Aerial Photographs in Geologic Interpretation and Mapping

GEOLOGICAL SURVEY PROFESSIONAL PAPER 373

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By RICHARD G. RAY

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The use of aerial photographs to obtain qualitative and quantitative geologic information, and instrument procedures employed in compiling geologic data from aerial photographs

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AERIAL PHOTOGRAPHS IN GEOLOGIC INTERPRETATION AND MAPPING

By Richard G. Ray

ABSTRACT

Aerial photographs today are widely used to obtain both qualitative and quantitative geologic information; vertical aerial photographs are used almost to the exclusion of other types. Techniques and procedures described herein relate primarily to vertical photography.

Geologic interpretation of aerial photographs is based on the fundamental recognition elements of photographic tone, color, texture, pattern, relation of associated features, shape, and size. The scale of photographs, as well as the vertical exaggeration that is present in most stereoscopic models, also are significant in photointerpretation.

The amount of geologic information that may be obtained from aerial photographs is primarily dependent on the type of terrain (igneous, metamorphic, or sedimentary), climatic environment, and stage of the geomorphic cycle. Because features are more readily recognized where strong differences exist in the erosional resistance of adjacent rocks, sedimentary terrain may be expected to yield the greatest amount of information from aerial photographs. Metamorphic terrain may yield the least information because metamorphic processes tend to destroy differences that may have existed in the unmetamorphosed rocks. Combinations of criteria such as photographic tone, texture, pattern, and vertical exaggeration permit inferences as to rock type and geologic structure, which are important in petroleum exploration, ore-deposits search, and engineering geology.

In petroleum exploration aerial photographs provide a wealth of information primarily with regard to potential structural traps. Folds commonly may be interpreted from a study of strike and dip of bedding and from stream patterns; anomalous stream characteristics, such as stream deflections, may suggest subsurface structures. The variety of photorecognition criteria that suggests faults permits aerial photographs to be of particular use in many ore-deposits studies. Analysis of soil patterns yields information regarding permeability of the surficial materials that are a concern of the engineering geologist.

The instruments used for viewing photographs, measuring geologic features, and compiling geologic maps range from simple stereoscopes and stereometers, or measuring bars, to complex double-projection instruments such as the multiplex or Kelsh plotter. Some instruments require the use of paper prints; others require the use of glass-plate diapositives. Measuring devices primarily provide spot heights or differences in altitudes; these quantitative data may be geologically significant in measurement of stratigraphic thickness and dip of beds and in structure contouring. Accuracy of vertical measurements is related fundamentally to the scale of photography and the instruments used for making measurements. In general, accuracy of measurement is greater when large-scale photographs are used and when double-projection instruments rather than simple parallax bars are employed.

INTRODUCTION

Use of aerial photographs to obtain geologic information—popularly called photogeology—has contributed to mineral and fuel discoveries, and to engineering geology studies, as well as to the general geologic mapping of many areas; it also has increased the efficiency of many geologic mapping groups by adding speed, economy, and accuracy to areal mapping as well as adding certain geologic information that is impossible, difficult, or economically impractical to obtain by routine field-mapping methods. The past financial success of consultants in geologic interpretation of aerial photographs attests to successful geologic application of photogeologic procedures and techniques, particularly in petroleum geology, and to lesser extent in mining and engineering geology.

Many technical papers on the geologic interpretation of aerial photographs have been published, primarily since the end of World War II; on several occasions symposia on photointerpretation, and specifically photogeology, have been presented. Much of the information currently available has been published as individual articles and they are scattered throughout the literature; comprehensive treatments on the geologic interpretation of aerial photographs are generally unavailable now (1959) (see Eardley, A. J., 1942; Smith, H. T. U., 1943b; and Petrusevich, M. N., 1954). In addition to the published information much unpublished information also has accumulated in recent years. The collection and synthesis of much of this information, together with discussion of photointerpretive and related photogrammetric procedures, are the main objectives of this paper. The paper is particularly intended as a guide to geologic interpretation of aerial photographs as applied as a tool in reconnaissance geologic mapping, and as a reference to published papers representative of the photogeologic literature.

