscopic model, he is in a position to draw a topographic map, *provided that he has adequate ground*

control. Without ground control, he does not know the scale of his model, nor does he know whether the entire model is divergent from the horizontal. All he knows is that he has a perfect stereoscopic view of the terrain. With ground control, he can adjust the model so that it is both horizontally referred and at a proper proportionate scale to true ground distances. Quoting Hunting Aerosurveys (82) again:

"Once given this information, the operator can make further adjustments to his apparatus so that the positions and heights of these four points bear the same ratio in his model as they do on the surface of the earth. He is then able to plot the true positions and read the heights of any other points covered by his stereoscopic model. That is to say, he can make a map of the area covered by the two photographs and he can draw contours of the area by setting the plotting table at heights corresponding to the scale of the 'model' and then 'steering' the reference mark round the landform.

"From the foregoing it appears that the mapping of an area of land by photogrammetry requires a series of stereoscopic pictures, each pair of which must be provided with four 'control' points surveyed on the ground. In practice, however, the number of points is usually less than four per pair of photographs [as shown in Fig. 24-5]. It will be seen from this that the stereoscopic photographs are taken in strips, so that each pair of photographs has another pair overlapping it on either side. Moreover, where a wide area is being mapped, each strip of photographs overlaps the next so that each single control point can serve as many as four pairs of photographs."

For medium and small-scale mapping, ground control can be reduced considerably from that shown in Fig. 24-5. The process used is one of "aerial triangulation," also called "bridging."

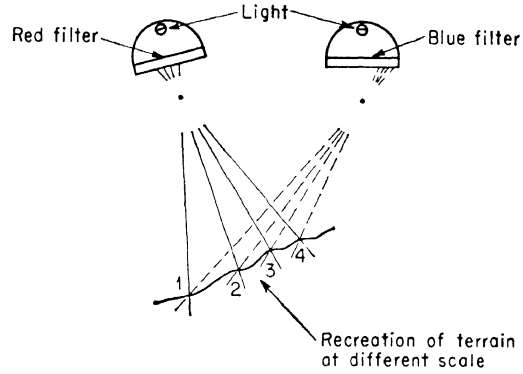


Fig. 24-4. Method of optical projection. [*After Hunting* (82).]

In optical projectors, bridging utilizes a chain of optical projectors arranged so that a portion of each stereoscopic model is common to three successive projectors. By this means, a properly controlled model may be used to orient and scale the next model by stereoscopic adjustment. The following models can be brought into adjustment by occasional, properly located ground control. A typical bridged photo-control set-up is indicated by Fig. 24-6.

In mechanical projectors, although only two projectors are used, bridging is accomplished by measuring tridimensional coordinates on a properly controlled model and resetting these coordinates on the next model (Fig. 24-7).

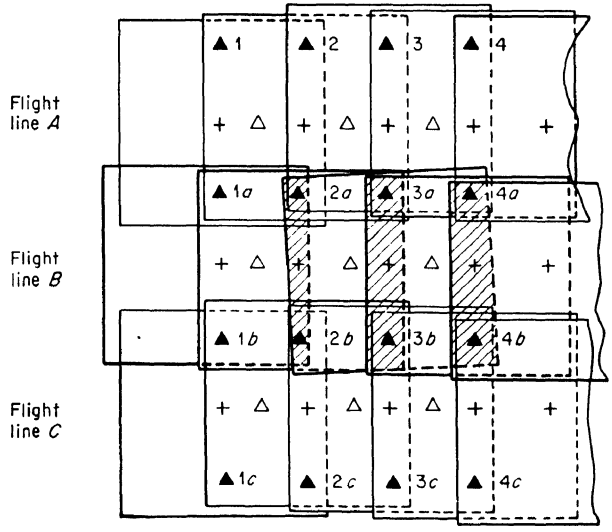


Fig. 24-5. A typical ground-control setup (filled triangles). Points 2a, 3a, 2b, 3b serve multiple photos. Points indicated by the open triangles are desirable for high-precision work but can otherwise be omitted. [*After Hunting* (82).]

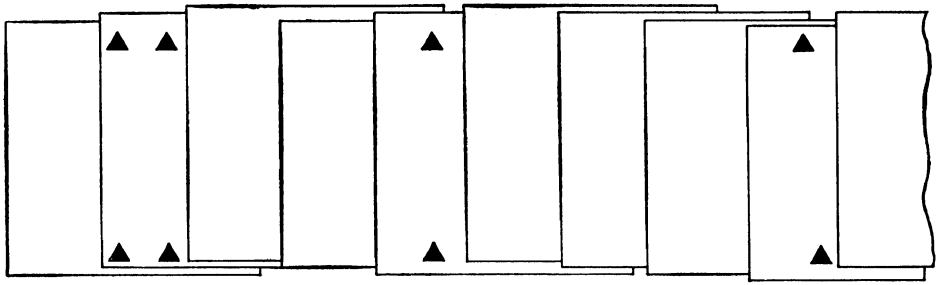


Fig. 24-6. A typical "bridging" setup, in which the ground control has been substantially decreased. [*After Hunting* (82).]

★ 24-5. Preparation of Planimetric Maps. So far in this section of the chapter, discussion has considered only topographic maps and their preparation using stereo-plotting instruments. However, there are many instances where both terrain and requirement are such that topography is not required but accurate planimetry is. Such planimetric, or "base," maps can be prepared without stereo-plotting instruments at considerable saving of time and money.

The fundamental basis for the relatively simple preparation of planimetric maps is the fact that every detail appearing on an aerial photograph lies in the same angular position, as measured from a central point of the photograph, as it would have if measured from the same point on the ground (Fig. 24-8). Extracting from Hunting Aerosurveys (82):

"We can therefore use the centre of our photograph as though it were a kind of theodolite or plane-table station. All the methods of radial line plotting are derived from this principle.

"[Figure 24-8] shows how a number of vertical photographs can be linked together in a manner similar to a triangulation net based on rays emerging from the centre points to corresponding points of

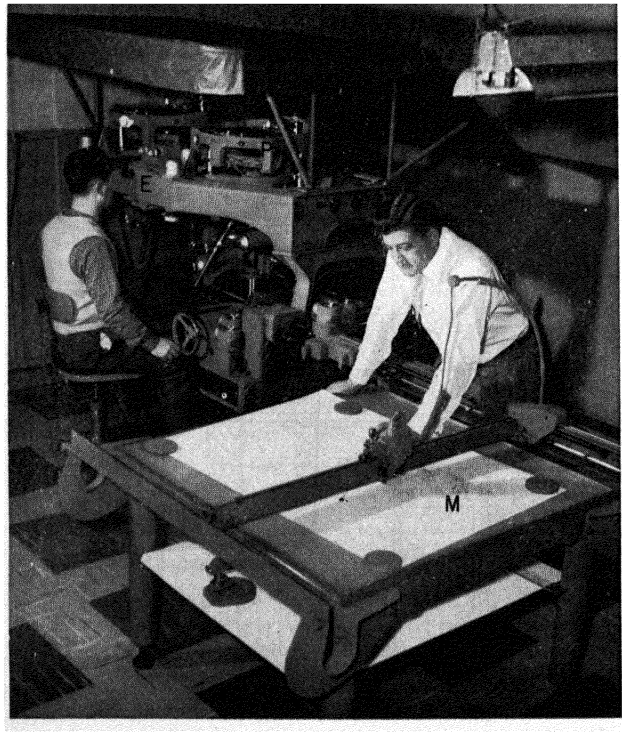


Fig. 24-7. A high-precision mechanical plotter showing the negative plates (dispositives), metal rods *R* replacing the optical rays, operator's eyepieces *E*, and the remotely drawn map *M*. (*Photographic Survey Corporation.*)

detail which occur on three adjacent photographs. These points of detail are chosen on the photographs (not on the ground) and are usually known as 'minor control points.' Any number of vertical photographs can be linked together in this way provided there is a common area between three adjacent photographs. Such a 'radial triangulation' can be built up without any ground control whatsoever and will be consistent in scale; the distance between any two points on the ground within the radial line plot will be sufficient to give the true scale of the whole since the two control points can also be intersected by rays and their positions on the plot determined.

"Once the scale is found in this manner the whole radial line plot may be enlarged or reduced to the required scale. If this is done we are in a position to make a map, since all the angles remain the same and we can intersect as many points of detail as we require by rays from any two centre points. In practice it is usual to intersect a large number of intermediate points (additional to the 'minor control' points); these are termed 'detail points' and are shown [in Fig. 24-8] by small crosses.

"The topographical detail is then filled in by tracing onto a transparent material placed over the photograph after local adjustment for scale between 'detail points.' Alternatively, the detail may be traced direct from the 'rectified' photographic enlargements, the scale of the enlargements being governed by the 'minor control points.'

"The accuracy of the resultant map will depend mainly on whether the photographs were all taken with the camera axis vertical. No technique of aerial photography has yet been devised which will ensure that truly vertical photographs are obtained from an aeroplane in flight; it is, however, usually possible to keep the camera axis within 2 degrees [1] of the vertical during photography and it can be shown mathematically that this degree of tilt of the vertical axis does not seriously impair the accuracy of mapping by the radial line method provided the terrain relief is not excessive in comparison with the flying height."

There are also semimechanical ways of producing a radial-line plot, such as the slotted template (Fig. 24-9). These methods have an advantage over the graphical approach in that, once set up, the scale of the plot can be adjusted to any scale within the limits of the slot lengths.

★ 24-6. The "Rectified" Photograph. It has been said (Sec. 24-2) that, in practice, tilted photographs cannot be avoided. However, the tilt can be minimized by proper flight instruments, discipline, and stabilizing camera mounts. Any tilt that does occur can be compensated for, in topographic mapping, by stereometric instruments, by the process of reproducing the position of the cameras, and adjusting the stereo model to ground control.

Small amounts of tilt may not have any significant effect upon the accuracy of the radial-line plots (Sec. 24-5). However, increased accuracy of such plots may be desired at times, or very-large-scale plots may be required. In such cases, the process of rectification may be applied to the photography, provided the terrain is such that rectification offers some chance of advantage. Rectification is also used in the production of controlled mosaics.

Hunting Aerosurveys (82) describes the process of rectification as follows:

"The term 'rectifier' is somewhat misleading as none of these instruments will rectify the actual perspective of the photograph; they merely serve to compensate partially for some of the effect present in a tilted picture. In order to explain what the rectifier can do, let us consider two aerial photographs of a perfectly flat piece of land on which four roads form a rectangle.

[1] Recent methods and devices are reputed to maintain the axis within one degree.

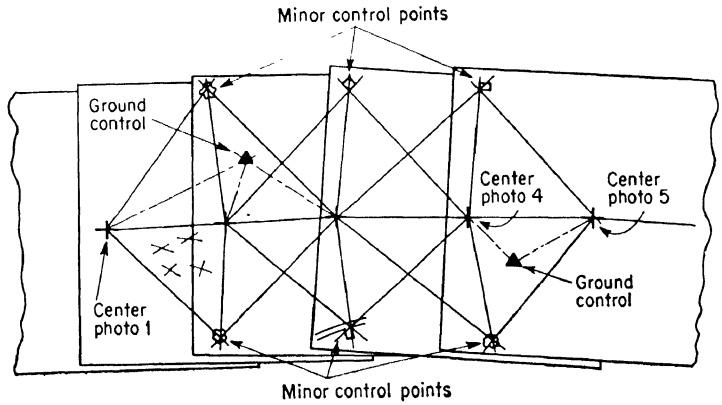


Fig. 24-8. An illustration of the method in which a radial plot is built up. Ground-control points *A* and *B* are those identifiable on the photograph. They are intersected by lines from the principal points of three photographs. Minor control points—identified on successive photos—are intersected from at least three principal points. [*After Hunting* (82).]



Fig. 24-9. A slotted-template assembly of a radial-line plot. The conical covers protect control points. (*Photographic Survey Corporation.*)

"If we take one photograph with the camera truly vertical, as in [Fig. 24-10*a*], we shall obtain a picture having the same proportions as the ground itself, and our rectangle of roads will appear as a rectangle on our picture.

"If, however, we take another photograph with the camera axis tilted, we shall get a picture which is larger in scale at one end than at the other. Therefore, our roads will no longer appear as a rectangle, but will appear as shown in [Fig. 24-10*b*]. In other words, the rectangle appears 'distorted' in the picture.

