AERIAL PHOTOGRAPHS IN GEOMORPHIC STUDIES*

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Prefatory Note

The paper reprinted below was originally intended for readers well versed in geomorphology but comparatively unfamiliar with the use of aerial photographs. In presenting such a paper to an audience having exactly the opposite prerequisites, a few words of explanation may be in order. To begin, *geomorphology* may be defined as a branch of geologic science devoted to the explanatory description of topographic features. It is included within the fields designated by the older terms, *physiography* and *physical geography*. Geomorphic study may be either an end in itself, or a means to some other end. Although this paper was written primarily from the former viewpoint, it is probable that the applications of geomorphic studies to other and more practical ends will be of greater interest to the readers of this Journal, and will thus bear brief comment.

Of the varied objectives served by geomorphic studies, the following may be mentioned: (1) topographic mapping, (2) military study of terrain for tactical purposes, (3) land classification and description, (4) soil erosion studies, (5) interpretation of bedrock geology, and (6) the discovery and exploitation of mineral resources. All of these ends require as thorough a knowledge of topography as may be obtained, and certain of them require also that the value of surface features as indicators of deeper features be understood. The value of the geomorphic method lies in its providing a genetic rather than an empirical approach. A given topography is approached not blindly, but discerningly. It is viewed not as an accidental assemblage of meaningless forms, but as the product of a definite series of geologic processes working on a particular set of geologic materials through an orderly sequence. Individual features are seen not as isolated and unrelated things, but as parts of a continuous and systematic pattern. Proper classification of the topography in geomorphic terms at once points to a great many additional facts about it which an empirical attack would be much longer in ascertaining. It suggests significant things to look for, and where to look for them, it aids in distinguishing between relevant and irrelevant detail, it facilitates intelligent generalization, it provides the basis for rational interpolation and extrapolation, and makes possible reliable predictions as to the types of material which may be found beneath the surface. Even in such routine work as topographic mapping, the geomorphic viewpoint can effect an appreciable economy of time and energy, besides relieving the usual monotony of the work. And in the military study of terrain, where speed is frequently essential and accurate generalization is important, the value of the geomorphic approach may be even greater.

In the paper that follows, the value of aerial photographs as an aid in geomorphic studies is set forth. It is believed, conversely, that an understanding and appreciation of the geomorphic approach may be equally valuable to the many workers who study aerial photos for other purposes. Viewed from that angle, the wealth of topographic detail so clearly shown on aerial photos cannot but assume an enormously increased significance, regardless of the particular objectives to which the photo interpreter is working.

Introduction

THE development of aerial photography as a basis for mapping has been recent and rapid. Although experiments in taking pictures from kites and balloons date back to the last century,[1] it was not until the first World War that much progress was made. At that time, the value of aerial photographs for studying terrain was quickly recognized, and the foundations were laid for systematic procedure in taking and using photographs. The potentialities of such photographs for geological studies were recognized by geologists at the time, and later were admirably illustrated by Lee.[2] Since then, planes, cameras, film, and technique have steadily improved. Precision methods of assembling photographs have been perfected, and a new science of mapping—aerial photogram-

* Reprinted from *Journal of Geomorphology*, Vol. IV, October, 1941, No. 3, pages 171–205 by Permission of the Editor and Author.

[1] Reeves, D. M., *Aerial Photographs, Characteristics and Military Applications.* The Ronald Press Co., New York, 1927. Chap. 1.

[2] Lee, W. T., *The Face of the Earth as Seen from the Air.* Amer. Geog. Soc. Spec. Publ. No. 4, 1922.

Aerial Photographs

FIG. 1. High oblique photograph of alluvial fan at mouth of Hanaupah Canyon, Panamint Range, California. Copyright Spence Air Photos.

metry—has evolved. Extensive areas have been photographed from the air, both for the preparation of base maps[3] and for use in guiding the development of mineral resources.[4] In economic geology, the use of aerial photography has become a well-established practice, and much credit is due to workers in that field for thus leading the way in a new method of attack on geologic problems.

For many research workers in pure science, the benefits of developments described above were long withheld by prohibitive costs. During recent years, however, large portions of the United States have been photographed from the air by or for various Federal agencies, and the resulting pictures have been made available to authorized persons for the cost of reproduction. A powerful new tool is thus placed in the hands of the geomorphologist, and promises to be fully as important in his field as was the introduction of the thin section in petrology.

The present paper presents no new or original methods, but aims simply to review the present status of aerial photography and cartography in the United States, to provide an introduction to the literature in that field, and to indicate some of the uses—and possible misuses—of aerial photographs in the interpretative study of landforms. If certain parts of the discussion seem unduly elementary, it is because experience has shown that the points in question are little appreciated by newcomers to the subject.

Acknowledgments: Acknowledgment is due first to the many officials in cartographic laboratories of the U. S. Department of Agriculture, who generously provided opportunity for studying their methods and examining their collections of photographs and mosaics. For critical reading of the manuscript, thanks are due to Dr. Kirk Bryan and to Dr. R. C. Moore. The photographic illustrations are drawn largely from a systematic collection being assembled at the University of Kansas, in connection with the writer's course in geologic interpretation of aerial photographs. The map, Figure 4, was drafted by Mr. Eugene Maxwell, as part of an NYA project.

Types of Aerial Photographs

Aerial photographs are of three main types: oblique, vertical, and composite. Individual prints of either of the two latter types may be fitted together to form mosaics. Oblique photographs are those taken with the optical axis of the camera inclined to the vertical. When the optical axis at the moment of exposure is more nearly horizontal than vertical, the photograph is termed a high oblique (Fig. 1). Unless taken at very low altitudes in mountainous country, this type shows the horizon. Low obliques are those taken with the optical axis more nearly vertical than horizontal, and do not show the horizon. Both types provide a perspective view of the landscape, and the high oblique type is essentially similar to a ground photograph taken from a mountain peak or other vantage point. It is widely used for pictorial and illustrative purposes, examples being found in many recent textbooks and papers.

Vertical photographs are those taken with the optical axis of the camera in a vertical or nearly vertical position. They provide a "flat" representation of the earth's surface, and have the appearance of a pictorial map (Fig. 2). The aerial photographs available in this country are predominantly of the vertical type. They are widely used in map-making, and for this purpose are generally taken

[3] Wright, M. S., The Aerial Photographic and Photogrammetric Activities of the Federal Government. PHOTOGRAM. ENG., 5, 168–176, 1939.

[4] Herzog, G. W., The Uses of Aerial Photogrammetry in the Petroleum Industry. PHOTOGRAM. ENG., 6, 103–108, 1940.

at such intervals as to provide some 60 per cent of overlap between successive photographs in the same line of flight, and some 30 per cent of overlap between adjoining photographs in parallel lines of flight.

Composite photographs are made with multi-lens cameras, and consist of two or more low obliques, either with or without a central vertical photograph. By means of a special printing machine, the oblique views are transformed to the same plane as that of a vertical photograph, so that the final product has the same appearance and characteristics as the latter. Of the multi-lens cameras

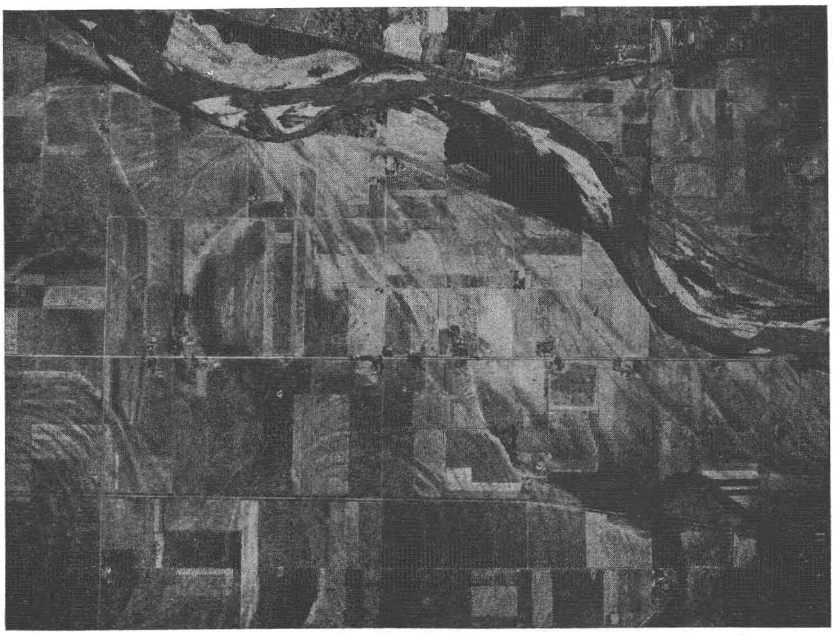

FIG. 2. Vertical (single-lens) photograph of the Kansas River valley in Douglas County. Kansas. Note truncation of an earlier meander plain by a later sand-bar plain, and the truncation of the latter by a still younger sand-bar flat. Photo courtesy of U. S. A. A. The black bar indicates scale, and is approximately one-half mile in length.

used in this country, two are particularly deserving of mention. The first is the five-lens camera, having a central vertical chamber flanked by four oblique chambers.[5] The transformed composite photograph from this camera has the form of a maltese cross. The second is the four-lens camera, having oblique chambers only. The finished photograph from this camera is square, and shows inconspicuous dividing lines between the original units (Fig. 3). This type has been widely used in the southwestern part of the United States. Multi-lens cameras in general have the advantage of providing a wider angle of ground coverage, and thus of reducing the time and cost of flying requisite for mapping.