The primary objectives of photogeology are (a) to contribute to geologic mapping, which in turn is basic to mineral and fuel exploration, engineering geology studies, some water-resources investigations, and related studies, and (b) to contribute to geologic knowledge through research. The objectives of photogeology may be economic or academic, and procedures used can be expected to differ widely, ranging, for example, from use solely of simple lens stereoscopes for qualitative interpretation to employment of precision stereoplotters for making geologic measurements. Regardless of procedures used, however, photogeology to date has contributed principally to the broad aspects of geologic study, that is, in mapping distribution of rock types and structures. The interpreter can only infer the composition of rock types from photographs; he cannot identify mineral types or absolute ages of rocks. Thus, maximum use of photogeologic procedures is attained by combining photogeologic studies with various laboratory studies and with field investigations.

The uses of aerial photographs and the various photogeologic procedures are discussed herein under the general headings of interpretation and instrumentation. The part dealing with interpretation is widely illustrated with stereoscopic pairs and triplets, single photographs, and mosaics, together with explanatory notes, to demonstrate the kinds and amounts of geologic information that can be obtained from aerial photographs of differing geologic terrains and to illustrate some uses of photographs in specific studies, such as the search for petroleum. These photographs demonstrate primarily the qualitative uses of the fundamental recognition elements in geologic interpretation; they represent only a sampling of the tremendous number of illustrations available. Because reproduction processes tend to obscure details only subtly expressed on aerial photographs, selection of photographs used in this paper was confined principally to those that illustrate clearly defined recognition elements and geologic features. All aerial photographs (figs. 39–114) are at the end of the paper. Agencies holding the negatives of these photographs are given in a list that follows the photographs.

Methods and significance of determining quantitative geologic information from aerial photographs are described under the heading of instrumentation.

THE AERIAL PHOTOGRAPH

The aerial photograph is an instantaneous record of the ground details as determined chiefly by the focal length of the camera lens, the flying height of the airplane at the time of exposure, and the film and filters used. It may also be defined as a composite of photographic images, which make up the recognition elements used for interpretation. The aerial photograph is a perspective photograph that is geometrically related to the type of camera in which it is taken; it may be a vertical photograph, taken with the camera axis pointing essentially vertically down, or it may be an oblique photograph, taken with the camera axis purposely tilted from vertical, generally 20° or more. Vertical photographs currently are used almost to the exclusion of oblique photographs for geologic interpretation, and most photogrammetric instruments used in photogeology in the United States are designed to accommodate vertical photographs; hence the following discussion is limited to techniques applicable to the study of vertical photography. Twin low-oblique photographs—those in which the apparent horizon is not shown—generally may be transformed and the resulting paper prints used as vertical photographs; however, low-oblique photographs cannot be used in many stereoplotting instruments unless the instruments are specially designed.

A general knowledge of the geometry and terminology used with vertical aerial photographs is necessary if one is to understand and make maximum use of photographs for interpretation and mapping purposes. The terminology and geometry of the vertical photograph are presented in figure 1.

FACTORS THAT AFFECT THE PHOTOGRAPHIC IMAGE

Factors that affect the photographic image, and hence interpretation, may be divided into two groups: (a) The relatively constant man-controlled factors, such as focal length of lens, flying height, film and filter combinations, and lens angle; and (b) the variable natural factors including color of objects photographed, position of an object with respect to the angle of sun, amount of haze in the atmosphere, and others. The constant factors are discussed briefly below; effects of natural factors on the photographic image are described where appropriate throughout the text.