"What the 'rectifier' does is simply to restore the distorted rectangle to its true shape; it does this by printing a new picture (called the rectified print) onto a tilted table [as shown in Fig. 24-10*c* and *d*].

"For maintaining sharp definition, it is a necessary condition that the planes of the negative, the optical axis of the lens, and that of the plan-board must meet in one line. The practical application of this principle is incorporated in all fully automatic rectifying enlargers.

"The above remarks concerning the rectifier and what it will do are true only so long as the ground photographed is absolutely flat. Photographs of hilly or mountainous country cannot be properly rectified. . . . Photographs of flat marshland, plains, or deserts can be rectified very well; photographs of country with low hills may be rectified with some success, particularly if the photography is done from a high altitude; but photographs of mountainous areas will not be much improved by rectification.

"From this it is clear that rectification has only limited applications in practice. As flat areas of limited extent are more common than large areas, the rectifier as an aid to mapping is more often used in connection with large-scale photographs in which the area covered on any one picture is small. (The word 'flat' is not intended to mean horizontal; rectification of a sloping area is quite successful provided the whole area is at the same slope within one photograph.)

"A simple method of revising existing maps has been built up on this basis; the existing map is used as control and each photograph is enlarged and rectified at the same time so that as far as possible the detail on the photograph fits corresponding points of detail on the map. The nearest points which are common to both map and photograph are used to obtain a local fix and the new detail is then transferred by direct tracing, or 'stylo,' with a steel point, and transfer paper interleaved between photograph and map.

"If carried out with skill and intelligence, this method is reliable enough for the revision of existing maps and plans up to a scale of 1:2,500. It is not, of course, as accurate as the work produced by stereo-

plotting machines, but it is speedier and much less expensive."

24-7. Preparation of Mosaics and Photo Lay-downs. In Sec. 1-3, the three general types of these presentations were defined. As discussed therein, they represent quite different products.

The "controlled mosaic" requires that the terrain and photography be suitable for rectification. Control for rectification can be obtained from survey data (if they exist in sufficient density), radial-line plot, or slotted-template assembly. After the photographs are rectified, they are carefully assembled *on a stable base to control points plotted on that base.*

The "scale-ratio mosaic" also requires suitable terrain conditions and topography for best results. Scale factors for projection printing are selected from existing map distances, radial-line plot, or slotted-template assembly. The individual negatives are projection-printed to these scale factors; i.e., although the prints are not corrected for tip and tilt, they are brought to a common scale. They are then merely assembled (but not to a plotted control network) to provide the best possible fit and orientation of contiguous photo detail (Fig. 24-11).

The "photo lay-down" is made by assembling unadjusted contact prints to form a pictorial representation of the ground. To provide some measure of control and orientation, the contact prints may be laid to copies of base maps or detail traces brought to the scale of the photography. However, this may not always be done. If the terrain is rough, or the photography not well flown, mis-

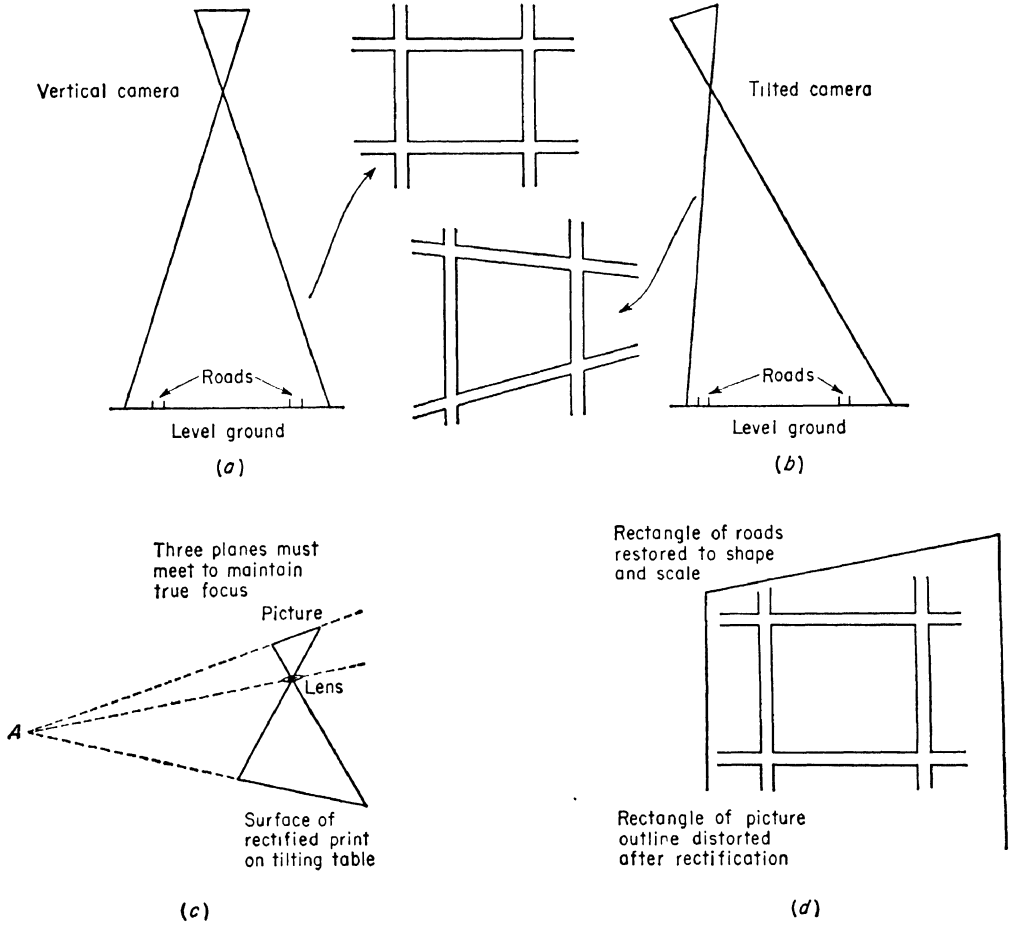


Fig. 24-10. These diagrams illustrate the nature of rectification. See text for description. [*After Hunting* (82).]

matching of detail can occur to varying degrees. The photo lay-down is the simplest and cheapest way of presenting a mosaic. The method of assembly varies, but common types are the "stapled," "waxed," and "cemented" lay-downs, each one referring to the manner in which the prints adhere to the backboard.

24-8. The Photogrammetric Mission from the Photogrammetrist's Viewpoint — Importance and Various Aspects of Proper Planning.[2] Although the relatively new science of photogrammetry provides a means of supplying detailed topographic map information for almost unlimited purposes, fullest use can be made of these services only by the practical application of a photogrammetric organization's facilities to the engineer's specific requirement. Full understanding by the photogrammetrist of the ultimate use to which his mapping is to be put is essential in order that an appropriate result can be produced. Such a condition can be achieved by the establishment of clear specifications by the ultimate user of a photogrammetric map for the guidance of the photogrammetric mapping agency. When supplied with full knowledge of the requirements for particular types of mapping, the photogrammetrist must plan to use appropriate data, materials, equipment, and personnel that will produce the required result. The various phases that make up a complete photogrammetric operation, and the important aspects to be considered in each, are described in the following paragraphs.

The key to successful photogrammetric mapping is good-quality, up-to-date photographic cover. This is now possible through the use of precision aerial cameras in suitable photographic aircraft, good-quality photographic materials, and controlled laboratory processing. For some mapping purposes existing photography, available from government agencies or possibly owned by the contractor, can be used. In most cases, however, new photography suitable for a particular requirement must be obtained. The planning of a photographic mission for such a requirement must be carefully executed. The flight plan must take into account the photo scale which is most suitable for the ultimate map scale and contour interval, plus the coverage that will present optimum terrain conditions and provide disposition of flight lines to facilitate the establishment of required ground control (Sec. 24-11). Experienced flight crews, the best equipment, and careful handling of the photographic materials will provide the basic data from which accurate mapping should result.

The next requirement in the photogrammetric process is survey data upon which the completion of accurate mapping must be based. Control data can be obtained from various sources and by different methods.

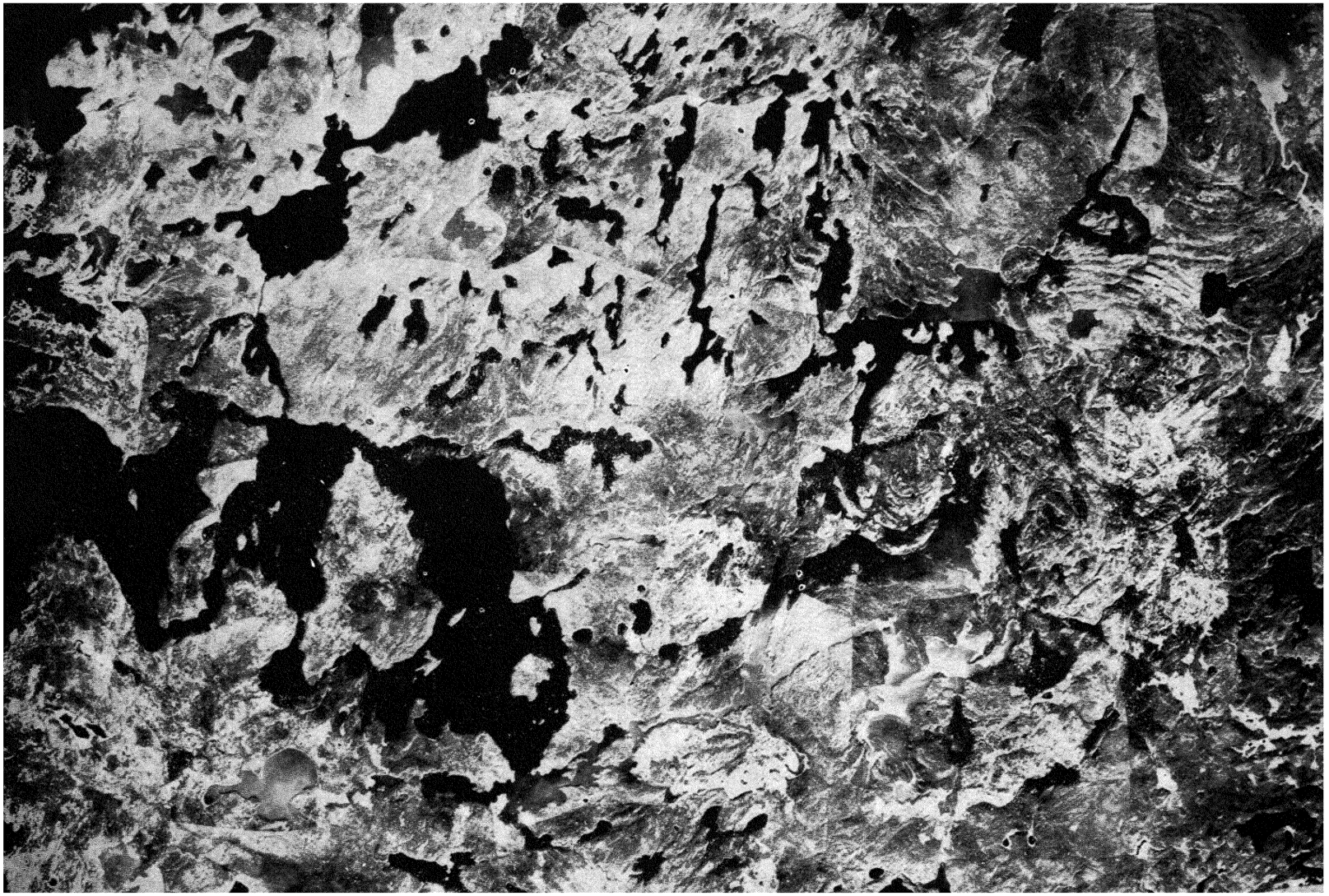
In the case of reconnaissance or preliminary-type mapping, if small- or medium-scale mapping already exists, these latter maps can be used to provide a measure of control for larger-scale maps on which greater detail can be shown. It must be remembered, however, that such larger-scale maps, based on existing mapping as control, will be only as accurate as the original maps, although the detail may be more extensive and up to date.

For accurate engineering plans or maps, compilation should be based on accurate surveys which are made for the purpose of establishing precise photo control or from existing surveys which can be used as reference for photo control in the photogrammetric process.