Mosaics are patchwork assemblages of either vertical or composite photographs, designed to present a continuous picture of larger areas than may be covered by a single photograph.[6] They are classified as controlled or uncontrolled

[5] Talley, B. B., *Engineering Applications of Aerial and Terrestrial Photogrammetry*. Pitman Pub. Corp., New York, 1938, Chap. 4.

[6] Talley, *op. cit.*, Chap. 17.

according to the degree of accuracy with which the assemblage is made. The controlled mosaic is constructed by making the adjustments necessary to insure uniform scale and correct orientation from one photograph to another, and to link the assemblage to suitable ground control. In areas of relatively low relief, it approaches a good map in accuracy. The uncontrolled mosaic is assembled simply by matching points along the borders of adjoining photographs, without making corrections of any kind. The reliability of the product varies with the care employed and with the quality of the original photographs. Not infrequently there are gross errors both in scale and in direction.

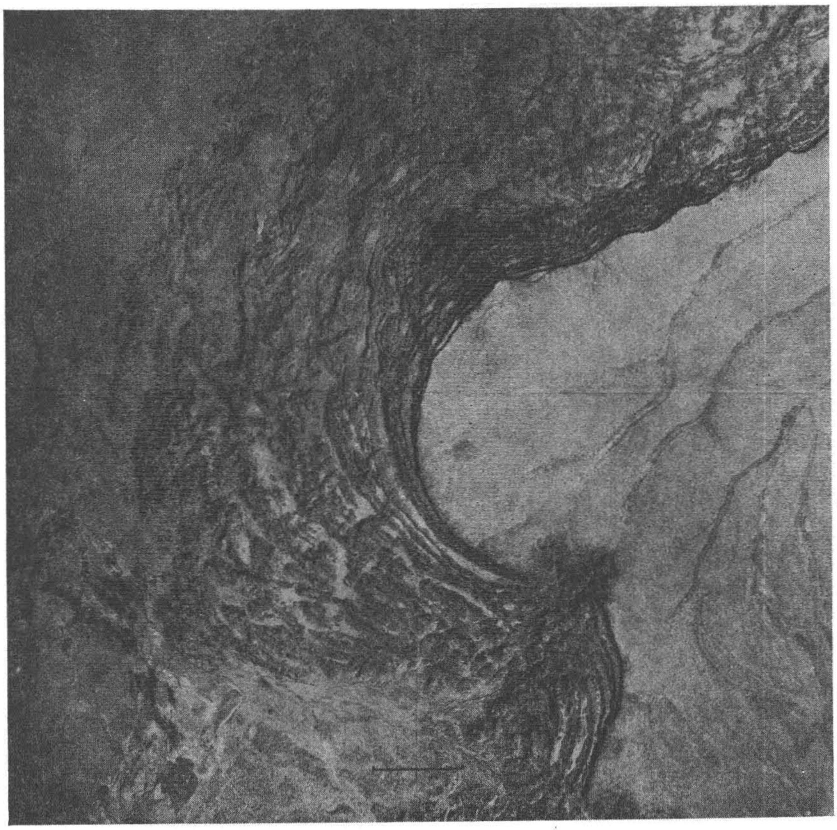

FIG. 3. Four-lens composite photograph of landslide slopes on Lucero Mesa, near Suwanee, N. M. The black bar indicates scale, and is approximately one-half mile in length. Photo courtesy of U. S. Soil Conservation Service.

An index mosaic is one showing the serial numbers of the individual photographs. It may be either of the controlled or of the uncontrolled type, more commonly the latter. The picture which it presents, although satisfactory for many purposes, is more or less interrupted by the numbers, and a slight amount of detail is locally obscured.

THE LITERATURE ON AERIAL MAPPING

With the development of aerial photogrammetry as a science, there has grown a voluminous literature, in part highly technical, dealing with widely

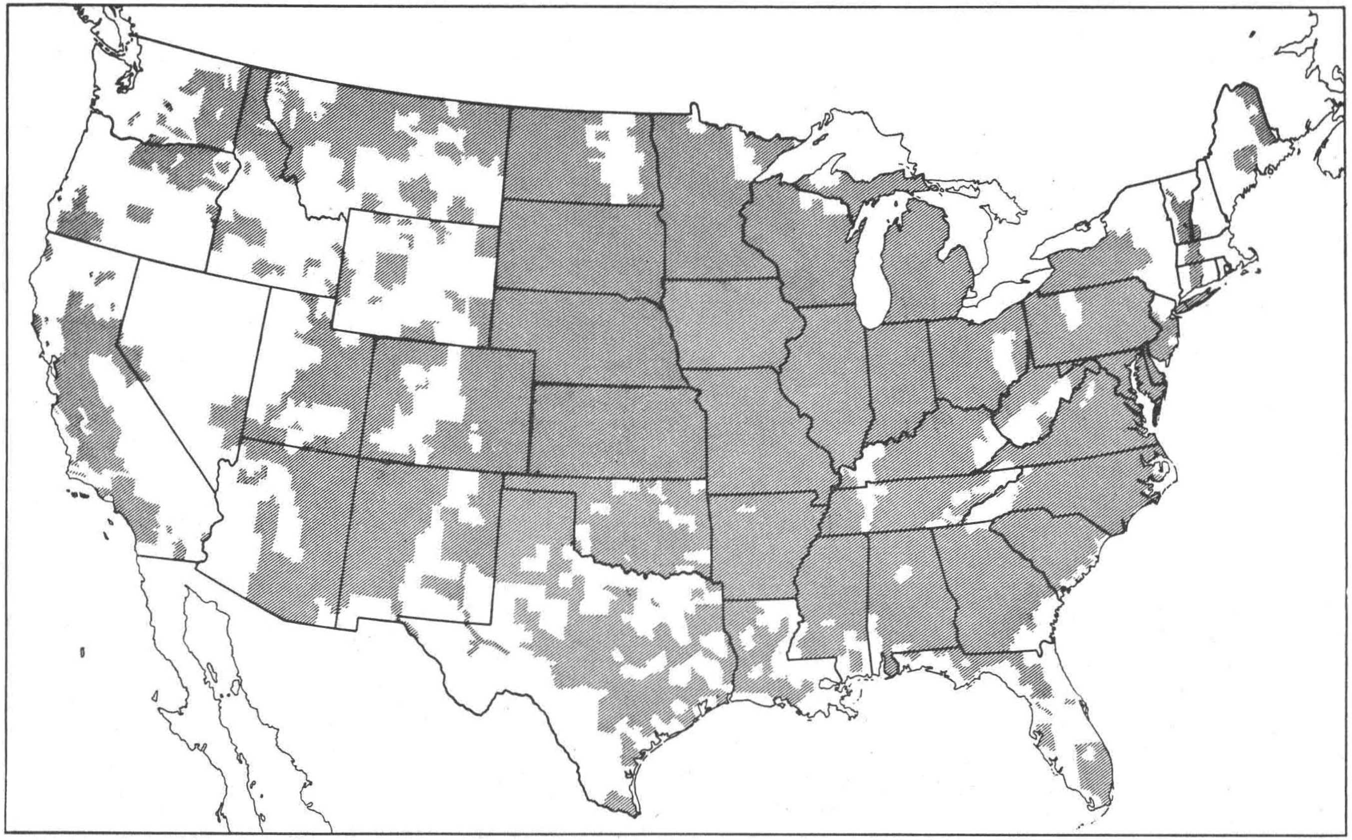

FIG. 4. Map showing extent of aerial photography for the U. S. Department of Agriculture up to Feb. 1, 1941. Additional areas are in project and areas in New England and along the Atlantic and Pacific coasts and elsewhere have been photographed by other agencies. Redrawn from a map issued by the Department of Agriculture.

varied aspects of the subject. Satisfactory introductory and summary works, however, are less numerous. Of these perhaps the most concise is found in Breed and Hosmer's manual on Higher Surveying.[7] More comprehensive are the books by Hotine[8] and by Talley,[9] either of which provides a good introduction to aerial cartography, although the latter is more up-to-date. More specialized and more technical in character are the discussions by Sharp[10] and by von Gruber.[11] Other works relating to the field are those by Reeves,[12] Winchester and Wills,[13] McKinley,[14] and Hart.[15] For an outline of practical procedure, two of the Training Manuals of the U. S. War Department[16] are also of interest.

An exhaustive bibliography on photogrammetry and its applications, up to 1936, is found in PHOTOGRAMMETRIC ENGINEERING,[17] Vol. 2, No. 4. Subsequent developments are reported in later issues of the same journal, in *The Military Engineer*, and in other technical journals.

The applications of aerial photographs to geological studies, particularly in the field of economic geology, are discussed in many recent papers, of which those by the following authors are representative: Willcox,[18] Eliel,[19] van Nouhuys,[20] Loel,[21] Desjardins and Hower,[22] and Reed.[23]

AVAILABILITY OF AERIAL PHOTOGRAPHS

To date, roughly two-thirds of the continental area of the United States has been photographed from the air (Fig. 4), mainly by or for the following Federal agencies:[24]

Geological Survey
Coast and Geodetic Survey
Army Corps of Engineers
Tennessee Valley Authority

[7] Breed, C. B., and Hosmer, G. L., *The Principles and Practice of Surveying, Vol. II, Higher Surveying*, 5th ed. John Wiley & Sons, New York, 1938. Chaps. 8 and 9.

[8] Hotine, M. *Surveying from Air Photographs*, Richard R. Smith, Inc., New York, 1931.

[9] Talley, *op. cit.*

[10] Sharp, H. O., *Photogrammetry*. Edwards Brothers, Ann Arbor, Mich., 1937.