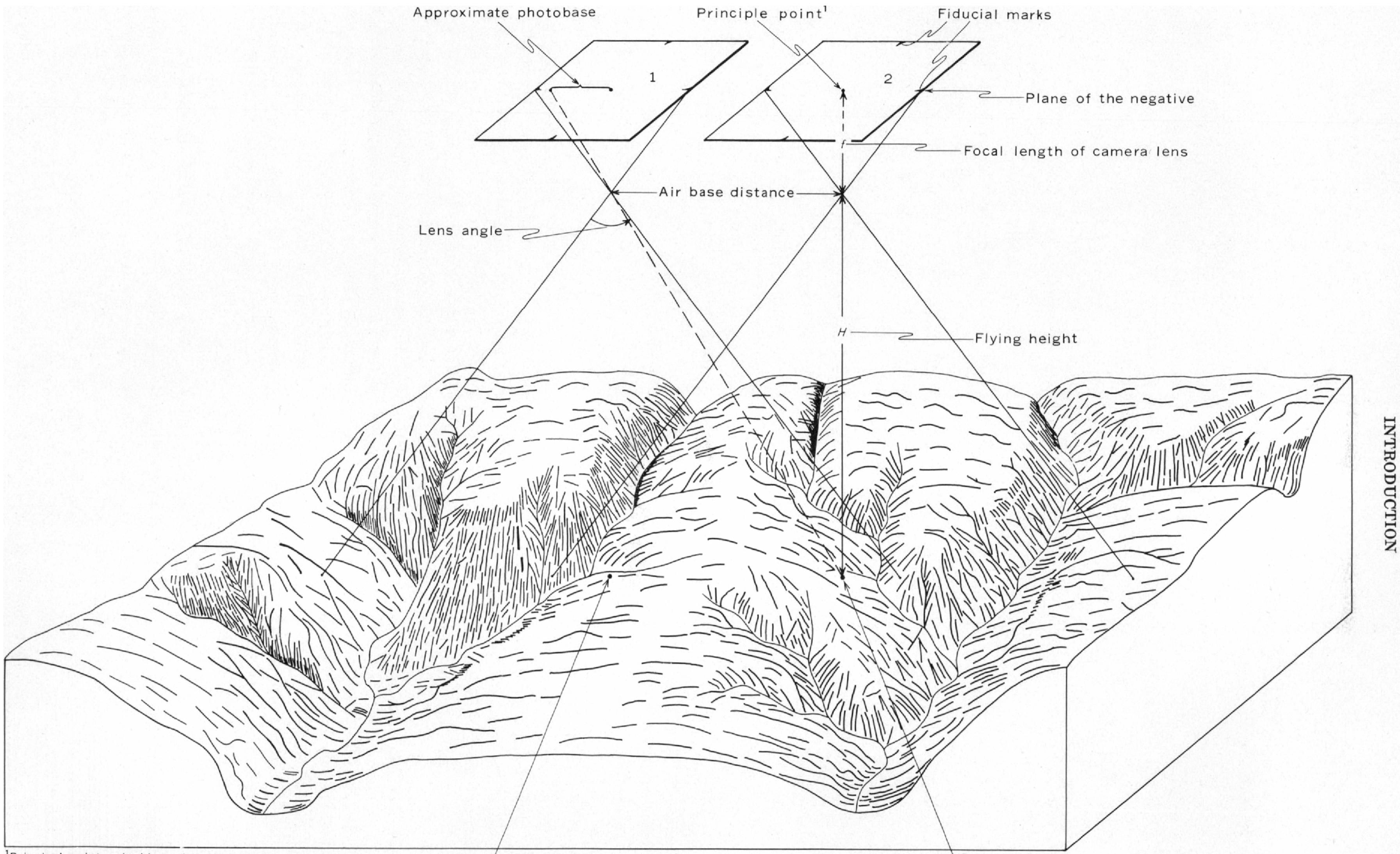
FOCAL LENGTH AND FLYING HEIGHT

Focal length and flying height may be considered together because of the relation of photograph scale to these two factors. In terms of focal length and flying height, the average scale of a photograph is expressed as

$$S=\frac{f}{H}$$

or

$$\text{Scale}=\frac{\text{focal length (feet)}}{\text{flying height (feet)}}.$$



[1]Principal point coincides with photograph nadir in truly vertical photograph.

Figure 1.—Geometry of the vertical aerial photograph.