The amount of survey work that may be needed varies with the mapping requirement and also with the type of terrain in the area to be mapped. It may not be generally realized that surveying to establish control for photogrammetric use *is a specialized type of work*. Photo-control surveyors, apart from being fully trained in the art of surveying, must also have a fundamental knowledge of photogrammetric operation. It is essential that a control surveyor be able to plan a photo-control survey in a manner that will be most economical from a field-operation aspect and at the same time provide optimum quantity and quality of data for the photogrammetrist. Positive photo identification of surveyed points to be used for map control is essential. Although basic surveys established for purposes other than for mapping control may already exist in many areas for which mapping may be contemplated, these data in themselves may not be sufficient for photogrammetric use since the disposition of stations and the difficulty of photo identification usually require some supplementary

[2] This section was written by J. G. Wilkinson, Technical Director, The Photographic Survey Corporation.

Fig. 24-11. A picture of a scale-ratio mosaic covering an area of approximately 750 square miles. The original scale was 1:63,360. Note that the boundaries between the trimmed portions of various individual photographs can be discerned but that there is a match between contiguous photo detail. (*Photographic Survey Corporation.*)



survey. In such cases, it is necessary to extend or break down these basic surveys to fix points of detail readily identifiable on survey-photographic models and selected to give good disposition on stereo models. Considerable economy can be effected by the use of experienced photo-control surveyors to supplement existing surveys or establish new surveys for photogrammetric use. Photo-control surveys have additional value in that, although previously used to control the mapping process, they also provide a permanent reference by photo record for future relocation when required. This is often valuable when detailed ground studies have to be made for specific areas.

Although horizontal and vertical control data in some form will always be required for the correct delineation of the terrain in plan or map form, modern developments in surveying and photogrammetric equipment and methods are reducing many of the problems and costs of photo-control surveys. Better survey instruments permit more accurate measurements, and therefore more precise basic control. Present-day precision aerial cameras now provide photography of excellent quality for use in fine stereo-plotting instruments. The close tolerances of measurement obtainable in these instruments and the application of proven photogrammetric methods make possible accurate instrumental control extension in many cases, thereby saving considerable field work. Whether full ground control is required, or whether minimum ground control supplemented by photogrammetric means is applicable, can be best determined by the experienced photogrammetrist in consideration of the mapping specification to which he has to work.

In addition to the many recent improvements made in the instruments mentioned above, developments have been made in other means of measurement for control purposes. Electronics is playing a large part in these new approaches. Distance-measuring equipment has been developed which can effect considerable savings in the establishment of horizontal fixations for control purposes, especially in areas where orthodox survey methods are difficult or impossible of application. Vertical control in difficult or inaccessible areas can now be established, for preliminary mapping at least, by radar altimetry through the use of Airborne Profile Recorder equipment (APR, Appendix A). The simultaneous use of the APR at the time of a photographic mission provides profile data from which selected spot elevations can be determined for vertical-control use and aircraft clearance, and air-base deviations measured for use in aerotriangulation. Further developments in these electronic measuring equipments are continuously being made, and their application should undoubtedly eliminate many of the present problems of control establishment.

Given the proper tools in the form of good equipment, data, materials, and technical skills, photogrammetry can produce almost any type of mapping, practically to any specified accuracy. It will not do the impossible, however, in that it is limited to applying what can be seen in a photographic image of the ground in map form. The main limitation is the inability of a photogrammetric operator to plot information which cannot be seen. This difficulty arises in the delineation of relief by contours in terrain covered by heavy vegetation or cultural detail obscured by heavy shadow or structural overhang. In the majority of cases, however, careful planning and procurement of aerial photography at times when optimum terrain conditions obtain can eliminate or reduce the importance of such problems.

There is no reason why a photogrammetric map cannot be produced to fulfill any required purpose as long as the whole operation is properly conceived in the first place. This can be done to the mutual satisfaction of client and photogrammetric contractor only by close liaison and understanding between them. Although certain standard specifications apply to photogrammetric mapping, it is often necessary to set up specific requirements for a particular project. For most purposes the type of final product required and the use to which it will be put are the criteria upon which the application of photogrammetry must be based.

24-9. Comparison of Mapping Bases. There are many types of mapping bases and many ways to prepare them. If we omit details associated with the nature of the compilation medium (drawing paper, acetate, linen, photographic paper, etc.), there are only two *major* methods. These are the various ground-surveying approaches and the various aerial-photographic approaches.

The ground-surveying methods involve planimetric surveying with transits, plane tables, theodolites, stadiarods, etc., followed by the reduction of field notes and plotting of details on some medium.

The aerial methods involve the photography of

the subject areas, followed by quantitative and/or qualitative aerial-photographic manipulations and/or exercises, with and without ground control, and plotting of details on some medium.

Ground methods have served mankind well, but, except in certain specific situations, their day is gone. Insufficient speed, accuracy, dependability, and economy have all been eliminated by the advent of proper aerial-photographic techniques. For this reason, practical mapping bases are largely confined to those prepared by aerial-photographic methods, and these are the only types considered in this section.

The various aerial-photographic mapping bases, going from the simplest and least accurate to the most complex and accurate, may be listed as follows: [3]

1. Bases primarily of a qualitative nature
   a. Individual unrectified contact prints and enlargements, or reductions from them
   b. Plain photographic lay-downs
   c. Tracings of pantographic reproductions of the above
2. Bases of a semiquantitative nature
   a. Rectified aerial photographs
   b. Scale-ratio mosaics
   c. Certain controlled mosaics
   d. Certain planimetric plots
3. Bases of a quantitative nature
   a. Controlled mosaics
   b. Certain planimetric plots

The unrectified aerial photograph is the simplest and cheapest base of all. However, it is also the least accurate from a scalar viewpoint because of the various distortions discussed in Sec. 24-2. Consequently, it cannot be used for more than the roughest of horizontal measurements, particularly near the edges. If enlarged or reduced, the nature and dependability of measurement do not change; only the scale does. Of course, measurements of angles from the principal point are fairly dependable (Sec. 24-5). Regardless of these limitations, the unrectified photograph is a very effective and useful mapping base for illustrative purposes. In the reconnaissance stage of any qualitative study, all that is often required is a general layout of geology, drainage, etc., and the unrectified photograph is suitable for this purpose. Also, it is usually available upon short notice and, even if flying is required, is usually quite inexpensive on a unit basis.

The plain stapled, waxed, or cemented photographic lay-down has much the same characteristics as the unrectified photograph. It merely covers a larger area. The chief differences are that horizontal measurements are even more inaccurate and angles can be measured only from the principal points of each component photograph. Even so, the lay-down provides an inexpensive and effective means of depicting qualitative and very rough quantitative factors in a given area. Geology, soils, drainage, damsites, reservoir areas, etc., can be shown in their environmental relationship, and *rough* road distances, dimensions, and areas can be measured. Obviously, the lay-down is a reconnaissance mapping base.

Tracings and pantographic drawings of the above may be prepared to emphasize special features of the terrain or may be used as overlays when the mapped details are so variable and numerous that compilation on a single base would be confusing. Such tracings have all the limitations of the photographic bases from which they are prepared. In addition, their stability variations may cause trouble.

Rectified aerial photographs, if used in the proper type of terrain (flat, Sec. 24-6) and up to the proper scale (1:2,400 to 1:4,800) can be used for scalar and angular measurements with some measure of confidence. For rather small (less than 0.25 square mile) flat areas (urban, deserts, marshland), distances between identifiable points may be measured, new details may be plotted in, and their geometrics analyzed, etc., in a preliminary manner. The use of single rectified photographs is rather limited, but in the right situation (tax mapping, preliminary plant design, etc.) they can prove quite valuable. It is more common to see the single rectified photograph used in conjunction with an existing base map to add details (Sec. 24-7).

The scale-ratio mosaic (Sec. 24-7), prepared from adjusted photographs, may cover a fairly large area with good matching of detail. If the area is topographically suitable and an existing but obsolescent base map is in existence, the map and mosaic may be superimposed and the map brought to date by tracing of details. This application is fairly rare, however, the procedure mentioned in the above paragraph being both preferable and more common. In general, the scale-

[3] These do not include bases that take in topography, i.e., photogrammetrically prepared topographic maps, which are, of course, the best mapping bases.

ratio mosaic is best used as a "picture piece," or qualitative mapping base.

Planimetric maps are prepared by any of the radial plotting methods (Sec. 24-5) and may be of semiquantitative or quantitative nature depending upon the density and accuracy of the ground-control points used in their production. Because ground control is extremely variable, an estimate of the nature of a planimetric map, with respect to its angular and horizontal accuracy, can be obtained only from its producer after he has had an opportunity to evaluate the various factors involved. It is possible, of course, with sufficient ground control, to produce very accurate planimetric bases.

Controlled mosaics (Sec. 24-7), similarly to planimetric maps, may be considered as semiquantitative or quantitative, depending upon the nature of the planimetric control grid to which they are laid and the success of rectification as adjudged in terms of the quality of photography and the nature of terrain. In general, a controlled mosaic should be of suitable quality for the measurement of all but detailed horizontal and angular measurements. It should be usable, for example, in fairly detailed urban analysis where *exact* distances are not required but where reasonably dependable geometrics is necessary.

Of course, as discussed in Sec. 24-8, the exact type of map that should be used for a given type of project and the accuracy of it when completed are matters that must be handled by a competent photogrammetrist in full possession of knowledge about project requirements.

24-10. Vertical Exaggeration. One of the things that must be remembered about the conductance of interpretation by means of stereoscopic-viewing instruments is that stereoscopic models are apparently exaggerated in a vertical direction. Thurrell (199) puts the matter nicely: "Vertical exaggeration is the change in a model surface created by proportionally raising the apparent height of all points above the base level while retaining the same base scale. This is a constant factor throughout the stereoscopic model. . . ."

There is no room in this book for a detailed discussion of vertical exaggeration. The interested reader is referred to recent articles by Miller (129) and Goodale (69).

The point to remember, in using stereo photography, is that vertical details always appear steeper and higher than they really are in relation to horizontal distances.

SOME PRACTICAL CONSIDERATIONS ASSOCIATED WITH QUALITATIVE TECHNIQUES

24-11. Photographic Scales for Interpretation and Photogrammetric Mapping. Aerial-photographic techniques, being applicable to such a broad variety of studies, may be carried out on photography having a variety of scales. There is no one scale that is "best" for all purposes. Some types of project require very large photographic scales. Others are most efficiently accomplished from small-scale prints. If the project is multipurpose in nature, several scales may be most desirable for various facets of study. In this latter case, a compromise usually must be made between the various optimums and project finances or time allotments. Like designing a multipurpose dam, the final design of the project photography completely satisfies no single one of the ideal requirements, but partially satisfies them all.

It must be emphasized that there are so many conflicting project objectives, degrees of interpretative efficiency and capability, combinations of techniques, types of terrain, orders of relief, plane types and availability, and meteorological or climatic limitations, that the final selection of a project scale should be made with the advice of a person both well informed about requirements and well acquainted with the possibilities and alternatives.

If the author were asked to select one range of scales and one scale that would be of most all-around value to the average reconnaissance and preliminary study for all types of studies, he would choose 1:12,000 to 1:25,000 as the range and 1:20,000 as the scale. He would also be very much impressed by 1:15,840 in countries using the English measuring system and might choose it in preference to 1:20,000 in spite of its higher cost, increased handling, and reduced interpretative efficiency (Sec. 24-12).

One example of scale importance is mentioned in Sec. 24-19.

24-12. Speed and Time Associated with Interpretative Studies. It should be apparent that the speed of interpretation and the time associated with the completion of interpretative studies are affected by a great many factors. Among these. there are many that have an important effect. These include scale of photography; nature of vegetative cover; compilation base; working conditions; ability, experience, and regional knowledge of the interpreter; quality of photography;

extent, detail, adequacy, and availability of existing information; type and detail of information desired; nature of report required; and conditions for field check.

The question of scale was considered in Sec. 24-11. But it must be remembered that there is an optimum scale in terms of pure *handling of prints*. The interpreter who must handle many prints at too large a scale not only wastes time but also becomes mentally frustrated because he cannot achieve a sense of reality or continuity and because he has to tie print-edge interpretation so many times.

Tree cover is discussed in Sec. 24-19.

The type of compilation base is important. If details can be compiled by *direct stereo transfer*, considerable savings of time and money are possible. Other methods are bothersome and time-consuming.

Working conditions are important. Adequate, *properly oriented* light, a *large* flat surface, and some measure of privacy or quiet are highly desirable.

The matter of ability and experience is considered in Secs. 7-24 and 24-20.