[11] von Gruber, O. (translated by McCaw, G. T., and Cazalet, F. A.), *Photogrammetry, Collected Lectures and Essays*. Amer. Photog. Pub. Co., Boston, 1932.

[12] Reeves, *op. cit.*

[13] Winchester, C., and Wills, F. L., *Aerial Photography*. Chapman and Hall, London, 1928.

[14] McKinley, A. C., *Applied Aerial Photography*. John Wiley & Sons, New York, 1929.

[15] Hart, C. A., *Air Photography Applied to Surveying*. Longmans, Green & Co., New York, 1940.

[16] No. 2180-5 Topography and Surveying—Map and Aerial Photograph Reading. Govt. Printing Office, Washington, D. C., 1938. No. 2170.6. Air Corps—Aerial Photography. Govt. Printing Office, Washington, D. C., 1938.

[17] Published by The American Society of Photogrammetry, P. O. Box 18, Benjamin Franklin Station, Washington, D. C.

[18] Willcox, H. C., Value of Aerial Photographic Surveying and Mapping to Petroleum Companies and their Geologists. *Amer. Inst. Min. & Met. Eng.*, Production of Petroleum in 1924, New York, pp. 78–81, 1925.

[19] Eliel, L. T., Aerial Reconnaissance and Contour Mapping in Mining. *Amer. Inst. Min. & Met. Eng.*, Tech. Pub. No. 756, pp. 4–20, 1936.

[20] van Nouhuys, J. J., Geological Interpretation of Aerial Photographs. *Amer. Inst. Min. & Met. Eng.* Tech. Pub. No. 825, 18 pp., 1937.

[21] Loel, Wayne, Use of Aerial Photographs in Geologic Mapping. *Amer. Inst. Min. & Met. Eng.*, Tech. Pub. No. 890, 54 pp., 1938.

[22] Desjardins, L., and Hower, S. G., Geologic, Topographic and Structural Mapping from Aerial Photographs. *Amer. Petrol. Inst.* Volume on Finding and Producing Oil, 1st ed., Dallas, Tex., 1939, pp. 29–33.

[23] Reed, J. C. The Use of Airplane Photographs in the Geologic Study of the Chichagof Mining District, Alaska. PHOTOGRAM. ENG., 6, 35–44, 1940.

[24] Wright, *op. cit.*

Department of Agriculture:
- Soil Conservation Service
- Agricultural Adjustment Administration
- Forest Service

In addition, some photographs have been made also for state and local governments, and for private enterprises. Of the photographs made for the Federal government, the great majority belong to the Department of Agriculture and are verticals made with a single-lens camera on a scale of 1:20,000. The size is generally about 7×9 in. or 9×9 in. In some areas, however, multi-lens cameras have been employed, producing larger photographs on a smaller scale. Those for large areas in the southwest measure about 10×10 in., and are on a scale of 2 inches to the mile. All pictures are marked with serial numbers, and many also are dated. Negatives for many photographs are filed in central offices at Washington, D. C., and others in regional offices elsewhere. Department of Agriculture prints or enlargements for local areas are generally available for examination in district offices, which are to be found in nearly every county within the agricultural areas of the country.

Index mosaics, mostly of the uncontrolled type, are available for much of the area photographed. They range in scale from about 1 to 2 miles per inch. Although intended primarily for reference to the contact prints for individual localities, they may also be used as maps. Despite inaccuracies, they constitute the best base maps available for many areas otherwise unmapped or poorly mapped. For some regions, controlled mosaics have been prepared on scales of up to 2 inches per mile. Where available, these provide excellent base maps for geologic and geomorphic studies.

Reproductions of aerial photographs and mosaics belonging to the Department of Agriculture may be obtained from the various offices of the Department at very moderate cost. Information on purchasing procedure may be had from district offices, or from the Office of Plant and Operations, Department of Agriculture, Washington, D. C. General information on areas covered by aerial photographs may be obtained from the Map Information Office, Federal Board of Surveys and Maps, Room 7206, North Interior Department Bldg., Washington, D. C.

Where aerial photographs of the desired type or scale are not otherwise available, it is entirely feasible for the geomorphologist himself to act as photographer. Any well-constructed camera having a fast lens and shutter and suitable film capacity may be employed. Those using 35 mm. film, such as the Leica and Contax, are particularly well qualified. For vertical photos, a plane with an opening in the floor of the cockpit or cabin is desirable. A bull's-eye level attached to the back of the camera, together with a rapid-winding device, are helpful, particularly when overlapping verticals are desired for stereoscopic study. Further information may be found in the discussions by Gaty[25] and by Ashworth.[26] Oblique photographs may be taken over the side of the plane, or through the cabin window. The precautions to be observed are mainly those of protecting the camera from engine vibrations and from air currents. An excellent series of photographs made in this way has been published by Rich.[27]

[25] Gaty, P. P., Aerial Photography. Chap. 27 in Morgan, W. D., and Lester, H. M. *The Leica Manual*, 2nd ed. Morgan and Lester, New York, 1937.

[26] Ashworth, F. L., Aerial Mapping. *Leica Photography*. Vol. 6, No. 9, pp. 7 and 16, 1937.

[27] Rich, J. L., A Bird's-Eye Cross Section of the Central Appalachian Mountains and Plateau: Washington to Cincinnati. *Geog. Rev.*, 29, 561–586, 1939.

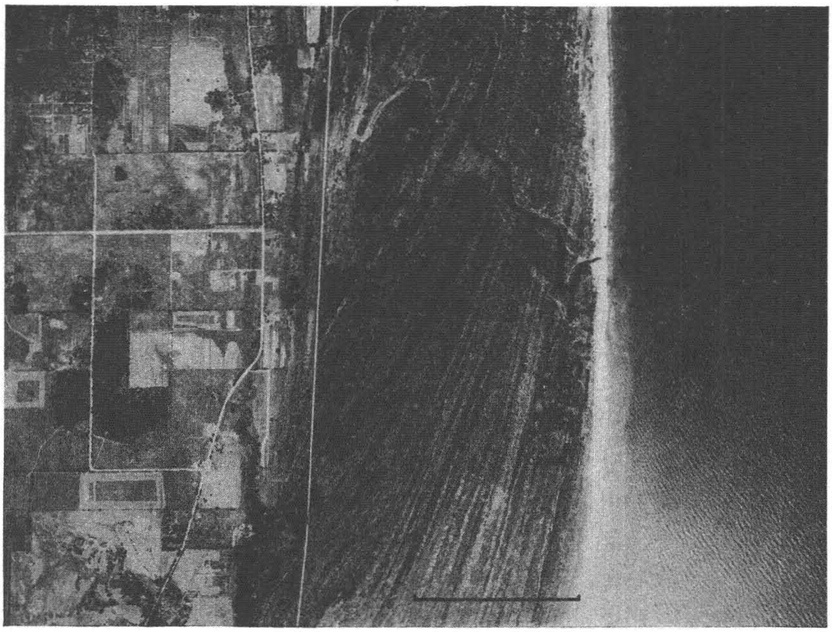

FIG. 5. Beach and dune ridges along the shore of Lake Michigan between Waukegan and Zion City, Ill. These features fail to register on the 10-foot contours of the Waukegan, Ill.-Wis., topographic sheet. The black bar indicates scale, and is about one-half mile in length. Photo courtesy of U. S. A. A. A.

INTERPRETATION OF VERTICAL AERIAL PHOTOGRAPHS

The interpretation of aerial photographs involves: (1) the identification of drainage, relief, and cultural features, and (2) a recognition of the significance of these features in terms of bedrock geology and geomorphic history. The principles of interpretation are essentially similar to those for topographic maps, but there are certain dissimilarities in application, arising from inherent differences between photographs and maps. These differences may be summarized in the statement that photographs are more faithful to nature than are maps in recording detail qualitatively, but are less accurate quantitatively, in terms of horizontal and vertical scale. Further explanation of the latter point is deferred to later paragraphs. In the representation of qualitative detail, however, aerial photographs give a far more complete picture than is possible on maps of comparable scale. Soil and vegetal features, as well as topography, drainage, and culture, are shown in maximum detail. Nothing is generalized, and everything is displayed as it would appear to the eye from the air, rather than through the media of conventional symbols. Interpretation is thus easier and more naturalistic than for maps, although less so than for high obliques or from ground photographs, owing to the absence of perceptible linear perspective in the verticals.

Cultural features, such as roads, trails, railroads, fence lines, buildings, artificial excavations, cultivated fields, orchards, etc., generally are readily distinguishable on aerial photographs. For further discussion on their interpretation, the reader is referred to the books by Reeves[28] and by Talley.[29]

[28] Reeves, *op. cit.*, Chap. 8.
[29] Talley, *op. cit.*, pp. 32–39.