Thus, for example, the scale of photographs taken at 10,000 feet above mean terrain with a 6-inch (0.5 foot) focal-length lens is

$$\frac{0.5}{10,000}=1:20,000.$$

It is evident that as focal length increases, the scale of photographs becomes larger, but as flying height increases, scale of photographs becomes smaller. Therefore, at any given flying height, long-focal-length lenses result in larger scale photographs than short-focal-length lenses. It follows also that at a given flying height a greater number of photographs are necessary to cover a given ground area when long-focal-length lenses are used. Doubling the focal length of the lens, for example, will quadruple the number of photographs required to cover a given area at a given flying height.

It should be noted that if a photograph is enlarged or reduced, the "effective" focal length for that photograph is also changed in direct proportion to the amount of enlargement or reduction. Thus, if photographs taken with a 6-inch-focal-length lens are enlarged two times, the effective focal length is changed from 6 inches to 12 inches. Parallax measurements (see p. 53), used in determining differences in altitude, are increased, but the absolute value for each unit of parallax measurement is decreased. Reducing or enlarging photographs thus has a significant effect with respect to choosing appropriate measuring and plotting instruments, and in measuring differences in altitudes.

For determining scale from the formula $S = f/H$ the effective focal length must be used where photographs have been reduced or enlarged. Particular note should be made in the use of transformed low-oblique photographs, in which the effective focal length is almost always less than the focal length of the camera.

FILM AND FILTER COMBINATIONS

The appearance of the photographic image may be controlled to marked extent by the sensitivity of the film and by the light transmission of the filter employed. The sensitivity of a film emulsion may be controlled when the film is manufactured so that all or only selected parts of the visible spectrum are recorded, or so that part of the invisible spectrum, such as infrared light, is recorded. Also, the wave length of light reflected from an object and actually recorded may be controlled in part by filter combinations. The recording of selected wave lengths of light, controlled by filters or type of film, or by combinations of film and filters, affects the photographic image, primarily by affecting the photographic tone. Conventional panchromatic aerial film is generally exposed through a minus-blue filter and permits the recording of blue-green, yellow, orange, and red light. When color film is used the entire visible spectrum is commonly recorded and a greater number of color differences can be distinguished than on conventional black-and-white film. Special color film or color film used with filters may distort the color of the objects photographed, but if differentiation of geologic features is permitted, then lack of color fidelity may not be detrimental to interpretation. Ideally, film and filter combinations may be used to accentuate specific features for a given type of interpretation (see p. 7–8).

LENS ANGLE

The angle of the camera lens—that is, the apex angle of the cone of rays passing through the lens—is important indirectly in relation to radial displacement and parallax measurements, which are in turn significant with regard to photogrammetric applications in geologic interpretation. Characteristically, long-focal-length lenses (greater than 6 inches) have a narrower lens angle than short-focal-length lenses (6 inches or less). Thus, to maintain a given scale and format size, photographs taken with a narrow-angle (long-focal-length) lens requires flying at a higher altitude than with a wide-angle (short-focal-length) lens. Under these conditions, radial displacement (also termed "relief displacement") of similar image points is less when narrow-angle lenses are used, but only because of the greater flying height required by the narrow-angle lens to maintain the given scale and format size. The parallax difference for an object of specific height is in turn affected as a result of the difference in flying height, the parallax difference decreasing directly with increased flying height for a given focal-length lens (see p. 53). Thus it can be said that lens angle indirectly affects parallax measurement. When a constant flying height is maintained, however, lens angle does not affect parallax measurements of similar image points. Image distortion at the margins of photographs taken with a wide-angle lens may be greater than on photographs taken with a narrow-angle lens and this is considered by many to be detrimental to photointerpretation, especially in high-relief terrain.

VIEWING OF PHOTOGRAPHS

Photographs may be viewed singly, as mosaics, or as stereoscopic pairs. Most commonly stereoscopic pairs of paper prints are viewed in reflected light with simple lens, prism, or mirror stereoscopes, notes are made directly on the prints or on transparent overlays, and information is later transferred to a base map or mosaic. Many paper prints can also be viewed with transmitted light, which may be helpful in revealing photographic detail. If vertical measurements are made from paper prints a separate measuring device must be commonly employed with the stereoscope. In recent years double-projection instruments, employing the anaglyph principle in forming the stereoscopic model from glass-plate diapositives, have been used increasingly in geologic interpretation.