The remaining factors have generally directly proportional effects.

One final comment. It is unrealistic to expect a qualified interpreter to work directly at *interpretation* for more than *four hours per day*, nor at *analysis* for more than *six*. Interpretation, because it requires an incessant mental process of induction and deduction, weighing of alternatives, and decisions based upon incomplete or lacking data, is mentally exhausting. It literally stupefies. Consequently, it is reasonable to allow two days of time for every one day of direct interpretative progress.

24-13. Special Advantages and Disadvantages of Aerial-photographic Techniques. Like all techniques, those based upon the use of aerial photography have special advantages and disadvantages that are peculiarly their own. Advantages are many:

1. Lack of climatic restrictions. In arctic, subarctic, tropical, and desert areas of the world, climatic factors severely restrict the time and speed of ground operations. The intelligent use of aerial-photographic techniques effectively circumvents the greater portion of these restrictions.

2. Lack of restrictions due to inaccessibility. In remote, mountainous, swampy, marshy, or heavily forested areas, conventional field operations are inhibited. Aerial-photographic methods, in large measure, surmount these difficulties.

3. Flexibility. By their very nature, aerial-photographic techniques frequently indicate the need for, and allow the making of, rapid changes and revisions that would absorb appreciable time and expense if executed in the field.

4. Personnel advantages. Personnel requirements, their attendant maintenance expenses, and the always-present dangers of sickness, disease, and replacement are greatly curtailed.

5. Over-all perspective. The perspective provided by the photographs allows the detection and evaluation of many features that are *actually undetectable* on the ground.

6. Speculative cost increases. The use of aerial techniques often eliminates speculative activities and cost increases involving land acquisition that usually follow the appearance of ground-survey groups.

7. Continuity of information. The aerial-photographic techniques provide a continuous picture of terrain conditions rather than one extrapolated between drill holes and observation points.

Disadvantages are few:

1. Seasonal restrictions on new photography. The occurrence of cloudy, hazy, rainy, and snowy weather and the effect of "leaf out" limit the periods during which *new* photography can be obtained. Of course, proper planning can often minimize such difficulties. Also, existing photography may be used in many cases.

2. Impossibility of use. In some cases, because of dense foliage, poor scale, poor quality, etc., the photographs will not allow a desired project to be completed. Such eventualities can and should be assessed in advance of any detailed study by an inspection of existing photography, or at least an analysis of probability in terms of ecological and climatic knowledge.

24-14. Selective Field Check. The importance of selective check was mentioned in Secs. 1-12, 1-14, and 1-16, and its general importance discussed briefly in Sec. 7-24. This section is concerned with some of its practical aspects.

The key factor in selective field sampling is photo planning. The techniques of interpretation and photo reading can be used to locate four things primarily: (1) representative areas, (2) areas of doubt and/or complexity, (3) existing exposures or indications of conditions, and (4) methods and locations for convenient sampling, including access.

The location of representative areas is accomplished by means of interpretation, and it may be said that an area of uniform photo pattern—*as well as all other similar areas*—has (have) equivalent and relatively uniform field conditions. This was expressed in Sec. 7-13 as the principle of the recurrent soil profile. It should be apparent that sampling in such a representative area is far superior to obtaining a sample with results that are confined to the hole from which it was taken.

Similarly to representative areas, areas of doubt and complexity can be delineated, and their sampling planned for maximum extrapolation and efficiency.

Existing exposures, indicators, locations, and access for sampling obviously can be best evaluated from the stereo view. Such a procedure ensures that sampling is truly representative of something, rather than that frustrating type, a representative sample of an anomalous or local condition.

As to the technique, the author once described the selective field-checking procedures that were used to map the state of New Jersey (106). With variation, the same methods could be followed anywhere.

24-15. Procedures for Regional Mapping. Procedures for regional mapping must vary frequently in detail and occasionally in general. However, the general approach is fairly uniform, and it may be represented again by the discussion included in the aforementioned paper on the soil mapping of New Jersey (106). In outline, the steps involved are as follows:

1. Study of available geological and agronomical references
2. Preliminary study of aerial photographs
3. Selective field reconnaissance
4. Selective field sampling
5. Laboratory testing and summary of data
6. Detailed air-photo study and mapping
7. Transfer of air-photo boundaries to base maps
8. Preparation of reports and tables and reproduction of maps

24-16. Problems of Interpretation in Tropical Regions.[4] Air-photo interpretation in tropical climates is complicated by several factors other than those found in more temperate climates. The major difficulty found in tropical, high-rainfall zones is the canopy of jungle vegetation which obscures the ground surface. The interpretation of soils and ground conditions depends mainly on a recognition of geomorphic landform; the analysis of ground slope; the type of rock outcrop; the examination of drainage patterns; and a detailed evaluation of the vegetative characteristics and actual land use. The interpretative elements of soil tone, erosion pattern, and boundary characteristics are of little value, except where the ground surface can be seen. Even in the latter type of tropical areas, with their reduced vegetative density, interpretation must be cautiously executed in full knowledge of tropical soil formation, the more severe weathering and erosion cycle, and the morphology of various common and unusual landforms.

A majority of tropical regions contain soils that can be classified as residual, colluvial, alluvial, and occasionally aeolian and marine, in origin.

Weathering of the bedrock *in situ* is often very severe in the tropics, producing moderately deep soils overlying variably weathered bedrock. This weathering and breaking down of the bedrock can extend to more than 20 feet in depth, depending on rock type, structure, vegetative cover, slope, and climatic factors.

The soils formed from this process often contain a very high clay content because of the rapid breakdown of the feldspar-mica components of the bedrock. If quartz and other minerals are also present, the final soil-textural description can range from a loamy sand to clay loam, with loam and sandy loam often predominating. Certain areas of the world, for example, in Brazil, exhibit a high clay soil that has all the appearance of a loamy sand: moderately high porosity, fairly steep bank angle of repose, and a scattered, sparse drainage pattern. Actually, however, these materials are clays, which, when dry, agglomerate, and form a sandlike porous structure. This effect is destroyed when the soil is wetted and mechanically worked, at which time it forms a fat, plastic clay.

Tropical areas that have high rainfalls, or once had high rainfalls, also often exhibit an unusual variety of ferruginous soils. The iron content of these yellowish-reddish soils can vary considerably, forming in some cases iron concretion as well as the peculiar pedological rock called "laterite."

The tropical clayey-reddish soils, when studied in the air photos, often exhibit dark uniform tones

[4] This section was prepared by R. A. Dunbar, formerly of the Engineering Division, Hunting Technical and Exploration Services.

due to reddish weathering colors, a moderately well drained appearance with well-defined drainage channels, and an unusually thick forest cover. These factors must be understood to be evaluated correctly from aerial photographs (Fig. 8-2).

24-17. The Designation of Map Units. One of the most bothersome and frustrating problems that faces a photographic interpreter is the making of decisions regarding the inclusiveness of his map units and their designation.

A map unit is simply a division of the terrain appearing on the photo that can be considered, described, and treated as a *whole* unit. Because the aerial photograph shows such a wealth of detail, much of some significance; because surveys for specific purposes usually have specific objectives in terms of information; and because nature has a habit of making things difficult by refusing to create sharp boundaries and simple cases; it is usually difficult to separate the "photographic terrain" into its significant components and designate them according to some logical and useful system.

It was mentioned in Secs. 24-14 and 24-15 that the author participated in the preparation of an engineering soil map for the state of New Jersey. In the process of preparing this map, certain portions of the state were completed before others. It was necessary to issue final reports and maps on these portions before the remainder of the state was mapped. Consequently, it was necessary to devise a uniform system for designating map units—not only in the area completed, but also in the area untouched. Such a system was devised and successfully used. In 1949 its full description was presented by the author (105). Its subsequent application, with slight modifications, by the U.S. Bureau of Public Roads in mapping soils along the Natchez Trace has been described by Smith (176), in East Pakistan by Smith and Koca,[5] and has been used by several groups. For mapping of engineering soils, the author has found this system to have wide applicability and usefulness. For the mapping of geology, agriculture, etc., the essential idea—that of basic genesis, and petrography or geomorphology, supplemented by a *limited* number of descriptive letters and numbers—appears to have merit. For these reasons, a discussion of the system is included in Appendix B.

24-18. Value and Use of Geological and Agricultural Soil Maps. The interpreter who neglects any reasonably dependable and readily available source of information regarding the terrain over which he is working is not only negligent, he is also foolish and wasteful: foolish because he refuses to utilize the efforts of others and gives no attention to their conclusions; wasteful of his client's time and money, because he enjoys doing the same work twice.

Geological and agricultural soil maps are of great aid to interpretation, and every effort should be made to use them as an aid in evaluating the photo patterns. However, such maps also have disadvantages and even dangers. In many cases, they are excessively generalized at best and imaginary at worst. The author, in 1951, discussed at some length their usefulness in the soil mapping of New Jersey (106).

In general, experience at that time, together with experience since then, has indicated that both soils and geological maps are highly useful and accurate in areas of residual soils and rocks, but are often of questionable value in areas composed of nonresidual materials, particularly of complex types and drainage conditions (glacial plains, coastal plains, large fluvial expanses). Frequent exceptions may occur in connection with road alignments where small areas are susceptible to ground check, and particularly where personnel familiar with the regional soils are available. However, if a reliability check of the agricultural information must be made, the cost of such a check, and its correlation, should be weighed against the cost of air-photo interpretation.[6]

24-19. The Question of Tree Cover. It sometimes comes as a surprise to the uninitiated to find that effective interpretation can be accomplished even though trees mask the terrain. They are willing to accept, tentatively, the possibility that interpretation can succeed if the foliage is off the trees. But if the cover is coniferous, or deciduous trees are in leaf, interpretation, they say, is impossible.

Now it is true that foliage inhibits interpretation,[7] but it does not prevent it. The author has

[5] Unpublished report.

[6] Recently, the U.S. Bureau of Public Roads has begun to concentrate its activities on the engineering evaluation of the soil maps produced by the U.S. Department of Agriculture. In all probability this will lead to combined engineering-agricultural maps and reports, rather than solely agronomic efforts. Such efforts will lead to greater progress in terrain understanding.

[7] Thick tree cover severely inhibits accurate photogrammetric mapping. The average heights of trees must be ascertained stereoscopically and must be automatically deducted from all stereometric readings. The tops of the trees are then contoured.

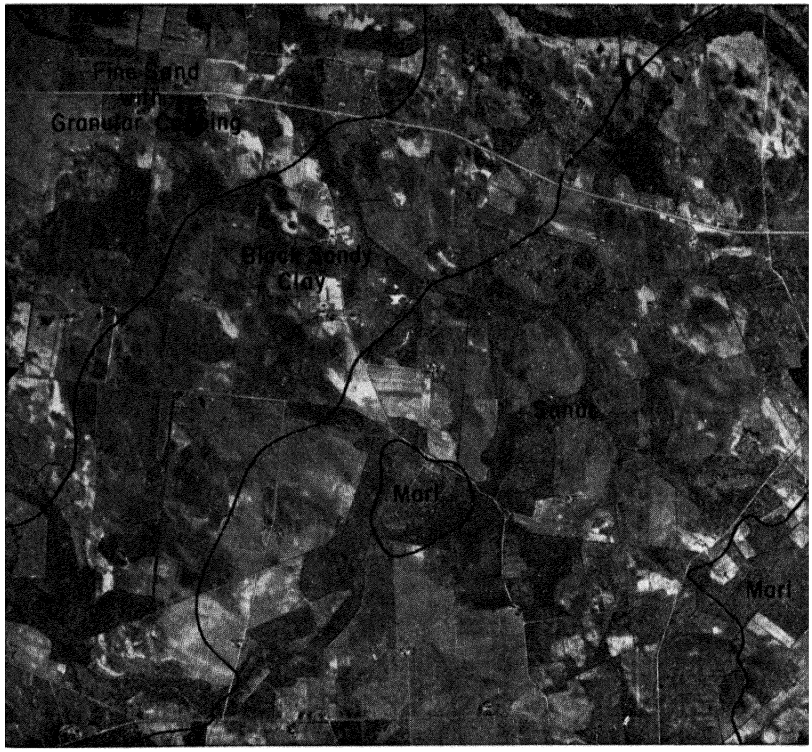


Fig. 24-12. Picture of a geological map (in black on photo) of a portion of the coastal plain of New Jersey. Compare the map with the details as they are revealed in the photo. The map is generally correct and thus serves its intended purpose. However, it does not reveal specific practical conclusions, e.g., drainage conditions, as does the air photo.

seen or conducted highly successful interpretations throughout Canada and the United States, as well as in the jungles of Venezuela, the Philippines, New Guinea, and Ceylon, that depended on landform and surface drainage, supplemented frequently by large-scale erosion features and the vegetation itself. Sections 17-15 and 17-19 describe two specific instances of overburden mapping (!) and materials location under tree cover.