The recognition of drainage features—streams, ditches, canals, lakes, ponds, and swamps—presents no particular problems.[30] Stream patterns are easily seen in all their detail, and the ghost-like evidences of channel shifting are much clearer on photographs than they are even to the observer in the field (Fig. 2). Bodies of standing water are represented by a uniform tone of black to white (Fig. 5) if the water is calm, or by a ruffled color pattern if the water surface is wavy; the amount of sunlight reflected directly toward the camera is the controlling factor. Under favorable conditions, certain subaqueous features, as sand bars, are shown by the appearance of the water surface.[31] Swamps are shown

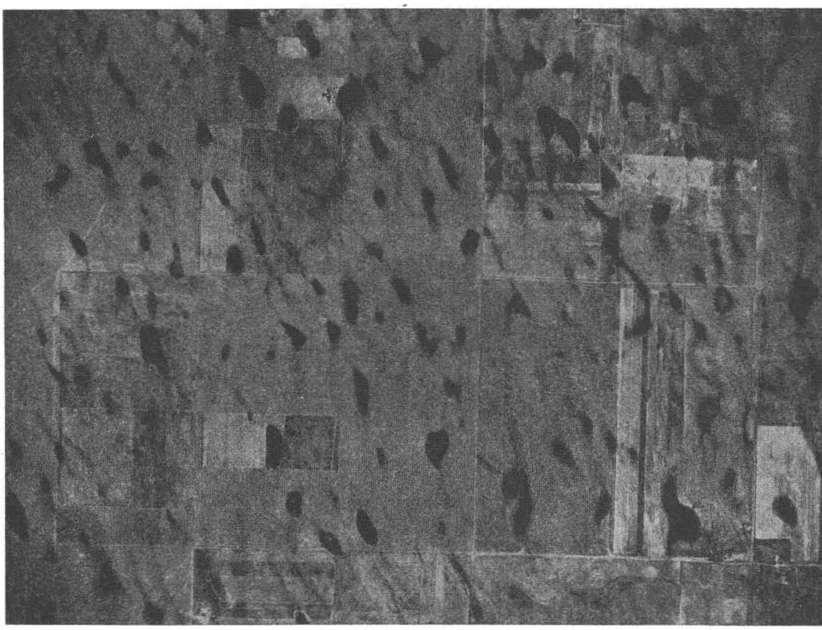

FIG. 6. Undrained depressions in southeastern Washington County, Colo. Probably an old-age dune topography, although possibly solution and collapse may have played a part. The section-line roads indicate scale. Photo courtesy of U. S. Soil Conservation Service.

in the darker shades of gray, and commonly are characterized also by distinctive textures, related to vegetal development. Undrained depressions (Fig. 6) may be represented by centripetal drainage lines, by bodies of standing water, or by patches of darker color conditioned by the character of soil and vegetation.

Relief features, on individual prints and on mosaics, are outlined roughly by the drainage pattern itself, and are represented also, to a greater or lesser extent, by shadows, by contour cultivation where present, and by differences in coloration related to variations in soil, vegetation and moisture conditions.[32] Under favorable conditions of topography and lighting, the photograph may have the appearance of a shaded relief map. If, on viewing the photograph, the relief appears to be reversed, with the streams flowing on ridge crests, it indicates only that the orientation of the photograph with respect to the light source

[30] Lee, *op. cit.*, Chaps. 6 and 9. Reeves, *op. cit.*, Chap. 7.
[31] Lee, *op. cit.*, Chap. 8.
[32] Reeves, *op. cit.*, Chaps. 5 and 6.

should be changed by rotating the photograph through an arc of from 90° to 180°.[33] Under unfavorable conditions, the photograph may have a flat appearance, and show relief indifferently if at all. With such photographs, and to no less a degree with others as well, it is only by stereoscopic examination that their wealth of topographic detail may be fully realized.

Stereoscopic study is possible only with overlapping photographs, and it is only the area included in the overlap which may be so examined. Adequate overlap, however, is provided by the great bulk of prints now available. The instrumental equipment employed varies widely in elaborateness and in cost, but is simple in principle.[34] There are two main types of stereoscopes, one employing a set of four mirrors, and the other employing a pair of lenses.[35] Either type may be constructed with little difficulty. The mirror type has the advantage of providing a larger field of view, and of allowing the prints to be placed sufficiently far apart to avoid interference. Unless auxiliary magnification is incorporated, however, it has the disadvantage of showing detail on a smaller scale. The other type of stereoscope utilizes two lenses having a magnification of from about 1.5 to 4.5 diameters. For the lower ranges of magnification, these lenses are preferably of prismatic form. The old-fashioned parlor stereoscope was of this type, and its lenses may be used for viewing aerial photographs when little magnification is desired. A similar instrument may be improvised by mounting two matched lenses having a focal length of from 3 to 8 inches in a suitable support. Lenses costing as little as ten cents apiece may be used, although those of better quality afford a picture of greater clarity and less distortion. The lens type of stereoscope has the advantage of showing detail on a larger scale, and the disadvantage of a smaller field of view, together with a narrower working strip, limited in width either to the interpupillary distance, or, if prismatic lenses are used, to a distance of a few tens of per cent greater. Where the amount of overlap is more than twice as great as the interpupillary distance, a part of the photograph will be excluded from stereoscopic examination with this type of equipment. For general use, a stereoscope of about 2.5 diameters magnification is perhaps most convenient.

With some practice, it is possible for most persons to dispense entirely with instrumental aid in studying photographs stereoscopically, except where magnification is needed.[36] This requires the disassociation of convergence and accommodation (or focus), which in normal binocular vision are automatically coordinated. Thus it is necessary that the eyes be focused for a short distance while convergence remains as for a distant object. To practice this, it is necessary only to align correctly a stereoscopic pair of prints, to select some sharply defined feature near the edge of one photograph, bring it close to its counterpart on the other photograph, and view it with a card held between the two eyes, so that the left eye sees the selected feature on the left-hand print only, and the right eye on the right-hand print only. It should then be possible, with a few trials, to obtain a fused image in stereoscopic relief. This done, the separation between the matched points is gradually increased, and the card is removed. After a few weeks of practice a separation of 2.4 inches or more should be attainable, and this direct method of stereoscopic study soon becomes easy and natural.

[33] Reeves, *op. cit.*, Chap. 4. U. S. War Dept. Training Manual No. 2180-5, *op. cit.*, pp. 99, 101.

[34] Hotine, *op. cit.*, Chaps. 2 and 3. Talley, *op. cit.*, Chap. 9.

[35] Various models of stereoscopes may be purchased from: Harrison C. Ryker, 365 Fifth St., Oakland, Calif.; Fairchild Aerial Camera Corp., Woodside, New York City; Bausch & Lomb Optical Co., Rochester, N. Y.; Abrams Instrument Co., Lansing, Mich.; Carl Zeiss, Inc., 485 Fifth Ave., New York City.

[36] Talley, *op. cit.*, pp. 221–222.

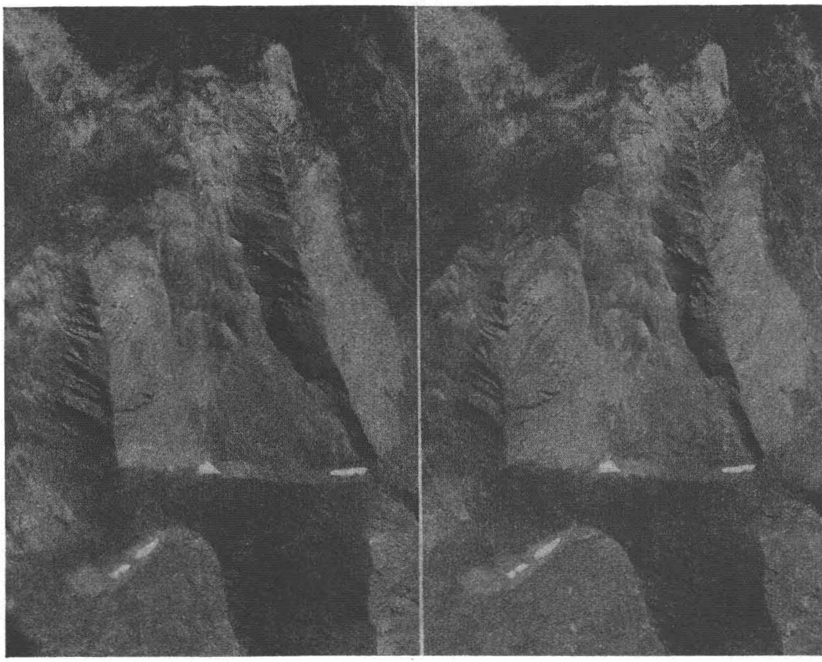

FIG. 7. Stereoscopic pair of photographs showing cirque and glaciated valley in the Culebra Range of southern Colorado, west of the Spanish Peaks. Each picture is approximately 1.1 miles in width. These photographs may be viewed either with a simple lens type of stereoscope, or with the unaided eye. Photos courtesy of U. S. Forest Service.

Viewed stereoscopically, aerial photographs have the semblance of a relief model (Fig. 7), and the third dimension presents an appearance of striking actuality. Relative relief, in fact, is considerably exaggerated, so that even slight topographic irregularities are clearly discernible. Without stereoscopic examination, it is impossible to exploit fully the wealth of detail which the photographs contain, and recognition of the less obvious topographic features is enormously handicapped.

The geologic interpretation of aerial photographs is based partly on the topographic expression of rock bodies, as viewed stereoscopically, and partly on differences in color tone related to soil and rock coloration, to vegetal zoning, and to soil moisture conditions (Fig. 8). Faults, flexures, dikes, veins, unconformities and other structural features commonly have a distinctive appearance from the air, even where their relations may be none too clear to the observer on the ground. Excellent illustrations of structural features as seen from the air may be found in the papers by van Nouhuys[37] and by Loel.[38] Obviously the clarity with which geologic features are displayed is conditioned by climate, being greater in arid and semiarid regions. Other variations are related to: (1) the season of year at which the photograph was taken; (2) the time of day at which the exposure was made; (3) antecedent weather conditions; and (4) the extent to which natural features have been modified or obliterated by the work of man.

[37] van Nouhuys, *op. cit.*
[38] Loel, *op. cit.*

FIG. 8. Ancient surface beveling steeply dipping beds of Arbuckle limestone in the Arbuckle Mountains of Oklahoma. Note minor faults, surface expression of beds, and indifference of drainage to structure. The black bar indicates scale, and is about one-half mile in length. Photo courtesy of U. S. Soil Conservation Service.