When photographs are viewed singly or in a mosaic, a two-dimensional view is obtained. The single photograph or mosaic is normally viewed along a line generally perpendicular to the photograph surface, but for some subtle linear features, an oblique view of the surface with a reflected light source moved to different positions may reveal photographic details otherwise difficult or impossible to see (see Lattman, 1958, p. 575). Many valuable relations of geologic and associated features can be observed, particularly as a result of the overall view permitted by mosaics or single prints of small scale, but a two-dimensional view reveals only part of the data available to the interpreter; the value of three-dimensional, or stereoscopic, examination of aerial photographs in contrast to studying the two-dimensional view cannot be overemphasized. Conspicuous geologic features are commonly visible on single aerial photographs or mosaics of aerial photographs, but the wealth of information seen in stereoscopic view is many times greater. Details, such as fine lines or textural differences not readily seen on single photographs—or even on the ground—commonly are shown clearly in the stereoscopic model. Such clarity is in many places a direct result of the common association of fine lines and textures with relief changes, which are exaggerated in most stereoscopic models. To take advantage of the exaggerated vertical dimension, which is so helpful in photointerpretation, aerial photographs should of course be viewed stereoscopically. It may be desirable also to view the photographs pseudoscopically by reversing the print positions so that hills appear as valleys and vice versa. In pseudoscopic view, stream patterns or anomalies may stand out (see fig. 95), or because of the unnatural view other features may be accentuated. Aschenbrenner (1954, p. 401) demonstrated by the use of a seemingly random distribution of dots, which may be likened to silver grains of a photographic emulsion, that information not visible on a single picture can be clearly seen in stereoscopic view.

INTERPRETATION

Interpretation was defined broadly by Summerson (1954, p. 397) as the prediction of what cannot actually be seen; and thus geologic interpretation of aerial photographs is not unlike certain geologic interpretations of field-observed data. Colwell (1952, p. 535; 1954, p. 433) defined interpretation as "* * * the act of examining photographic images of objects for the purpose of identifying the objects and deducing their significance." However, geologic interpretation, more often than not, is a result of combined deductive and inductive reasoning, based on the principle of cause and effect. For example, certain features easily identified on aerial photographs, such as terminal moraines and kettle holes, are inductively concluded to have resulted from glaciation, and this in turn may lead by deductive reasoning to the specific identification of less readily recognizable features, such as certain kame terraces. Further deduction may lead to conclusions concerning the type of material present in these terraces. On the other hand, interpretation may be directed mainly toward understanding the geologic significance or history of a broad area, and specific features such as positions of beds and measurements of stratigraphic thicknesses combine by inductive reasoning to reveal the probable geologic conditions that resulted in those features.

Geologic interpretation of aerial photographs can be considered generally a two-step process. The first step includes observation, fact-gathering, measurement, and identification of features on the photographs. The second step involves deductive or inductive mental processing of these data in terms of geologic significance. According to Stone (1951, p. 755) a procedural or methodical approach to interpretation should be used because "The establishment of procedure prepares the way for orderly and complete analyses of complex subjects." A procedural or methodical approach appears to be especially applicable to the observational phase of a photogeologic study, and it will give a firm basis on which the interpretive phase is dependent.

Observational data, also termed "first-order" information (see Hopkins, Karlstrom, and others, 1955, p. 142), may be subjected to either the empirical or rational method of processing (Smith, H. T. U., 1953, p. 9–10). According to Smith (1953, p. 9) the empirical process is largely mechanical rather than perceptive, and involves matching images of a photograph with similar reference images; reasoning is largely by analogy and this "Reasoning by analogy alone is notoriously deceptive, unless extreme care is taken to make certain that the analogy is truly complete." Smith (1953, p. 9) also made the particularly significant statement that "Nature is not always so obliging as to provide the desired simplicity and uniformity of conditions" that would permit the ready application of empirical methods. Indeed, much in nature is complex and nonuniform, many terrain features are polygenetic, and thus interpreting the geologic significance of observational data is dependent largely upon a thorough understanding of the principles of the sciences that explain the observational data. "The physical conditions of a particular terrain change, and the adjustment to that change is a gradual one, allowing all manner of intermediate forms and combinations between the norm for the old situation and that for the new" (Summerson, 1954, p. 396).