The inhibition imposed by tree cover depends upon many things besides the vegetation itself. Scale and landform are two of the most important. If tree cover is heavy, a scale of 1:60,000 is far better than one of 15,840, for example, in route analysis. The larger scale allows one to see the trees. The smaller one shows the forest and gives environmental perspective. On certain landforms, particularly in the laterized tropics, where functional drainage occurs (Sec. 3-18), the lack of surface drainage under heavy foliage may make interpretation quite uncertain.

24-20. Final Comments on Experience and Training—Value of a Consultant. Much has been said in this book about the extreme importance of experience (Secs. 1-12, 3-19, 4-26, 5-23, etc.) and background (Chap. 7). This section merely repeats the same theme. Interpretation is not a technician's job. Analysis, occasionally. Reading, yes. Interpretation, no. Nor is it an avocation to be developed on gray Sunday afternoons. It is a *natural science* and, like most of these, is usually best practiced by people who have been "through the mill." Only in such a way can the best results be

obtained per unit of time and money expenditure, and only in such a way can possibilities be given their best evaluation and limitations be recognized (Sec. 7-24).

When one wishes to build a structure, one goes to a specialist—the architect or engineer. Then is it not reasonable to expect that when one wants a photographic terrain analysis, or the design of a project for terrain analysis, that one should go to a qualified, experienced interpreter—a consultant, if the word must be said?

24-21. Interpretation Is Interpretation—Not Fact. The writer has heard people complain that interpretation said this and it was really that—or at least not quite this. From this sad experience, they proceed to condemn the entire process—rather like damning honey because one was stung by a bee. Nothing could be more unrealistic. The author knows of no engineer or earth scientist who has not been wrong—many times. Learning from error is the cornerstone of scientific progress. Is not Pisa a monument to some pioneer foundation engineer's "mistake"?

Interpretation is not a demonstrable fact until it is proved as such in the field. It is an *interpretation*, backed by the reputation, experience, and capability of the interpreter. When an interpreter is employed, this is what is purchased—not *necessarily* facts. If one could always determine *facts* from the photograph—and always be *sure* of them—the costs of interpretation would be a lot higher than they are.[8]

SOME MATTERS OF CURRENT INTEREST

24-22. Academicism, Specialization, Generalization. A few remarks are in order on these pregnant subjects. Academicism is defined by Webster's New Collegiate Dictionary as "adherence to conventional manner and theme; formalism." In the minds of most people today, academicism implies overformalism, the expression of simple concepts with complicated words and phrases, as well as overspecialization, compartmentalization, etc. Some academicism, particularly for complicated subjects—of which earth science is one—is inevitable, but it is deplorable to take formalism beyond the point of promoting clarity and understanding. There is a tendency today to clutter aerial-photographic techniques with a specific jargon, a body of specialized discussion subjects, and pseudo-intellectual belaboring of evident and obvious facts that can be considered overformalism.

It is hoped that this tendency will not obscure a basic value of the photographic perspective, i.e., a means of applying a terrain specialty more effectively and a simultaneous means of becoming an integrated earth scientist, both through the medium of the human brain.

24-23. The Questions of Keys. The question of aerial-photographic-interpretation keys has received considerable attention within the past five years, largely through stimulation from various military branches of the United States government. Indeed, the question of keys is very interesting, because it is reflective of the ever-continuing battle between the proponents of better brain usage and those who encourage brain stultification via the use of an ever-increasing array of intellectual labor-saving devices.

First, what is a photo-interpretation key? Roscoe (157) has reported that the accepted United States interservice definition is "reference materials designed to facilitate rapid and accurate identification and the determination of the significance of objects or conditions from an analysis of their photo images." Roscoe then goes on to say that any key is divided into two parts. One of these consists of "an organized collection of annotated or captioned stereograms or other materials illustrative of objects or conditions to be identified." The second consists of a "graphic or word description, which sets forth in some systematic fashion, the recognition features of those objects or conditions."

Now it is difficult to define such a nebulous subject as a photo-interpretation key, but this definition with its amplification is very broad. By it, certainly Part II, and probably Part I, of this book are "keys," a possibility which appalls the author. Also, a book on geomorphology is a key to the ground perspective of landscape. Steichen's "Family of Man" (182) is a ground photo-perspective key to human emotions. French and Vierck's "A Manual of Engineering Drawing for Students and Draftsmen" (60) is a key to the vertical graphical depiction of real objects. This substitution—or at least confusion—whereby the word "key" comes to mean a wide range of methods

[8] Of course, facts *are* revealed through interpretation, analysis, and reading. It is just that they are not always known to be facts, until proved so. The wise interpreter, therefore, will not be overpositive in his statements. He will use what some people may like to call "weasel words." This is not as attractive an approach as that used by the proponents of unflinching positiveness. It is merely more honest.

by which human knowledge is systematized and/or presented (including most manuals and textbooks) does not seem either helpful or wise. There must be some better way of presenting the concept of a key.

To investigate this possibility, it is necessary to examine the subject at greater length by delving into various currently popular terms descriptive of keys. First, there is the "regional key," defined by Roscoe (157) as "concerned with the interpretation of the significant objects or conditions characteristic of a particular region. The importance of illustrating any particular image is directly proportional to the number of times that that type of image appears on photographs of that region"; and a "subject key" is concerned with "the various photo images presented by one subject regardless of the region."

These definitions are both good and valid. According to them, if the broad definition of key is accepted, Part II of this book becomes a subject key, while the geological and land-use *reports* of West Pakistan (Sec. 23-14) are regional keys.

There are other recondite terms in popular usage that describe keys: "dichotomous," "integrated-selective," "mechanical," "positive," "inference."

The dichotomous key is merely one in which the various subjects subdivide systematically, and more or less automatically, so that interpretation is reduced largely to a process of finding the starting point on a chart. An integrated-selective system is somewhat analogous, but the user has an opportunity to exercise his judgment to some extent in selecting from more than one starting point and subdivisional point. A mechanical key is just that—a punch-card, electronic, etc., system where one or two mechanical operations provide an answer regarding the nature of the object being interpreted.

Positive keys, as defined by Frost (63), "permit direct identification of objects by pointing out or by comparing easily recognized objects." Inference keys, contrarily, are "those requiring the use of logic, deductive reason, and detailed analysis of regional and local environment."

It is easy to see that the entire question of keys is confused and, because of the broadness of the subject, not susceptible to early resolution. Nevertheless, the above descriptive terms seem to throw some light on the true nature of an interpretative key. First, if one accepts the two major types of keys, i.e., regional and subject, the remaining terms can be descriptive of either. Secondly, with the sole exception of Frost's inference key, which is probably not so much key as manual or text, all the descriptive terms imply that pure mental reasoning, as associated with knowledge, ability, and experience, is "short-circuited," channeled, or, at the very best, subjected to the insidious efficiencies of mental laborsaving devices.

Thus, we arrive at a more specific definition of a photo-interpretative key. Paraphrasing Roscoe's reported definition as much as possible, it is *a reference system designed to facilitate more efficient, effective identification and analysis of objects or conditions, from examination of their photo images, than would be accomplished by average semitrained mental processes, largely by substituting mental laborsaving and channelizing techniques of one sort or another for the normal processes of logical inference and sufficient experience.*

Next, it must be determined whether or not keys have a place in the modern aerial-photographic field. The answer is "yes." However, it is a qualified "yes," and the uses are more specific than general.

The real places for photo-interpretative keys are in fields where interpretation is concerned with objects or items that have both repetitive characteristics and significance, i.e., certain general or specific studies of urban culture, operation, etc., and certain military logistical or operational studies; or in fields where large volumes of low- to medium-quality work, of below-average to average complexity, must be produced rapidly, effectively, and routinely by great numbers of semitrained technicians, i.e., military photo "interpretation" (really photo reading and/or analysis, Secs. 1-6 and 1-7). The applications described by Weiner (218) and Maynard (119) are pertinent to this usage.

The improper place for *true* keys is *not* associated with the interpretation of more than the most elemental terrain conditions, unless the *proper place and significance of the key in the interpretative process are realized and accepted.* The reader interested in the subject of keys should read the symposium on the subject that was held under the auspices of the American Society of Photogrammetry (included in 157), in particular the comments of Whitmore, Heath, and Colwell.

The human brain is the most marvelous chemico-electro-memory-integrative instrument that we know. Properly used (to reply to a question once put by Amrom Katz), it can examine a "high-cost"

aerial photograph with a "ten-cent" magnifying glass and produce something of value.

Interpretative keys, properly used and understood, may *aid* the brain in its work. However, when they seriously become a subject of discussion as a possible substitute for brain work, humanity is on the wrong track.

To realize the proper use of a key in terrain studies, as well as the complexities involved in its preparation, see the paper by Heath (73).

24-24. Quantitative Evaluation of Aerial-photographic Interpretation. Young (230) has pointed up the desirability of making some evaluation of the quantitative analysis of the results of photo "interpretation." This subject—again, because of military stimulation for evaluating and increasing efficiency—has received some attention within the last few years. Among the papers that have considered it are Bateson (7), Young (230), and Rogers (156), on what might be more accurately termed photo-analytic procedures, largely in forestry. Also Pomerening and Cline (148) and Young and Stoeckler (231), as well as a semiquantitative unpublished evaluation some years ago by the author and a recent unpublished effort by Mollard and Dishaw, have given some consideration to the quantitative evaluation of qualitative mapping. The reader is referred to these publications for a survey of the subject.

The author can say about these studies only that, valuable as they ultimately may be, they rest on very shaky terrain when they attempt to evaluate *real* interpretative results on a quantitative basis. How can one evaluate the generally successful results of a damsite study with its multitude of variable factors, analyzed to varying requested and/or possible degrees? Even in such relatively uniform surveys as areal soils studies, how can one evaluate the capability of the interpreter and his scheme of reference? Where is the random sample? Ultimately, these answers may be forthcoming, but it is believed that their early appearance should not be awaited with drawn breath. In connection with the more mechanical photo analysis of routine subjects, such as those which occur in forestry, military planning and operational analysis, and urban studies, quantitative analysis might well be effective and accurate.

A second point is, why the hurry? We have only begun to use aerial photographs and have not even convinced a *respectable minority* of existing earth scientists, teachers, and consequently the students and earth scientists of the future, that air photos have anything to contribute to their fields. Until we do, how can we analyze the quantitative results of interpretation? First there must be a sufficiently large and representative sample of a sufficiently large population of interpreters and interpretative results to analyze.

24-25. Intellectual and Philosophical Role of Interpretation. One extract that is of moment to the subject of this section was selected by Katz (90) from Wiener's book on cybernetics (218*a*):

> For many years Dr. Rosenblueth and I had shared the conviction that the most fruitful areas for the growth of the sciences were those which had been neglected as a no-man's land between the various established fields. Since Leibnitz there has perhaps been no man who has had a full command of all the intellectual activity of his day. Since that time, science has been increasingly the task of specialists, in fields which show a tendency to grow progressively narrower. A century ago there may have been no Leibnitz, but there was a Gauss, a Faraday, and a Darwin. Today there are few scholars who can call themselves mathematicians or physicists or biologists without restriction. A man may be a topologist or an acoustician or a coleopterist. He will be filled with the jargon of his field, and will know all its literature, and all its ramifications, but, more frequently than not, he will regard the next subject as something belonging to his colleague three doors down the corridor, and will consider any interest in it on his own part as an unwarrantable breach of privacy.
>
> These specialized fields are continually growing and invading new territory. The result is like what occurred when the Oregon country was being invaded simultaneously by the United States settlers, the British, the Mexicans, and the Russians—an inextricable tangle of exploration, nomenclature, and laws. There are fields of scientific work . . . which have been explored from the different sides of pure mathematics, statistics, electrical engineering, and neurophysiology; in which every single notion receives a separate name from each group; and in which important work has been triplicated or quadruplicated; while still other important work is delayed by the unavailability in one field of results that may have already become classical in the next field.