The geomorphic interpretation of aerial photographs is essentially similar in principle to that of contour maps. Differences lie only in the more naturalistic appearance and greater detail provided by photographs, and in the want of quantitative data on slopes, gradients, and actual relief (unless contouring methods, described in later paragraphs, are first applied). What is lacking in the one medium is present in the other, and, where both are available, the two thus complement one another ideally. On aerial photographs, the relation of bedrock geology to topography is generally shown more clearly and more fully than on topographic maps, and with but little practice the characteristic erosional and depositional forms associated with the work of slope processes (Fig. 3), streams[39] (Fig. 2), glaciers[40] (Fig. 7), wind[41] (Fig. 9), waves[42] (Fig. 5), and ground water[43] may be readily identified. With further experience, deductions as to the origin and chronologic development of landforms may be made, and geomorphic inter-

[39] Melton, F. A. An Empirical Classification of Flood-Plain Streams. *Geog. Rev.*, 26, 593–609, 1936.

[40] *Luftbild-Topographie*. Hansa Luftbild, Berlin, 1936. Distributed by Carl Zeiss, Inc., 485 Fifth Ave., New York City. Contains excellent illustrations, in part stereoscopic, of a wide variety of landforms.

[41] Aufrere, L., Utilisation de la photographie zénithale dans l'etude morphologique et dans la cartographie des dunes. *Comptes Rendus du Congrès Int. de Géog.* Paris, 1931. Paris, 1932. *Tome premier*, pp. 155–162. Melton, F. A., A Tentative Classification of Sand Dunes, its Application to Dune History in the Southern High Plains. *Jour. Geol.*, 48, 113–174, 1940. Smith, H. T. U., Geologic Studies in Southwestern Kansas. *Kans. Geol. Surv. Bull. 34,* Pl. 24, 25, 27, 28, 1940.

[42] Lee, *op. cit.*, Chaps. 8 and 12.

[43] Dicken, S. N., Soil Erosion in the Karst Lands of Kentucky. U. S. Dept. Agri. Circ. No. 490, Figs. 18, 21, and 22, 1938. Smith, *op. cit.*, Pl. 30.

FIG. 9. Dunes northeast of Tuba City, Arizona. Longitudinal, transverse, "parabolic," and complex types are represented. The black bar indicates scale, and is about one-half mile in length. Photo courtesy of U. S. Soil Conservation Service.

pretations formulated. This aspect of the topic is discussed more fully in later paragraphs.

In all phases of the interpretation of vertical aerial photographs, the importance of continued cross-reference between photograph and terrain in the field cannot be too strongly emphasized. It is only in this way that judgment is sharpened for correctly evaluating the innumerable minor variations in form, color, and pattern so faithfully recorded by the camera.

PREPARATION OF PLANIMETRIC MAPS FROM AERIAL PHOTOGRAPHS

Maps play so important a part in geomorphic studies and in the presentation of results that the application of aerial photographs to map-making is of considerable interest. In the preparation of planimetric maps, either vertical or oblique photographs may be employed. The latter have been widely used in Canada. The methods entailed, however, are comparatively tedious,[44] and of limited interest to the geomorphologist. In this country, vertical and composite photographs are

[44] Narraway, A. M., Oblique Aerial Surveys. In McKinley, *op. cit.*, Chap. 21. Talley, *op. cit.*, Chap. 15. Miller, O. M., The Mapping of Northernmost Labrador. In Forbes, A. Northernmost Labrador Mapped from the Air. *Amer. Geog. Soc. Spec. Pub. No. 22*, pp. 165–185, 1938.

used almost exclusively.[45] Any discussion of their application to cartography entails at the outset a consideration of certain inherent differences between vertical photographs and maps of any kind. These differences have to do primarily with scale, as set forth below.

On aerial photographs, scale is not uniform except under certain ideal conditions, sometimes approached but rarely attained.[46] Ordinarily, differences in scale from one part of a photograph to another are introduced by one or more of the following factors: (1) tilting of the camera at the instant of exposure; (2) parallactic displacement of points due to relief of the topography (Fig. 10); and

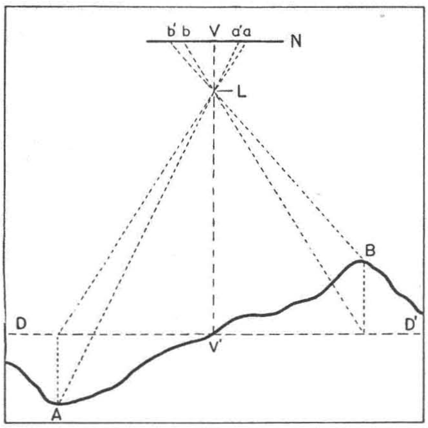

FIG. 10. Diagram illustrating distortion in scale due to parallactic displacement. *N* represents the negative film, *L* the lens of the camera, VV′ the vertical, DD′ the datum plane, and *A* and *B* two arbitrary reference points. The true projections of *A* and *B* on the film are represented by *a* and *b*, the actual projections by *a′* and *b′*; *aa′* and *bb′* represent the displacement or distortion due to parallax. Note that point *A*, below the datum plane, is displaced toward the center of the picture, while point *B*, above the datum plane, is displaced away from the center point.

(3) differential shrinkage of film or paper, or both. In addition, changes of scale from one photograph to another result when the aeroplane is unable to maintain a constant altitude. Of these factors, parallactic displacement is perhaps the most important. It varies inversely with the altitude at which the photograph was taken, and directly with the distance from any given point to the center point (more strictly speaking, the plumb point) of the photograph, and with the difference in elevation between these points. The amount of displacement due to this factor may be computed by a simple equation.[47] Examples may be observed on any vertical photograph showing tall buildings, smokestacks, or towers well toward the edge of the field; the tops of these structures will appear farther from the center of the picture than their bottoms. In rugged mountainous country, displacement of this type reaches objectionable proportions, amounting to hundreds or even thousands of feet. Thus distances on aerial photographs are

[45] Woodward, L. A., Mosaic and Planimetric Mapping. PHOTOGRAM. ENG., 5, 177–182, 1939. Birdseye, C. H., Stereoscopic Phototopographic Mapping. PHOTOGRAM. ENG., 6, 109–125, 1940. Massie, E. S., Jr., Forest Service Planimetric Maps. PHOTOGRAM. ENG., 6, 151–155, 1940.

[46] Talley, *op. cit.*, Chap. 2. U. S. War Dept. Training Manual No. 2180-5, *op. cit.*, pp. 120–132.

[47] Sharp, *op. cit.*, pp. 27–28. U. S. War Dept. Training Manual No. 2180-5, *op. cit.*, pp. 121–122.

not to be regarded as true to scale. Only when an area of negligible relief is photographed with the optical axis of the camera in an exactly vertical position from a plane flying at a constant altitude can the photograph or mosaic provide a strictly accurate representation of the land surface.

The planimetric maps used by geomorphologists fall into two general classes: (1) large scale maps of small areas to show detailed geomorphic features, and (2) base maps of larger areas on smaller scales. Those of the first class, commonly sketch maps, may be prepared by direct transfer of the desired detail from contact prints of vertical photographs. This may be done in any one of the following ways: (1) By tracing on to any suitable transparent medium. For this purpose, a thin sheet of transparent celluloid with one side frosted[48] is advantageous. This method is perhaps the simplest and quickest. (2) By the use of a pantograph. This permits either enlargement or reduction if desired. (3) By inking the desired features on the print directly, and then bleaching out the photographic detail. This, of course, has the one disadvantage of destroying the photograph itself. (4) By the use of a camera lucida. For persons having normal vision in both eyes, a mirror stereoscope may be employed, by placing the photograph under one mirror and a sheet of drawing paper under the other. The pencil point on the latter, when lighting is properly adjusted, will appear to be in contact with the features on the former, and any desired degree of detail may be traced.

The accuracy of maps prepared by any of the above methods depends to a large extent on the relief of the topography. In relatively flat areas, the amount of error is insignificant, unless tilt is in excess of that permitted by standard specifications. In areas of rugged topography, however, where local relief ranges up to hundreds or thousands of feet, considerable distortion is inevitable unless some method of correction, such as the radial line method mentioned below, is employed.

The preparation of base maps for areas of such extent as to require a large number of photographs for their coverage presents additional problems. Where mosaics have already been prepared, base maps may of course be traced directly from them, if they provide the desired degree of accuracy. Where only contact prints are available, however, there arises the problem of accurately aligning and assembling these prints. Several methods are feasible, and choice among them depends both on local conditions and on the degree of accuracy desired.

In areas of moderate relief where the township, range, and section method of land subdivision is used, and section-line roads are numerous, topographic and cultural detail may be compiled from the photographs by direct transfer to a section-line grid. If the grid is on the same scale as the average for the photographs, this may be done simply by tracing. If the land-line map is on a smaller scale, the transfer may be effected by the use of a pantograph or projection lantern, or by free-hand sketching. Similar procedure may be employed in revising other types of preexisting base maps, provided that the latter show a sufficient number of features common also to the photographs to allow each photograph to be correctly oriented with respect to the map.

Where section-line roads or other guides are absent, the assemblage must be based on internal features of the photographs themselves. The simplest method—but the least accurate—consists in "shingling" the prints by matching points along the edge of one print with corresponding points inside the adjoining print. Once aligned, the prints may be fixed in position by stapling to a board or by the use of scotch tape on the reverse side. The result is an uncontrolled mo-

[48] Sold under the trade name "Trace-O-Film" by The Lustro Co., 117–125 E. 13th St., Chicago, Ill.