Surface expressions of geologic features—the observational data—range from the very obvious to the very subtle. Sorting those data that are significant to a particular problem and properly relating these features one to another provide a measure of the ability of the individual interpreter. Where more than one plausible explanation of observational data is possible, the experience as well as the fundamental geologic ability of the interpreter become especially significant. Thus a rational processing of observational data will yield the most meaningful interpretive results. This does not imply that an empirical method of processing observational data, exemplified by the numerous photointerpretation "keys," may not yield satisfactory results in certain geologic problems and terrains, but the logical, scientific approach demands a rational processing of observational data, particularly where inferences based on subjective interpretations are required.

If observational data cannot be rationally interpreted, they may still be of some empirical value. For example, an interpreter may recognize two zones of vegetation on aerial photographs. Without knowledge of plant ecology, he may infer that a geologic contact exists between the two vegetation types. But a knowledge of plant ecology, permitting a rational interpretation, might well have allowed a further inference that one type of rock or soil was likely to be highly permeable in contrast with the other, thus revealing information with regard to certain physical characteristics of the rock or soil, which in turn may suggest something of the lithologic character. Thus "* * * the understanding of any particular terrain requires more than the knowledge of the geology * * *" (Summerson, 1954, p. 397). The greatest understanding will be by individuals grounded in the natural sciences and who understand, as a result, the various factors that contribute to a particular region. Because any geologic terrain is normally a complex that also includes features of fundamental interest to the botanist, forester, soil scientist, and others, photogeologic interpretation must take cognizance of these related sciences. The combined use of vegetation, soils, and geologic features to interpret geology is an example of what has been termed the "convergence of evidence" principle (Colwell, 1952, p. 566).

Interpretation, then, begins with the observation, identification, and measurement of features on photographs. One of the most obvious features is that of landform, and it has been stated by Johnstone (1953, p. 265) that analysis of landforms constitutes the basis of photogeology. Smit Sibinga (1948) also pointed out the importance of landform, or geomorphic expression, in interpreting the lithologic character of rocks; but analysis of landform, however important, cannot be the complete basis for photogeologic interpretation, for there is additional "first-order" information such as vegetation patterns, soil patterns, and stream patterns; photogrammetric measurements also provide first-order data. Features other than landform may actually be more important for certain structural interpretations. For example, vegetation may grow along and mark the location of a fault. Thus, interpretation is based not only on landform but also on photographic tone differences, color differences, drainage patterns, erosion patterns, soil patterns, vegetation patterns, and any other surface expression of underlying geology. It is fundamental that photointerpretation is only applicable to those geologic features that do develop such surface expressions.

The many features of surface expression used in photogeologic interpretation are identified on the basis of recognition elements—characteristics of the photographs that result from the scale selected; the color of the rocks, vegetation, and soils of the terrain photographed; the kind of film and filters used; the processing of the film; and related factors. The most significant recognition elements are relative photographic tone, color, texture, pattern, and association of features. Shape is important in identifying many constructional landforms. Finite size as a recognition element for geologic interpretation has been used very little, although relative size is commonly considered by the interpreter. The increasing use of photogrammetry in geologic interpretation, however, portends an increasing importance for size, not so much as a recognition element in the usual sense of the word, but as an interpretation element (see p. 13). Shadows may help in distinguishing certain tree types, which in turn may have geologic significance.

INTERPRETATION FACTORS

RECOGNITION ELEMENTS

PHOTOGRAPHIC TONE

Photographic tone is a measure of the relative amount of light reflected by an object and actually recorded on a black-and-white photograph; it is fundamental to all other recognition elements, except color. Tones on conventional photographs are usually shades of gray, but may be black or white. Because of the ability of the human eye to differentiate subtle tone changes, relative photographic tone is a significant asset in geologic interpretation of aerial photographs. However, photographic tone is subject to wide variation and there are limits to its usefulness as a recognition element because of the many factors that can influence it.