The author has long held this viewpoint, and has observed the increasing trend toward a state of intellectual and scientific anarchy. Jargon and specialized knowledge are increasing so rapidly that there is a definite danger of isolating each science in an intellectually autonomous area bounded by its own erudition. As a result, terrain studies are becoming more and more complex, are

requiring more time, more money, more specialists, and are leading to more and more specialized approaches.

Overspecialization is as fatal to humanity as it was to the dinosaurs and other dead beings of the past, and a series of techniques for the logical integration of the earth sciences, as well as a system of semantics for their use, are the first steps toward combating this tendency.

Aerial-photographic interpretation is one such technique, and this is one reason that, throughout this book, the integrating value of interpretation has been emphasized.

Interpretation is also a natural science (Sec. 7-23), and the best interpreter is not a photogeologist, photophytogeographer, photoengineer, phototobotanoecologist, etc., *ad absurdam* primarily, but rather an integrated earth scientist, always questing, always humble, that uses photography to advance his special interest without losing sight of the numerous affecting and effected terrain components that also enter the picture. Perhaps some day interpretation will serve as the basis of a course in earth science that emphasizes fundamental rules and shows how they are translatable into differently named parameters for different sciences.

APPENDIX A THE AIRBORNE PROFILE RECORDER

By F. M. Hanna [1]

A-1. General. One of the most critical and difficult phases of an aerial-mapping operation is the provision of control for either planimetric or topographic purposes. Most of the techniques currently in use require occupation of ground-control points by field parties. In undeveloped areas this often presents a serious problem. Point-to-point barometric altimeter leveling requires occupying each control point and is subject to terrain surface-pressure anomalies. The use of stereo-plotting instruments for bridging or extension is limited because of accumulation of systematic errors. The adaptation of radio and radar aids to distance measurement has facilitated the provision of control. Some of these aids, used for horizontal control, require occupation of only widely spaced sites, and intermediate spot determinations are made from the air, thereby reducing the number of access points. This method depends critically on the determination of plumb points for the intermediate measurements.

A precision radar altimeter has been employed in Canada, the United States, Alaska, Venezuela, Costa Rica, Peru, and Colombia since 1950, for elevation control of medium- and small-scale mapping. With this technique it is unnecessary to occupy any control points, and the control may be obtained simultaneously with the survey photography. Although its original application involved only vertical control, it has now been adapted to measure the terrain clearance of the aircraft, for the purpose of aerial triangulation. Elevation control can be provided at any time, although most economically when taking the survey photography. Since the terrain clearance is used to reconstruct the space geometry at the time of the survey photography, simultaneous operation is essential.

The PSC Airborne Profile Recorder (APR) is an electronic device which consists of a highly accurate radar altimeter to measure terrain clearance and a very sensitive pressure altimeter to measure variation in aircraft flying height above sea level. Both functions are combined in a single equipment. Two simultaneous and continuous records are supplied by the APR: (1) terrain clearance, which is used for photogrammetric scale determination, and (2) terrain profile, as provided by the difference between the radar and pressure altimeter measurements, which is used for vertical control in topographic mapping.

The clearance data are used with simultaneous high oblique photography, which provides azimuth control for the survey photography. The current program of equipment-development and data-reduction study is intended to exploit this application further. Positional photography is also provided to enable correlation with geometric features.

A-2. Historical Background. The development of the radar-profile-recorder concept began at the National Research Council of Canada in 1947. A device was required which would produce terrain profiles in remote areas of Canada to assist in the compiling of aeronautical charts for navigation purposes. An experimental equipment was constructed and proved capable of giving profiles with an accuracy of better than ±200 feet. Since the aeronautical maps require contour intervals of 500 feet, the technique was considered satisfactory and a small quantity of these equipments was built for use by the Royal Canadian Air Force.

[1] Formerly Assistant to the President (Engineering), The Photographic Survey Corporation.

In 1949, a project was initiated to extend the use of radar altimetry control.[2] An equipment was built, called the Airborne Profile Recorder, a name derived from the fact that only a profile record along the flight path was made in its original application. In 1950, the APR was used operationally for control of 200-foot contour mapping with satisfactory results. Parallel with operational use, a continuous development program has been responsible for a number of improvements in performance and provision of the facility of measuring terrain clearance. Tests and operational experience with the MK-4 system, in use in 1955, have proved it to be capable of establishing selected vertical control points to an accuracy of ±15 feet.

The National Research Council of Canada (NRC) initiated a research project in 1955, on behalf of the Canadian government mapping departments, to study the radar altimetry technique. The principal objectives were to determine the accuracy obtainable and to develop improved data-reduction methods. A flight program was drawn up, including distances up to 600 miles and heights from 5,000 to 30,000 feet. Locations and elevations of ground positions derived from the APR data by NRC were checked against information obtained by conventional ground-survey methods. The accuracy obtained in previous tests and operations was confirmed, and an improved reduction technique has evolved which minimizes random and systematic errors. Detailed information concerning the test project is now available.

Equipment development is continuing, and recent major design changes are expected to reduce the clearance error to ±5 feet, with a corresponding reduction in profile error, and already flight tests confirm these expectations. This MK-5 equipment will also feature a reduction in weight and power requirements over earlier models.

A-3. Factors Affecting Accuracy. As with other methods of measurement, there are many factors which may affect the accuracy of APR data. In order to realize maximum precision, a survey must be carefully planned and processed with these factors in mind.

Velocity of Propagation. Basically, the terrain-clearance measurement is obtained by timing the echo of a short pulse of microwave energy which is directed vertically downward to the terrain. The precision of the timing operation may be appreciated when it is realized that 5 feet of distance corresponds to 0.1 microsecond of time.

[2] By The Photographic Survey Corporation.

One obvious factor, affecting accuracy, is variation in the propagation velocity of the radar pulse (velocity of light). Fortunately, this is remarkably constant, variation normally being less than 1 part in 20,000 from day to day. Also, the error introduced by the variation in velocity with air density (i.e., altitude) is compensated by the equivalent aerial refractive distortion introduced in the survey photograph, which makes the terrain appear slightly closer in both cases.

Slant-Height Error. It is necessary that the radar beam be directed vertically downward at all times. At an altitude of 30,000 feet, a 1° error in verticality produces a height error of only 4.5 feet. However, the height error increases as the square of the vertical deviation, so that stabilization of the dish-camera assembly may be necessary under some conditions.

Instrument Noise and Drift. Errors introduced by the instrument are of two types: (1) noise errors, i.e., rapid fluctuation or roughness of the record, and (2) drift, or long-term, errors extending over minutes or hours.

Excessive noise will make reading of the record difficult and is an indication of misadjustment or aging of components, particularly in the radar head. Drift errors in excess of 2 or 3 feet are in general caused by severe fluctuations in the power-supply voltage, ambient temperature conditions, or aging of components in the timing circuits. Regular maintenance is required to avoid both of these errors.

Beam Angle. The antenna of the radar altimeter illuminates an area of the terrain immediately below the aircraft. The size of this area is determined by the beam angle of the antenna system and the height of the aircraft. Since an accurate measurement is obtained only when the entire area illuminated has the same elevation, it is necessary that this area be as small as possible, particularly in rough terrain. The beam angle of the MK-5 equipment is approximately 10, giving an illuminated-area diameter of 1/57 of flying height on flat and level terrain.

Selection of Control Points. Although the APR provides continuous profile and clearance records, obviously not all points in the record will be of equal accuracy. It is essential, therefore, that points chosen for control purposes be selected carefully.

Factors adversely affecting the accuracy of any point on the records are (1) slope of the terrain, (2) presence of multiple reflecting surfaces such as partial tree cover or loose snow, and (3) poorly reflecting surfaces such as rough, dry, loose sand.

An echo-quality indicator has been devised which is sensitive to all these conditions. Selection of the most accurate measurements for control points is facilitated by this indicator, the output of which is recorded simultaneously with the profile and clearance data.

Isobaric Gradients and Anomalies. These errors are external to the equipment and are introduced through the pressure altimeter. Therefore they appear on the profile record only. A formula has been developed which relates isobaric gradients to wind velocity through regular drift-angle measurements. The application of this formula is simple, and experience has confirmed that profile accuracy is considerably improved with its use.

Each APR flight is normally "tied" at both ends to known elevations such as water surfaces or airports. "Closure" error after correction for gradient is then distributed uniformly over the flight line. Isobaric anomalies have precluded the use of the aneroid altimeter for the accurate measurement of elevation at ground level, particularly in rough country. These anomalies are caused principally by the dynamic effects of wind being deflected by terrain irregularities and decrease rapidly with increasing altitude. There is some evidence of anomalies of a few feet equivalent height even at high altitudes, probably caused by air turbulence. Generally, this type of disturbance is not associated with the "photographic" weather required for survey flying.

A-4. Summary. The APR has proved its suitability for elevation control in medium- and small-scale mapping. The convenience and speed, compared with conventional techniques, make it particularly attractive in undeveloped areas. Although its application to scale determination has not been fully explored, already there is evidence of marked advantages. It is expected that this feature will also assume great importance.

APPENDIX B A BASIC SYSTEM FOR DESIGNATING MAP UNITS ON AERIAL PHOTOGRAPHS

The following discussion is taken from an article of the author's (105) presenting a basic system for designating soils on engineering soil maps in humid-temperate areas. With relatively minor changes, additions, or subtractions, the basic idea may be applied to several other fields and climate regions.

The simplest soil maps merely delineate soil areas. The most effective soil maps, however, also tend to describe conditions within soil areas. This self-descriptive quality necessitates a logical conversion of soil information into map units, or designations. Such an operation is always difficult, sometimes critically so. The inclusion in a map unit of all the varied soil information which is ordinarily available yields only a hodgepodge of data. Yet, map units which contain only single groups of facts, such as geology or laboratory-test results, do not give a sufficiently complete picture of the soil and its environment. The feasible methods lie between these two extremes.

One such method, which this paper describes, is based upon an initial selection, for emphasis, of certain important items of soil information, which are then converted into map designations according to a logical system which satisfies a number of practical criteria. . . . The highway engineer has been interested for some time in the formulation of a practical system for soil appraisal which will incorporate the factors that bear directly upon his problem. The initial efforts to formulate such a system have centered around the development of laboratory classification systems. Most of these systems have differentiated soils on the basis of their physical laboratory indices. Soils having similar indices have then been grouped together. The points of similarity have, of course, depended upon the purpose and comprehensiveness of the system. In all cases, however, the correlation of indices with field soil behavior has enabled the systems to be used with considerable success.

In the majority of these systems, the classification tests are performed on the soil in a highly disturbed, or at least removed, state. Because of this, a most important factor, which might be termed the "factor of environment," is disregarded. Many engineers can testify that soils with almost identical test constants and classifications may react quite differently in the field, even if subjected to equal traffic volumes and loads acting upon similar structures. The essential reason for these differences in performance is that the soils are characterized by different natural environments. The effect of such factors as parent material, topographic position, profile development, etc., have caused internal modifications which are significant in so far as the engineering characteristics of the soils are concerned. Realizing this, many engineers are convinced that soils must be considered in relation to their environment and that areal studies of in-place conditions are particularly valuable. . . . Although the methods of accomplishing the soil survey are many in number, the systems used to present the acquired information in the form of usable soil maps are even more variable. If soil surveys are to increase in number and extent, and if the highway-engineering profession is to derive maximum benefit from the assembled information, it appears highly desirable, if not imperative, that some standardized system of map units be devised. Much of science's progress has occurred because qualified specialists have been able to discuss their problems and techniques with reference to well-established, widely accepted bases of classification. Thus, the pedologists have the Glinka soil classification, the climatologists have the Köppen and Thornthwaite notations, the geomorphologists have the Davis nomenclature, etc. It is believed that the effective interchange of ideas, and the progress of discussion, comparison, and research in the highway field, will be facilitated to a significant degree by the adoption of a standardized system of map units. It is almost certain that such a system will facilitate the exchange and dissemination of constructional experiences and techniques.

Before discussing any particular type of map-unit system, it appears desirable to investigate those characteristics of a system which will make it effective in the preparation and use of engineering soil maps. The following attributes are suggested as being a minimum:

1. Simplicity. The system should be relatively easy to learn, remember, apply, and interpret. This should not imply that the learning be accomplished without effort, but rather that the effort should be justified by the benefit derived.

2. Conciseness. The system must provide concise identifications to satisfy the requirements of simplicity and allow small areas to be properly labeled.