FIG. 11. Dissected pediments along the Chama Valley in the Abiquiu quadrangle, New Mexico. The scale bar indicates a distance of about one-half mile. Photo courtesy of U. S. Soil Conservation Service.

saic, and from it a map may be prepared by tracing or by one of the other methods described above.

A variation of the matching method, designed to increase accuracy somewhat, is based on the matching of points within the overlap area of successive prints, rather than on the edge. Two or more control points well within the overlap area are selected and marked on one print, and then are located and marked on the next print under the stereoscope. Where the amount of overlap exceeds 50 per cent, the center points of the prints are particularly valuable for orienting them in the line of flight. Detail is then traced from each print separately, adjustment of the tracing sheet from one print to another being determined by superimposition of control points traced from the last print to corresponding points on the next print. In order to minimize distortion, only the central part of each print is used in compilation. Where points fail to match exactly, compromise is necessary, and if these discrepancies are too numerous or too large, the need for a more accurate method of assemblage is indicated. Barring such difficulties, a map of moderate accuracy is readily to be had by this method. If reduction in scale is desired, this may be effected photographically or by the use of the pantograph. The average scale of the final map may be determined by measurement between points separated, on the ground, by a distance already known or easily measurable. More complete adjustment to ground control would naturally increase the accuracy of the map, but is hardly practicable for others than professional cartographers.

Where the relief of the topography or other factors are such as to introduce objectionable distortion of scale, the simpler methods outlined above are inadequate, and a more elaborate procedure is necessary. This involves the adjustment of the prints to one another and to ground control points by a system of office triangulation. Using the line connecting the center points of the first two prints as a base line, the true position of selected reference points is determined by the intersection of radial lines from the center points of successive prints. A complete exposition of this method is obviously beyond the scope of the present paper, but may be found in the literature.[49] For many areas in the west, large-scale base maps have already been prepared by this method by the Forest Service[50] and the Soil Conservation Service.[51]

On maps prepared by any of the above methods, many special features of geomorphic interest may be included—shore features, sand dunes, sinks, glacial landforms, the outlines of dissected erosion surfaces, etc.—either in preparation for anticipated field study, or in the light of field study already completed. Thus the writer, after completing a field sketch map of erosion surfaces in the Abiquiu area, New Mexico, was enabled, through a study of aerial photographs (as Fig. 11), to completely remap the area in much greater detail. Had the aerial photographs been available prior to field study, the greater part of the physiographic mapping could have been done in the office, leaving for the field only certain problems of correlation and verification, thus considerably reducing the time necessary for field work.

Construction of Contour Maps from Aerial Photographs

Aerial photographs may be used for the construction of contour maps in three ways: (1) as the base for a plane table survey, (2) by the use of mechanical contouring instruments based on the principles of parallax, and (3) by controlled sketching, either in the field or in the office. Choice between these methods depends on the degree of accuracy required, on the scale and contour interval to be used, on the equipment to be had, and on the time available.

For large-scale maps of small areas, where considerable detail is desired and the distortion occasioned by topographic relief is not too great, the contact print or enlargement may be used directly on the plane table. For larger areas on a smaller scale, controlled mosaics may be utilized where available, or a planimetric map first compiled from the aerial photographs may be used with the plane table. The latter procedure is used in some areas by the Topographic Branch of the U. S. Geological Survey.[52]

Mechanical contouring devices are of many types and represent many degrees of precision. All require some degree of ground control. Only the simplest types, such as the Talley-Fairchild Stereo-comparagraph,[53] the Zeiss Tracing Stereometer, and the Abrams Contour Finder, are feasible for use by others than

[49] Sharp, *op. cit.*, pp. 44–50. Breed and Hosmer, *op. cit.*, pp. 400–406. Talley, *op. cit.*, Chap. 13. The Use of Aerial Photographs for Mapping. *Can. Topog. Surv. Bull. No. 62*, pp. 41–57, 1932. McCurdy, P. G., Manual of Aerial Photogrammetry. Hydrographic Office, U. S. Navy Dept., Washington, D. C., pp. 43–57, and Fig. 21, 1940.

[50] Massie, *op. cit.*

[51] Woodward, *op. cit.* Cude, W. C., Planimetric Mapping in the Soil Conservation Service. Photogram. Eng., 6, 131–135, 1940.

[52] Wright, *op. cit.*

[53] Talley, *op. cit.*, pp. 542–551.

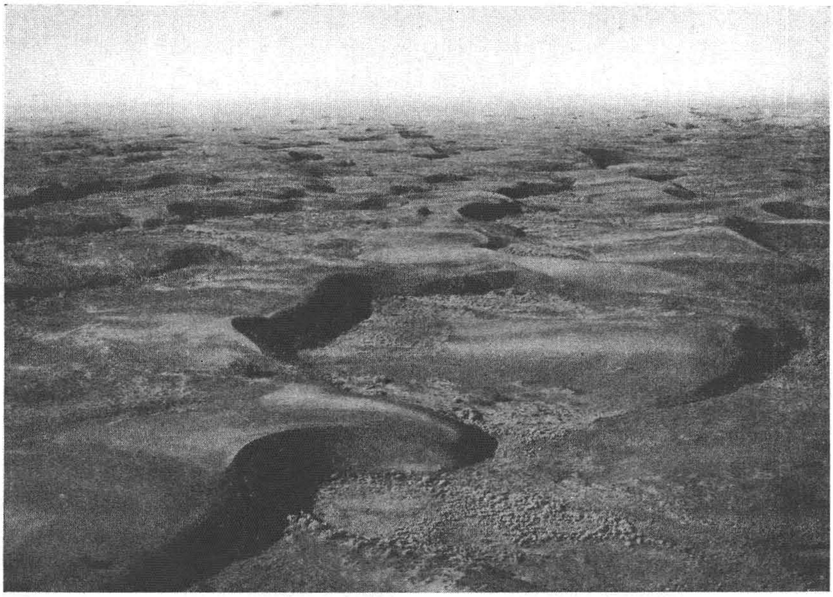

FIG. 12. High oblique photograph of sand dunes south of Moses Lake, Washington. It is impossible to photograph such features as these very satisfactorily from the ground. Photo courtesy of U. S. Soil Conservation Service and 41st Division Aviation, Washington National Guard.

professional carographers. These are all essentially similar in operation, being based on the simple principles of parallactic displacement of points, which may be summarized as follows: the horizontal distance between corresponding points on the overlap area of two successive prints correctly oriented in the direction of flight, when measured parallel to the line of flight, is the same for all points of the same elevation, but is different for paired points of different elevation, decreasing systematically as the height of the points increases. The difference between the measured distances separating two pairs of points at different elevations is termed the *Parallactic displacement*, and may be expressed in terms of a simple equation.[54] The principle is illustrated by stereoscopic examination of two sets of dots separated by different distances.[55] In the instruments listed above, two "floating marks," controlled by precise adjustments, are superimposed on the oriented photographs under the stereoscope. When so adjusted as to fuse into a single mark which appears to be in contact with the stereoscopic relief model, a form line representing the elevation of the contact point may be traced by so moving the instrument as to maintain continuous contact between the mark and the relief model. By changing the distance between the two marks, form lines may be drawn in similar fashion at other elevations. To draw these form lines on a specified contour interval, it is necessary either to start from points of known elevation, as determined by previous field survey, or to calculate parallactic displacement from data on the spatial relations of the photographs, if these are known. Where the necessary equipment is available, this method provides a convenient, fairly rapid, and easily learned technique for the preparation of contour maps of moderate accuracy for limited areas.

[54] Sharp, *op. cit.*, pp. 28–29; Breed and Hosmer, *op. cit.*, pp. 390–391.
[55] Hotine, *op. cit.*, p. 19; Talley, *op. cit.*, p. 207.

The method of contouring by controlled sketching is less accurate, but requires no special equipment and is more rapid. It may be carried on either in the field or in the office, or partly in each. Ground control is established by the use of the hand level, plane table, or other surveying methods in the field. Guided by the control points thus determined, and by the stereoscopic image itself, contours are sketched on the prints or on a transparent overlay, as of Trace-O-Film. According to Desjardins,[56] it is possible, with sufficient experience, to sketch contours with considerable accuracy in the office, relying mainly on the trained eye for estimates of vertical distance. A mechanical aid to contour sketching is found in the Barr and Stroud Topographical Stereoscope,[57] which superimposes a reference grid over the stereoscopic image, and provides for adjustments which change the apparent height of the grid.

Aerial Photographs for Purposes of Illustration

For illustrating geomorphic discussions, both aerial photographs and maps prepared from them may be used. For showing the broader relations of many geologic and geomorphic features, high obliques are ideal. Over ground photographs they have the advantage of unlimited choice of vantage point, and over vertical photographs they have the advantages of covering much larger areas, and of showing the landscape in familiar perspective. By judicious choice of altitude, angle of inclination, direction, time of day, and season of year, features difficult or impossible to photograph satisfactorily on the ground may be shown to best advantage (Figs. 1 and 12). Excellent examples may be found in the publications of Nichols,[58] Johnson,[59] Cooper,[60] Van Tuyl and Lovering,[61] Washburn,[62] Rich, [63] Melton,[64] and others. It is to be noted, however, that oblique photographs are primarily illustrative and suggestive. Although providing a bird's-eye view of certain field relations, their value as evidence on moot questions of interpretation is subject to definite limitations. The picture which they provide is not necessarily complete or true to proportion. In fact, their representation of the field facts may be decidedly selective in some instances, for the vantage point best suited to show some features may entail the suppression or distortion of others equally significant, particularly in areas of strong relief. Linear perspective is sometimes misleading, distances, directions, and elevations being confused through foreshortening. Oblique photographs may supplement maps and profiles, but cannot substitute for them. Used, however, with due appreciation of these qualifying factors, they may contribute notably to the clarification of geomorphic description.