Photographic tone depends on light reflectivity, which in turn depends on location of an object with respect to the sun; thus the time of day and month of year are influencing factors. Haze strongly scatters light, particularly at the short or blue end of the spectrum and hence affects photographic tone unless corrective filters are used. Geographic latitude, angle of reflected light, sensitivity of film, light transmission of filters, and processing also may exert considerable effect on photographic tone. Hence a standardized tone scale (Daehn, 1949, p. 287) would appear to have little usefulness unless relative photographic tones on different photographs could be equated in terms of the tone scale. It is probable that the use of a densitometer to measure relative photographic tone in terms of the density of the negative would be a satisfactory measure of tone, even though many factors influence the density. Particularly in quantitative studies the use of a densitometer to measure relative photographic tone may prove very worthwhile in differentiating certain geologic features (Ray and Fischer, 1960).

Photographic tone, despite the many factors that may affect it, can be a particularly useful interpretation element; its usefulness depends on the problem under consideration and on how tone is used in conjunction with other recognition elements. For example, if the fracture pattern of an area were studied and it were known that a lush and dark-toned vegetation grew along the fractures because of concentration of moisture, the relative photographic tone probably would be a significant recognition element regardless of the limiting factors mentioned above. On the other hand, as a means of distinguishing between two types of trees that reflect similar amounts of light but which might signify differences in the underlying geology, photographic tone might be of little value unless used in conjunction with other recognition elements, such as crown texture.

Raup and Denny (1950, p. 120), in work along the Alaska Highway, considered photographic tone the least satisfactory criterion in identifying and interpreting vegetation. But Tator (1951, p. 717) considered tonal contrasts to be major keys for recognizing landscape features of low relief in the coastal region of the Gulf States, such tonal differences resulting mainly from soil and vegetation differences. Schulte (1951, p. 697) pointed out, with regard to pure stands of trees, that at large scales photographic detail is more important, but at small scales tone becomes relatively more important.

Because the analysis of photographic tone is highly subjective it has been suggested that photographic tone might not be as useful as other recognition elements in interpretation. Because of differences that may arise from position, angle of reflected light, processing, and other factors, Stone (1956, p. 125) stated that photographic tone in interpretation probably has been overemphasized. This is true if the factors that affect tone prevent photographic distinction of images that might otherwise be made. But if changes in relative photographic tone are present on a photograph, the interpreter should expect that these changes might be geologically significant. Indeed, photographic tone is probably the most used recognition and interpretation element, although it is generally used in conjunction with one or more other recognition elements. The absence of photographic-tone changes, as a result of processing and other factors, where such tone changes might normally be expected, does not detract from the possible usefulness of tone changes on other parts of a photograph. It merely suggests that the potential of photographic tone differences has not been accomplished for the photographs in question.

It is worthy of note that in interpretation strong tonal contrasts are generally desirable. Yet modern automatic dodging devices commonly used in printing photographs generally reduce overall tonal contrasts, although locally, as in darkly shaded areas or brightly lighted areas, automatic dodging may strengthen tonal contrasts. Because most aerial negatives are slightly lighter in the corners than in the center, hand dodging is commonly necessary if automatic dodging is not employed in making prints. However, undodged or hand-dodged prints are probably the best for general photointerpretation.

For special interpretation problems it may be possible to enhance tonal contrasts within a limited range of the tone scale by film intensifiers or other photographic processes, such as use of selected filters. Ray and Fischer (1960) used selected filters in photographing weathered samples of the Bernal and San Andres formations of New Mexico. The Bernal formation is a red thin-bedded shale and shaly siltstone; the San Andres limestone is primarily a grayish limestone. Spectral reflectance curves, based on spectrophotome-

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ter studies, show significant differences for these two formations (fig. 2). Particularly at the short or blue end of the spectrum a strong difference in intensity of reflected light is present; the San Andres limestone reflects almost twice as much light as the Bernal formation. A noticeable difference is also present at the long or red end of the spectrum. But the spectral reflectance curves of the Bernal and San Andres formations within 500 to 675 millimicrons—the wave lengths generally recorded on conventional black-and-white aerial photographs—show that the overall light reflectance from these two formations would average out to be generally similar and little photographic distinction should be expected within this range. It is significant that strong reflectance differences which exist in one part of the spectrum may be masked by reflectance characteristics in another part of the spectrum, and therefore to achieve photographic distinction of two features, it would probably be necessary to record a restricted part of the spectrum. Photographs of the Bernal and San Andres formations taken through filters that permit recording only of reflected light at the short or long end of the spectrum show a marked photographic distinction of the two formations.