3. Talkability. The map units must be of such nature that they can be used in conversation, research, and publication. It is comparatively easy to devise a complicated code which will allow for every variable within a given soil occurrence, but such a system defeats its purpose because it cannot be thought of and used as an entity.

4. Uniformity. Identical map units should be provided for soils which are identical within the limits of the system.

5. Informativeness. The map units should convey enough information concerning a soil area to allow an immediate rough evaluation of the soil's environment, major properties, and field characteristics.

6. Reproducibility. The system should be adaptable to easy, rapid, economical reproduction on common highway base maps. Colors and complicated patterns, while an aid, should not become a necessity.

Each of the above attributes imposes severe restrictions upon any attempts to devise a satisfactory system of map units. Probably the most troublesome requirements are those which relate to conciseness and informativeness. It is difficult to conceive of a system that provides brief symbols which, nevertheless, convey a considerable amount of information. For instance, if one were asked to list those soil characteristics which are desirable in a map-unit system, the following enumeration might result:

1. Climatic influences and corresponding profile type
2. Origin of parent formation
3. Types of parent formation
4. Physical characteristics of parent formation if consolidated
   a. Hardness (and other engineering properties)
   b. Orientation
   c. Structure
   d. Depth below surface
5. Landform
6. Existence and characteristics of a significant underlying formation
7. General characteristics of the developed soil profile
   a. Number of horizons
   b. Depth of horizons
   c. Predominant physical characteristics of each horizon
   d. Predominant mineralogical characteristics of each horizon (especially with regard to clay minerals)
   e. Predominant chemical characteristics of each horizon
8. Predominant existing drainage conditions
9. Associated engineering soil problems

The inclusion of the above information in a mapping system which could also be characterized by the properties of simplicity and conciseness presents difficulties that are obvious. Therefore it is necessary to eliminate some of the listed factors. To preserve simplicity, conciseness, etc., and for various other reasons, all but the following factors have been eliminated in the proposed system:

1. Origin of parent formation
2. Type of parent formation
3. Landform (for transported materials only)
4. Existence of profile contrast
5. Texture of important horizons
6. General drainage conditions
7. Underlying materials (where important with regard to construction)
8. General engineering problems (by interpretation), etc.

The system will be described briefly, and without elaboration, in the following paragraphs. It will then be discussed in more detail. It is hoped that the description and discussion will be read with the following points in mind:

1. The method described has been used with, and is particularly adaptable to, the techniques of air-photo interpretation.

2. The method described is based upon humid-temperate to humid-cool climatic conditions. This does not invalidate the general technique for other climatic regions. It merely indicates that certain changes must be made within the framework of the whole.

3. The method described is of particular benefit when the soil map is supplemented by a companion descriptive bulletin which, for each area, will include information not presented by the map unit, as well as an amplification of the map unit.

Proposed System of Map Units for Soils

Origin of Parent Formation. The soils of any area which are to be identified by map units are first classified as:

1. Residual soils—derived from consolidated parent formations
2. Nonresidual (transported) soils—derived from unconsolidated, or very weakly consolidated, materials

Residual soils are then differentiated, according to the origin of their parent formations, into the three geologic classes, each class being identified by an appropriate capital letter:

1. Sedimentary—*S*
2. Igneous—*I*
3. Metamorphic—*MM*

In a parallel fashion, the nonresidual soils are differentiated according to the origin of their parent formations into the five geologic classes: [1]

1. Glacial—*G*
2. Alluvial—*A*
3. Wind-blown—*W*
4. Marine—*M*
5. Colluvial—*C*

Type of Parent Formation. Residual soils are differentiated according to the lithological character of the parent formation, i.e., shale, limestone, granite, gneiss, etc. Each of these lithological types is identified by a characteristic lower-case letter such as limestone (*l*), sandstone, (*s*), shale (*h*), granite (*g*), and gneiss (*g*). When these letters are combined with the proper letters of origin, characteristic symbols result: *Sl* (limestone), *Ss* (sandstone), *Sh* (shale), *Ig* (granite), and *MMg* (gneiss).

Nonresidual soils are differentiated according to their types of landform. Each of these landform types is identified by a characteristic letter or letters, such as ground moraine (*M*), marginal moraine (*MM*), outwash plain (*O*), dunes (*D*), and fan (*F*). When these letters are combined with the proper letters of origin, characteristic symbols again result: *GM* (glacial ground moraine), *GMM* (glacial marginal moraine), *GO* (glacial outwash plain), *WD* (wind-blown dunes), *AF* (alluvial fan). A master diagram, showing the general nature of these divisions together with the appropriate symbols, is shown in Fig. 2-2.

Landform. A consideration of landform is included in the discussion of the proposed system.

Degree of Contrast within the Profile. As will be explained in the discussion, the degree of contrast within a soil profile is a relative term in so far as engineering is concerned. It is indicated by significant differences in the engineering properties and/or problems associated with different horizons within the same profile. It is indicated in the following manner:

1. Soil profiles with significant contrast (with regard to highway-construction problems). The capital letter *C* is placed behind the proper origin-type combination. Thus, *GMC* and *IgC* both indicate soils whose profiles exhibit sufficient difference between their *B* and *C* horizons to create different engineering problems for each horizon.

[1] According to the newer ideas of the author (Sec. 2-29 and Fig. 2-2), these classes should be:

1. Fluvial (*F*)
2. Marine (*M*)
3. Lacustrine (*L*)
4. Glacial (*G*)
5. Glaciouvial (*GF*)
6. Aeolian (*A*)
7. Organic (*O* or *Z*)
8. Fluviocomposite (*FM*, *FL*, etc.) (Fig. 2-2)

2. Soil profiles with little contrast. The capital letter *C* is merely omitted.

Textural Nature of Profile. Estimation of Laboratory Indices. The general textural nature of the profile, and an indication of the associated laboratory test constants, are indicated by one or two numbers. Each number represents a textural and physical class, as established by the Highway Research Board. These group classifications, together with the analogous classifications incorporated in the proposed system, are shown in Table B-1.

It is seen that the group subdivisions for *A*-1, *A*-2, and *A*-7 have been replaced by a single number in the proposed system. This has not been done in an attempt to better reflect the characteristics of the soil,

Table B-1. Texture and Depth to Ground Water in Proposed System

Texture

HRB group	*HRB* subdivision	General nature of material	Number in system
A-1	*A*-1-*a* *A*-1-*b*	Stone fragments, gravel, and sand	1
A-2	*A*-2-4 *A*-2-5 *A*-2-6 *A*-2-7	Silty to clayey gravel and sand	2
A-3		Fine sand	3
A-4		Silty	4
A-5		Silty (elastic)	5
A-6		Clayey	6
A-7	*A*-7-5 *A*-7-6	Clayey (elastic with high volume changes)	7

Depth to Ground Water

Position of water table, ft	Ground-water condition	Letter in system
Below 10	Excellent	*e*
6–10	Good	*g*
3–6	Imperfect	*i*
1–3	Poor	*p*
0–1	Very poor	*v*

but rather to meet the requirements of simplicity and conciseness. A further consideration of this matter will be found in the discussion. The numbers indicate the nature of the profile according to the following method:

1. Soils exhibiting a significant contrast. The one or two numbers in the map unit refer to the texture of the *B* horizon (of the material in predominant topographic position or positions).

2. Soils exhibiting an insignificant contrast. The one or two numbers in the map unit refer to the effective texture of the profile (usually the *C* horizon in unconsolidated materials).

Drainage Condition. By interpreting the complete map unit, the internal drainage potential, the capillary potential, and the height of the ground-water table can be individually or compositely evaluated in a general way. The internal drainage characteristics can usually be estimated from the textural category and the degree of profile development. Information concerning the capillary potential is supplied by the textural category, together with the following code for ground-water positions. The height of the ground-water table over the major portion of the area (neglecting surface intersections and their accompanying effects) is indicated by [various letters]. . . . Variations in the position of the water table can be indicated by combining two letters such as *ip*, showing a water-table position varying between 1 and 6 feet from the major portion of the surface, depending upon position.

The only other factor of major importance in an estimation of drainage condition is the surface-drainage potential. This is considered in the discussion.

Special Symbols. A few letters are used to convey special meanings in situations which depart from the normal. These letters are:

X—Exceptional. Usually used when the parent formation, textural classes, or drainage conditions are not correctly implied by the regular system.

R—Variable. Usually used when individual factors vary in such a manner that mapping, according to the rules of the system, is not feasible.

d—Depression. Usually used to indicate a depressed position when such information will facilitate the correct interpretation of a map unit.

a, *b*, *c*, etc. Usually used at the end of identical map units, which, nevertheless, refer to areas that are different in some respect. These letters should be used very sparingly.

Typical Map Units. In order to form each map unit,

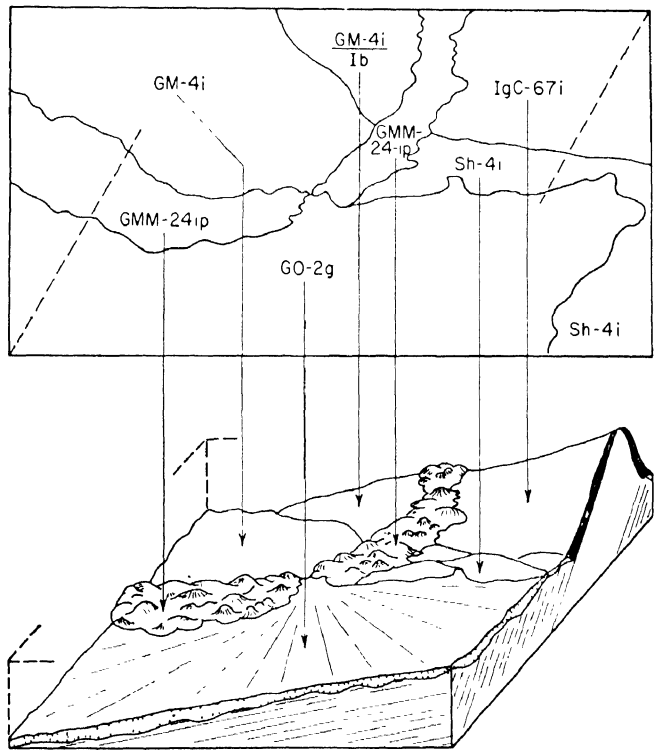


Fig. B-1. Schematic block diagram indicating the method of designating map units.

the various letters and numbers are [merely combined in order].

Uniformly Intermingled Soils—Existence and Type of an Underlying Significant Stratum. In some areas, two significant phases of a soil may be uniformly intermingled on an areal basis. For instance, in some very gently rolling glacial ground morainic areas, slight differences of position may create differences in soils. If both positions are equally widespread and also intermingled, a problem of labeling is created. The proposed system uses the diagonal bar in such cases. The above area might be mapped as $(GM\text{-}4i)/(GM\text{-}6p)$.

In many areas, it is extremely important to indicate the existence and type of an underlying stratum which is significant with respect to engineering construction. In the system as proposed, this may be done using a fractional symbol. Thus, the symbol $\frac{GM\text{-}4i}{1b}$ denotes silty ground moraine with an immature, imperfectly drained profile overlying, at a significant depth, igneous basaltic bedrock.

The discussion goes on to consider the effects of climate and to state that the proposed system could be adapted to other climates. It also discusses the importance of origin, landform, and rock type—major factors of environment—to successful designation and shows how landform immediately indicates many related characteristics. Finally, it discusses contrast, texture, and drainage.

Figure B-1 shows how an actual area might be designated.

Of course, the above system may be simplified by omitting any parts to allow for special conditions. For example, in glacial areas, the letter *G* may seem redundant to the interpreter (although not necessarily to the reader).

Smith (176) disagreed with the omission of surface-drainage potential, in mapping the Natchez Trace, and added a series of letters at the end of the map unit. Smith and Koca removed drainage completely for their map of East Pakistan, substituting letters indicative of topography. They also added *L* for laterite and *V* for geologic variation. In some cases, the letters *a*, *b*, *c*, etc., have been used as indicators of depth of overburden and water table conditions have been neglected.

APPENDIX C INTEGRATION OF PHOTOGRAMMETRY AND ELECTRONIC COMPUTATION IN HIGHWAY ENGINEERING

The advent of the tremendous, federally aided highway-construction program in the United States has given great impetus to the slowly blooming integration of photogrammetry and electronic computation for highway engineering.