Vertical photographs may be used for illustrative purposes where a plan view is preferred, or where the effect of a pictorial map is desired. If data on elevations and gradients are important, these may be shown by contours drawn

[56] Desjardins, L., Reversing the Contouring Problem, as a Step in Geologic Structural Mapping with Aerial Photographs. Photogram. Eng., 6, 163–165, 1940.

[57] Hotine, *op. cit.*, p. 34–37. Talley, *op. cit.*, pp. 540–541.

[58] Nichols, D. A., Solifluction and other Features in Northern Canada Shown by Photographs from the Air. *Trans. Roy. Soc. Can.*, 3rd, Ser., Vol. 26, sec. 4, pp. 267–275, 1932.

[59] Johnson, G. R., Peru from the Air. *Amer. Geog. Soc. Spec. Pub. No. 12*, 1930.

[60] Cooper, W. S., The History of the Upper Mississippi River in late Wisconsin and Postglacial time. *Minn. Geol. Surv. Bull. 26*, 1935.

[61] Van Tuyl, F. M., and Lovering, T. S., Physiographic Development of the Front Range. *Bull. Geol. Soc. Amer.*, 46, 1291–1350, 1935.

[62] Washburn, H. B., Jr., Morainic Bandings of Malaspina and other Alaskan Glaciers. *Bull. Geol. Soc. Amer.*, 46, 1879–1890, 1935.

[63] Rich, *op. cit.*

[64] Melton, *op. cit.*

on the photograph. Also, topographic or geologic features of particular interest may be emphasized in ink, if need be. Where the effect of a relief model is necessary to do full justice to the landforms concerned, stereoscopic pairs of vertical photographs may be used, as shown in Fig. 7 and in the booklet, *Luftbild-Topographie*.[65] This method, although as yet virtually untouched, gives promise of providing the greatest single advance in geomorphic illustration since the introduction of the block diagram.

Aerial Photographs for Purposes of Record

In studying the progress of erosion, deposition, volcanism, and current diastrophism, accurate data on changes in the shape, size, and position of geomorphic features are necessary. This requires the comparison of detailed records of the feature in question at successive points in time. For such records, topographic maps, ground surveys, and ground photographs have been used. The record provided by aerial photographs, however, is more accurate and more complete than that afforded by any save the most elaborate maps, thus anticipating fortuitous changes and allowing an unlimited number of points for future comparison. The same area may be rephotographed at any time desired, even under conditions, such as flooding, which might render ground methods impracticable. Records of certain processes in action—floods, storm waves, dust storms, igneous extrusion—may be included in the sequence. Thus for studying shifts in stream channels, the growth and migration of dunes, glacial advance and retreat, changes in the position of shorelines, slow landslide movements, etc., aerial photographs provide an ideal medium. Photographs such as those shown in Figures 2, 5, and 9 might provide starting points for studies of this type. Either vertical or oblique photographs may be used, the former being best for quantitative comparisons, and the latter being sometimes adequate for purely qualitative comparisons. Photographs made at both the beginning and the end of the observation period are naturally desirable, but if the latter are not feasible, ground measurements made from points identified in the former may provide an adequate basis for comparison. Fortunately, however, the photographic program of the U. S. Department of Agriculture provides for the rephotographing of many areas at more or less regular intervals, and for some areas a second set of photographs is already available.

Value of Aerial Photographs in Teaching

Aerial photographs provide a valuable aid in teaching geomorphology, both in the classroom and in the laboratory.[66] In the classroom, lantern slides made from both oblique and vertical photographs provide excellent illustrative material for lectures and discussions. For some purposes, ground photographs and aerial photographs of the same localities supplement one another advantageously. Slides of selected subjects may be obtained from various commercial agencies,[67] and others may be prepared by copying photographs obtained from the sources noted on preceding pages. Although still in the developmental stage, stereoscopic lantern slide projection offers a three-dimensional picture of landforms. Equipment for this purpose is already on the market.[68]

[65] *Op. cit.*

[66] Melton, F. A , Aerial Photographs and the First Course in Geology. PHOTOGRAM. ENG., 5, 74–77, 1939.

[67] Geo-Aero Photo, P. O Box 750, Oklahoma City, Okla. Spence Air Photos, 2404 West Seventh St., Los Angeles, Calif.

[68] Stereoscopic projection machines may be obtained from: Bausch & Lomb Optical Co., Rochester, N. Y., and The Three Dimension Corp., 1162 Merchandise Mart, Chicago, Ill.

In the laboratory study of geomorphology, attention is commonly centered on the areal relations of landforms. Topographic maps have long been used as the basis for this mode of approach. But although their value is unquestionable, they represent the land surface only in its grosser aspects,[69] and only through the intermediacy of conventional symbols. What is lacking in topographic maps, however, is fully provided in vertical aerial photographs. Both for the beginner and for the advanced student, these provide an ideal medium for bringing the field into the laboratory.

For elementary classes, aerial photographs contribute to a more vivid and naturalistic picture of topographic features. Their pictorial character minimizes the problems of interpretation, permitting a more direct and rapid acquaintance with selected examples of the various types of landforms. The only limitations on this method of instruction are those of an economic nature, particularly where large laboratory classes are involved. Photographs are less durable than maps, and the initial cost is greater. Stereoscopic equipment is still another item of expense. These problems, however, may be at least partially solved by training students to see stereoscopically with the unaided eye, by improvising equipment for the minority who cannot readily do this, and by devising a rotation system whereby each set of photographs is studied by the individual student for a limited time, and then is passed on to the next student. The use of half-tone or full-tone reproductions of selected photographs would offer a more satisfactory solution, but, to be efficient, would require the services of some centralized distributing agency.

For courses of more technical character, aerial photographs may be used in many ways. Exercises of the familiar question-and-answer type may be forced to focus the student's attention on significant features, and familiarity with the detailed form and pattern of erosional and depositional features may be acquired through the preparation of outline maps, hachure maps, or contour maps from the photographs, using methods outlined on preceding pages. Geologic as well as topographic features may be studied in this way, and the influence of the former on the latter clearly delineated. From the study of simple landforms the student may be led to the analysis of more complex topography, with the application of criteria for multi-cycle history and the tracing of successive stages in the geomorphic evolution of selected areas, such as those shown in Figures 5 and 11. Particularly instructive is the use of aerial photographs and contour maps of the same areas. A proper coordination of the two media leads to a better appreciation of their respective advantages and limitations, and of their mutually complementary character.

For advanced studies in geomorphology, the possibilities disclosed through the use of aerial photographs are quite as unlimited as those afforded by the use of thin sections in studying rocks. Photographs of new areas repeatedly present new problems of interpretation, suggest new hypotheses, and lead to new field projects. Although the basic principles of interpretation are quickly mastered, skill in the recognition and appraisal of innumerable minor forms, patterns, and color tones continually enlarges with experience. A broad new field of geomorphic interpretation awaits the user of this new technique, and with its more widespread application we may anticipate that present concepts in the science will be greatly refined, if not in some measure revised.

[69] For example, compare Fig. 5 with the corresponding topographic map, or Plates 27 and 28 in Smith, *op. cit.*, with the Syracuse and Garden City (Kansas) maps, respectively. Yet these and adjoining quadrangles have been used in many laboratory manuals to illustrate typical dune topography.

Aerial Photographs as an Aid in Field Studies

Throughout the course of a field project, from the laying of plans through the field survey itself to the completion of the manuscript, aerial photographs may render invaluable service. During the preparatory stage, preliminary study of photographs in the office provides a basis for more effective planning of the field work to follow. The general nature of the problem is scrutinized, working hypotheses are evolved where possible, specific questions to be answered in the field are raised, the accessibility of field areas is noted, and base maps showing features of geomorphic interest may be prepared. As a result, the actual time spent in the field is used more efficiently, and each step in the work becomes more purposeful.

Field study, in general, involves the following steps: (1) the outlining of the problem, (2) the search for significant localities or exposures where clues to the solution of the problem may be revealed, and (3) interpolation between these localities by traversing or aerial mapping, frequently a more or less routine procedure. These steps may be taken either by reconnaissance or by detailed methods, or by a combination of the two. Specific applications of aerial photographs vary with the mode of approach to be followed.

Field reconnaissance frequently constitutes the initial stage in a geomorphic project. It may be devoted to a delimitation of the problem, to the formulation of working hypotheses, and to the selection of place and methods of attack. During this stage of the work, aerial mosaics are especially helpful, and even the rough, uncontrolled type is valuable. Where topographic maps are available, they may be used in conjunction with the mosaics. On entering the field, the mosaics provide a guide in planning traverse routes, and serve as base maps for subsequent observations. Thus the writer, in studying the extensive dune fields of western Kansas, was enabled, through a study of aerial mosaics, to find critical localities which otherwise could have been discovered only by hundreds of miles of traversing requiring many weeks of time. In some cases, the study of aerial photographs and mosaics may itself take the place of preliminary reconnaissance, either wholly or in part. Upon completion of the reconnaissance, mosaics are of further assistance in interpolating between traverse lines, and thus in integrating widely scattered observations. Places most promising for detailed examination are indicated, and the need for contact prints of specific localities is suggested.

Helpful though they are, aerial mosaics are by no means unequivocal as indicators of geomorphic features. Frequently they are merely suggestive. Forms having low relief and gentle slopes may not be distinguishable without the stereoscopic view afforded by overlapping contact prints, although in many instances they are more readily seen on mosaics than on the ground. The interpretation of mosaics, in general, is facilitated by continued correlation between photographic detail and topography in the field.

In detailed field study, overlapping contact prints are preferable to mosaics. Careful stereoscopic study of the prints for critical areas on beginning field examination leads to a much clearer picture of local relations suggests specific questions to be answered on the ground, and indicates places most promising for investigation—places where sedimentary deposits are exposed, where structural affiliations may be noted, where topographic unconformities may be appraised, where the relations of ground water, soil and vegetation may be observed, where obscure features shown on the photographs may be interpreted, and where detailed maps or profiles might be desirable. During the prosecution of field study, the prints are invaluable as guide maps and location maps. Desired data may be plotted either on the prints themselves, on a transparent overlay, or on planimetric maps previously prepared from the prints. For interpolation between the localities thus detailed, the prints provide either a detailed field guide along the contacts or boundaries to be traced, or a basis for tracing these lines in the office upon completion of field work. In either case, a considerable economy of time is effected, much random traversing is avoided, and the accuracy of the results is increased.

Detailed studies of limited areas frequently provide a key for the interpretation of regional geomorphic features. In applying the results of the former to the latter, reconnaissance methods are commonly employed, and under favorable conditions critical studies of aerial photographs or mosaics alone may suffice.[70] The implications of this proceeding are discussed below.

Aerial Photographs as a Direct Basis for Geomorphic Interpretation

It is a truism to state that field facts constitute the broad foundation of present geomorphic knowledge. In the gathering of these facts, however, there has arisen a certain division of function. Where adequate topographic maps or aerial photographs, or both, are available, the essential field work, insofar as morphology alone is concerned, may be said to have been carried out by the topographer or by the aerial photographer. The need for much laborious traversing by the individual investigator is removed, and one very important aspect of the field is literally brought into the laboratory. Furthermore, it would appear that, in many areas, the published results of previous field surveys, either geologic or geomorphic, and made without benefit of aerial methods, might contribute such requisite information of an other than morphologic nature as to provide a sufficient foundation for subsequent studies based immediately on aerial photographs. Thus the results of earlier investigators might be refined, enlarged, extended, or modified. Is it to be inferred, then, that the need for original field study is minimized or obviated when aerial photographs are available? The possibilities challenge attention, and demand a critical examination of the part which may be played by aerial photographs in geomorphic interpretation. Such an appraisal is essayed in the following pages.

The validity of aerial photographs as a basis for geomorphic analysis rests, essentially, on two questions: (1) to what extent does surface form alone constitute an adequate basis for analysis, and (2) to what extent do aerial photographs provide an adequate picture of form? Considering first the second of these questions, it is obvious that form is a three-dimensional quality, comprising outline in ground plan and profile in cross section. It is only the first of these which is directly represented in quantitative terms on aerial photographs. This, however, is shown in much greater detail than is possible on contour maps of comparable scale. Delicate shadings of color tone, together with stereoscopic exaggeration of minor relief features, display intricacies of form beyond the capacity of contour lines to resolve. This is especially true in areas of low relief, where forms and patterns which fail to catch a contour line, and which may be obscure even to the observer on the ground, are shown with striking clarity—meander scrolls (Fig. 2), undrained depressions (Fig. 6), shore features (Fig. 5), dune forms (Fig. 9), intricate ramifications of drainage patterns, and innumerable other features. What might be termed a "microgeomorphic" approach to the study of landforms is provided, and problems which might otherwise pass unnoticed are brought to light. In areas of rugged mountainous topography,

[70] Cf. Hack, J. T., Dunes of the Western Navajo Country. *Geog. Rev.*, 31, 240–263, 1941.

however, distortion of scale by parallax may be objectionable, and for the representation of the larger landforms *in gross*, contour maps, where available, have certain advantages. But on the whole, insofar as geomorphic analysis may be based on the study of landforms and drainage features *in ground plan*, vertical aerial photographs provide an ideal medium.

It is in their representation of the third dimension that aerial photographs may be found wanting. Unless special instrumental equipment is used and ground control established, it is only relative slope and relative relief that are shown. Where exact data on gradients, slopes, and elevations are required, as in certain studies of erosion surfaces, aerial photographs alone are not adequate, and recourse must be had to topographic maps or to measurements in the field.

The factor of scale may introduce still another limiting factor. Certain important minor features, as weathering forms, glacial scorings, eolian fluting, niches, stone nets, etc., are too small in size to be shown adequately on aerial photographs of standard scale. For the study of these, the field approach is obviously necessary. And at the other limit of scale, it is sometimes the regional rather than the local picture which is desired. In such cases, the wealth of detail shown on aerial mosaics may be of no particular advantage, and the lack of vertical control might be a serious handicap. Contour maps, or profiles prepared from them, might be preferable. However, there are large areas in the United States, well covered by excellent aerial photographs and mosaics, for which topographic maps either have not yet been made, or are so generalized as to be of little value.

The adequacy of surface form as a basis for geomorphic interpretation is a more searching question, too far-reaching to be discussed very fully in this paper. In brief, however, it may be said that geomorphic studies are of two general types, (a) those concerned with the formulation of principles, and (b) those involving the application of established principles to specific areas or problems, as to the unraveling of erosional chronologies. In practice, the two are sometimes combined, but not uncommonly the second is separated in place and in time from the first. In both, however, the emphasis is on surface form. In the first, the approach is essentially inductive. Form is correlated with genetic processes and with environing factors, through the synthesis of direct observations on processes in action, indirect chains of circumstantial evidence, experimental findings, evidences from internal constitution, comparative verification of consequences deduced from working hypotheses, and scattered data drawn from the body of geologic knowledge. Gradational variations in form, moreover, are correlated with successive stages in an ideal sequence through which the process or processes in question operate. In this type of study, clear delineation of surface form is an essential starting point, but is only a starting point. Aerial photographs may thus have an important auxiliary role.

For many types of landforms, studies of the above type are already history. The major generalizations have probably been made. Nevertheless, there are many questions which have not yet passed beyond the stage of bland generalization. The genesis of such familiar phenomena as graded slopes, for example, is still debated. Certain of the criteria for establishing erosional history likewise remain a source of contention. Many of our concepts have yet to be set forth in quantitative rather than qualitative terms. For nearly all types of landforms, there remains the need of defining detailed conditions of genesis more critically. Not until form is thoroughly understood in terms of process, stage, and environmental factors does it constitute a valid criterion for interpreting geomorphic history.

The application of genetic principles to the interpretation of a given landscape is based primarily, but not exclusively, on form. The approach here, however, is essentially deductive. Form is used as a criterion of process, stage, climatic environment, and tectonic background. Attention is focused on the distribution, orientation, and interrelations of landforms, on the transection of older forms by younger, and on the recognition of ancient forms which have suffered modification or partial destruction. It is this method of approach which is followed in studying successive erosion surfaces, stages in shoreline development, changes in wind direction and potency as recorded in dune fields, etc. It presupposes the accurate differentiation and identification of forms—the recognition of superficial differences between forms genetically similar, and of superficial similarities between forms genetically different. It is to be noted, however, that form is not always unequivocal. Forms genetically diverse may be morphologically indistinguishable. In such cases, it is to the evidence of internal constitution—lithology, bedding, cross-bedding, soil zones, disconformities, etc.—that appeal must be made. Certain depositional forms are distinguishable from erosional forms, and from one another, only on this basis. This applies particularly to glacial features, as in the distinction between morainal topography and heavily pitted outwash.[71] It applies similarly to the distinction between rock-cut and cut-and-fill terraces. The recent controversy as to the origin of the Carolina Bays presents still another case in point. And insofar as internal evidence is requisite for a solution of the problem, aerial photographs can lead but halfway to the goal. They cannot take the place of hammer, shovel, and drill. They can suggest working hypotheses, and may narrow the probabilities, but cannot point to the final decision. Where form is diagnostic, however, and does provide a reliable indicator of process and stage, aerial photographs, within the limits already outlined, may provide a satisfactory basis for interpretation in problems of limited scope, such as the distribution and orientation of dune forms, the study of simple terrace sequences, the analysis of detailed drainage patterns, etc. Similarly, when a clearer and more detailed knowledge of morphology is all that is needed to build upon the results of previous field studies, aerial photographs alone may suffice. It is in problems of a less specialized character that additional field study may be necessary to refine the given picture of form, or to make collateral observations of a more purely geological character. In deciphering the complete geomorphic history of any very large area, for example, stratigraphic as well as geomorphic methods must be employed. A part of the erosional history is recorded only in correlative sedimentary deposits, and it is in these that the answers to many questions must be sought.

In summary, the adequacy of aerial photographs as a direct basis for geomorphic interpretation depends on the type or types of topography to be studied, on the scale of the investigation, on the importance of accurate vertical control, on the nature and scope of the study, on the extent of previous field studies on the same problem, and on the reliability of purely morphologic criteria for the given problem. Frequently the photographs are suggestive rather than definitive. In some cases, their primary role is to reveal the existence and nature of the problem. In many types of investigation, they need to be supplemented by contour maps on the one hand, and by field study on the other. To evaluate their potentialities and limitations in specific projects is a problem for trained judgment. Error in the one direction may lead to unwarranted speculation, and error in the other direction may result in a needless waste of effort. Used, however,

[71] Thwaites, F. T., The Origin and Significance of Pitted Outwash. *Jour. Geol.*, 34, 308–319, 1926.

with a discrimination commensurate to the advantages attainable, aerial photographs provide a new and revitalized approach to many fields of geomorphic inquiry.

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The following additional references have come to the author's attention since the original manuscript of this paper was prepared:

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