The following synopsis of a general method by which these separate techniques can be used to facilitate highway engineering is based upon data from several published sources, including the *Engineering News-Record* (56*a*), the Massachusetts Institute of Technology (128*a*,*b*), and Ridge and Preston (155*a*). Other information has been derived from the staff of Geotechnics and Resources, Incorporated.

The method herein described is a composite one. No single one of the sources uses it entirely or exactly, but all use substantial parts of it. The general sequence of steps follows that described in Chap. 17: (1) area study to select route corridors (first-stage reconaissance), (2) corridor study to select route strips (second-stage reconnaissance), (3) analysis of route strips and selection of final center line, (4) design, and (5) determination of final quantities.

There are two basically different ways of digitalizing the terrain within a possible location *corridor:*

1. Visual selection of a center line (trial or final) and digitalization of the X, Y, Z coordinates of cross sections taken at right angles to the center line, at specific even station intervals and breaks in terrain. In this case, all digitalizations are referenced to the given route center line (at right angles) and must be changed as the center line changes. Only narrow strips of terrain, occasionally intersecting (as the center line alternates come into existence), are digitalized.

2. Digitalization of the entire route corridor according to X, Y, Z coordinates that are referenced to some accepted system (such as the state plane coordinate system). In this case, since the route center line has not been selected, the digitalizations, when referenced to a given center line at given transverse intervals, occur along *skew sections* whose inclinations with respect to given center lines change as the direction of the center lines change. A broad strip of terrain is digitalized, and the digitalization does not require any revision so long as the selected center lines fall within boundaries of the digitalized strip.

The first method may be called *center-line–strip* digitalization. The second may be called *terrain-band* digitalization.

It is desirable to compare the steps that would be used in each method in completing a given highway-route study.

Center-line–Strip Method	*Terrain-band Method*
Area Study (Selection of Corridors)	
1. The general area of study is defined on the basis of traffic demands between terminal and intermediate points.	1. Same as for center-line–strip method.
2. Existing (or new) small- to medium-scale topographic maps, having 10- to 20-foot contours (or 5 to 10 meters), together with existing aerial photography (1:20,000 to 1:63,360) are collected and examined to select corridors having a width of 1 or 2 miles.	2–4. Generally, and particularly in certain urbanized areas where corridor selection is governed by other factors, the terrain-band system is identical with the center-line–strip method. However, there are situations where two to four closely spaced corridors have equal a priori attractiveness. In such cases, digitalization of a broad band of terrain (4 to 10 miles) may be justifiable. Such a course is doubly attractive if it is expected that the digitalization can be used ultimately for other routings (of roads, railways, canals, microwave transmission, pipelines, transit systems) and if *existing* maps can be used to plot the terrain digits with sufficient accuracy.
3. In all areas, and particularly in urban ones, land use, right-of-way costs, traffic demands, and general transportation economics are important governors of corridor selection. Aerial-photographic interpretation is often used to determine land classification.	
4. Frequently, a scale-ratioed mosaic (1:20,000 to 1:31,680) is prepared; this, with enlarged overlay copies of the topographic maps, aids selection. In such cases aerial-photographic interpretation is often used to determine general areas of terrain that have adverse general construction characteristics (Chap. 17).	
5. Quantitative route data used during this stage are confined to preliminary profiles and grade lines.	5. In addition to profiles and grade lines, the digitalized terrain can now be processed to give very rough earthwork figures along any line whatever.
6. Corridor or corridors are finally selected.	6. Same as for center-line–strip method.
Corridor Study (Selection of Route Strips) and Analysis of Route Strips	
1. Aerial photography of corridors exposed at 1:12,000 and prints made for stereo study.	1. Same as for center-line–strip method.
2. Strip mosaics, at contact scale, prepared for compilation of data.	2. Same as for center-line–strip method.
3. Ground control for topographic mapping is planned using information as to existing topographic control information and possibilities for bridging. Preferably, specific new points of control should be selected from inspection of the new photography.	3. Same as for center-line–strip method.
4. Ground control is installed by either ground extension of survey control from existing points or by photogrammetric bridging with a high-accuracy photogrammetric instrument. Adjustment of bridging is done by electronic computation. The latter method saves much money and time on long strips.	4. Same as for center-line–strip method.
5. A topographic strip map of the corridor, at normal preliminary scale of 1:2,400 with 5-foot contours, is made.	5. Usually the same as for center-line–strip method, but the topographic map may occasionally be eliminated or reduced in extent to those portions which have a priori feasibility. Whether or not a topographic map is produced, the corridor of study is digitalized where location seems feasible. New skew coordinate axes may or may not be used. The X, Y, Z coordinates for digitalization may be procured:

Center-line–Strip Method	*Terrain-band Method*
Corridor Study (Selection of Route Strips) and Analysis of Route Strips (*Continued*)	
	a. At the same time that stereo models are set for 1:2,400 topographic strip mapping (if a sufficiently narrow band for digitalization can be selected directly from the results of corridor study). *b.* After preparation of the 1:2,400 map, and using same as source, or resetting the models. When digitalizing according to *a*, above, it is desirable to have a scanning and automatic read-out device for the photogrammetric instrument in order to develop the full advantage of the system. This scanning system is oriented to the skew coordinate axis plotted on the manuscript, and actual readings may be taken by a variety of systems, depending upon terrain.
6. Concurrent with the installation of ground control and topographic mapping, aerial-photographic interpretation is used to map soil, geology, and drainage conditions. A selective field check, preplanned from the photographs, uses cut inspection, auger borings, and occasional samplings, and is incorporated in the survey. Complete drainage nets, covering the corridor, are prepared. When a mosaic is available at 1:20,000 or smaller (step 4 under Area Study, above), drainage is compiled thereon to extend the net beyond the limits of the corridor photography. A complete report is prepared.	6. Same as for the center-line-strip method, except that the survey should precede digitalization of the terrain. Various soil and geological classifications are made so that they can be digitalized when the terrain is digitalized. It is also conceivable that land use and associated presumed land costs could be classified and digitalized.
7. With topographic, soil, geological, drainage, and cultural data, possible route strips are selected. Trial center lines through these strips are also selected, and profiles and trial grade lines prepared. Some center lines may be eliminated; others may be revised and refined.	7. With topographic and/or digital data, and soil, geological, drainage, and cultural information, route strips are selected. These strips are analyzed and trial center lines are selected as in the center-line–strip approach.
8. For each remaining center line preliminary criteria are computed with electronic computers. The computers are entered with the following data: stations at suitable cross-section intervals, elevation of ground surface at the break points of each cross section (taken manually from topographic map), station and elevation of each P.I. on the proposed grade lines, length of proposed vertical curves, and typical section information. Output from the machine includes individual and cumulative cut-and-fill quantities by stations, slope intersection points, and net earthwork volume for preparation of the mass diagram (the latter may be plotted automatically).	8. For each trial center line, preliminary criteria are computed with electronic computers. The computers are entered *initially* with the following data: state plane coordinates of origin, terminus, and each P.I., plus the curve radius at each P.I. The *first-run output* from the computer then supplies the stations, P.C.'s, P.T.'s, and their elevations (plus similar data for offset profiles if desired) as well as an automatically plotted profile, if an automatic line plotter is available. If such a plotter is available, a great many trial grade lines and center lines may be studied. The computers are entered, the *second time* with data from the trial grade lines, i.e., approximate station and elevation for each V.P.I., origin, and terminus, plus the length of each vertical curve, and the basic design template and specifications (widths and slopes of roadway components for various cut-and-fill situations). This *second run* through the computer results in an output of cross-sectional areas

Center-line–Strip Method	*Terrain-band Method*
Corridor Study (Selection of Route Strips) and Analysis of Route Strips (*Continued*)	
9. The earthwork quantities and mass diagram, together with soil, rock, drainage, cultural, and traffic data are studied to determine costs of construction. Revisions in alignment may be made and recomputations completed. Eventually, a center line is chosen for detailed analysis.	(for the automatically determined proper template) and the individual and cumulative cut-and-fill quantities by stations. 9. Same as for center-line–strip method.
Selection of Final Center Line	
1. The center line chosen for detailed analysis is staked, signalized, and surveyed with regard to elevations. 2. A strip 1,000 to 2,000 feet wide, centered on the staked center line, is *photographed* from the air at a scale of 1:3,000. 3. From this very low level photography, a planimetric map at 1:600 to 1:1,200 is prepared in a photogrammetric plotter and cross-section data are taken at desired intervals along the signalized line. This cross-section data is taken with the aid of a reading bar, which is made so that it can slide along the center line while oriented perpendicular to it. By sliding a *coupled* photogrammetric (Kelsh) plotting table along the bar to breaks in elevation or other points, the side distances and relative elevations of ground along each cross section can be easily determined. By proper means, this information—together with the station of the reading bar along the center line—can be recorded automatically on punched tape. 4. The punched-tape information, together with grade-line control data, are processed so as to be fed to an electronic computer, which produces the center-line elevations of each station. These output data, again with the cross-section data and accompanied by information on center-line geometrics and typical sections, are *again* fed to a computer. The output consists of coordinates for the design section, including allowances for superelevation and changes in cut-and-fill slopes. The original cross-section data, together with this output is fed to a computer to yield earthwork quantities and information for the mass diagram. 5. Earthwork and mass-diagram information is then analyzed to select a final center line and grade.	1. Selection of a final center line is virtually made by using a number of lines and grades in the above manner and comparing their results. However, in the interest of greater accuracy, one or more of these center lines may be subjected to detailed analysis as in the center-line–strip method. Because the only justification for this additional work is increased accuracy, the terrain strip covering the center line (s) chosen for detailed analysis must be redigitalized, using the new low-level photography and ground control on the photogrammetric plotter. The entire skew system is then rerun to obtain detailed earthwork quantities for each center line chosen for detailed analysis. The earthwork data is then examined, and necessary revisions made until a final line and grade are chosen. At this point, *use of the skew system* ends, and a conversion program is used to convert the skew data to the center-line–strip method of approach for final design.

For a discussion of the application of electronic computers to detailed design and determination of final quantities see References 56*a* and 155*a*.

No attempt is made here to evaluate the relative desirability of the two methods. However, the terrain-band system seems to have certain advantages, especially during preliminary phases of study, if *real accuracy* is of *real moment*, as is indicated by the following comments (128*a*):

The second problem of requiring a separate set of cross sections for each horizontal alignment places a limitation on the number of possible solutions which it is practical to consider. To evaluate ten trial lines or possible solutions would be essentially ten times more work than a single line. Therefore, it is common practice to reduce the number of trial lines to two or three by inspection or map study. Often the final line is selected without the numerical evaluation of any alternates. Earthwork (cuts and fills) is *balanced* by variation in the vertical alignment or grade line.

It can be said that the conventional approaches to highway-location practice with respect to earthwork achieve an acceptable solution but not necessarily the optimum solution. It has heretofore been considered impractical to numerically evaluate a large number of trial solutions because of the engineering time and costs involved despite the possible savings in earthwork costs. Two different highway-location engineers independently studying the same location problem with respect to earthwork will often arrive at quite different solutions to the problem, although both solutions will be good and acceptable. The extent to which either solution approaches the optimum is really not known, although each locator is confident that he has the "best" solution.

With respect to the desire for more thorough analysis of highway location with respect to earthwork, the argument is usually raised that earthwork seldom controls the location. It is pointed out that land use and right-of-way cost is often the controlling factor, or that the earthwork volume is so small that it is not considered a location factor. This is certainly true in many cases, and more attention to earthwork is not advocated under such conditions. However, even in such cases, because of the time and cost involved, determining the earthwork, even if it is a small amount, warrants consideration of more efficient methods of obtaining the data and computing the quantities.

Although the complex and expensive urban highway projects are in the forefront of consideration by many highway engineers, rural locations are still very much in the picture. Depending on the terrain, earthwork may vary from a minor to a major role as a location factor. In many cases, there is ample justification for a more thorough numerical analyis of possible location solutions with respect to earthwork if such analysis can be made within practical reason. Even the most conservative estimates of the amount of money which will be spent on earthwork in accomplishing the national highway program indicate that a relatively small percentage saving in earthwork volume will account for hundreds of millions of dollars.

On the other hand, the center-line–strip system has the advantage of a conventional and more familiar approach to the highway problem.

Perhaps, in the final analysis, the value of the terrain-band system rests upon its great value for *other uses in the digitalized band*, and on its modification for other completely different purposes, several of which may come to mind after some thought.

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