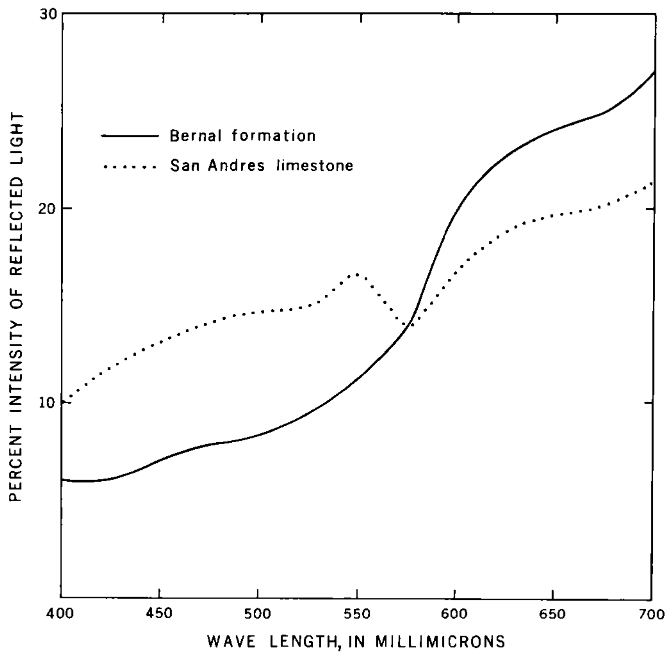

Figure 2.—Spectral reflectance curves of weathered samples of Bernal formation (red thin-bedded shale and shaly siltstone) and San Andres limestone (primarily a grayish limestone), New Mexico.

COLOR

Color as a recognition element could be one of the most useful, if not the most useful, criterion for interpretive purposes (see Kent, 1957; Ray, 1958; Fischer, 1958; and Minard, 1960). The significance of differences within a photograph is interpretation and the greater the number of differences, such as color contrasts, the greater is the potential for detailed interpretations. It is a well-established fact that the human eye can differentiate about 1,000 times as many tints and shades of color as it can tints and shades of gray, characteristic of black-and-white photographs, and hence it may be concluded that color aerial photographs will permit a greater amount of detail to be recognized and interpreted. However, it is possible that two rock types of similar color might be differentiated more easily on certain black-and-white photographs than on color photographs because of mineralogic, chemical, or other differences that may permit significant contrasts in reflected light to be recorded when selected films and filters are used.

Petrusevich and Kazik (1955, p. 5, 8) reported that where color contrasts of rocks are not strong, boundaries between these rocks are more clearly seen on black-and-white photographs than on color photographs. Where color contrasts are strong, interpretation is facilitated in areas where individual beds are rather thick and the color of formations is retained for considerable distances along the strike. Petrusevich and Kazik (1955, p. 8) also reported that "A comparison of aerial color photographs of scales 1:15,000; 1:10,000; 1:8,000; and 1:5,000 for the same area, taken under the same conditions, shows that * * * the practical use of aerial color photography for geological purposes should be limited to a scale of 1:10,000 and larger." This conclusion was based on a study of photographs taken with an 8.25-inch lens. Recently developed short-focal-length lenses (3.5 inches and 6 inches) now permit useful color aerial photography to be achieved at a scale smaller than 1:10,000.

Aerial color negative film may prove particularly useful in photointerpretive studies. Unlike positive transparencies (reversible-type color film), which require use of filters during exposure of the film, negative-type color film is processed with filters inserted during the printing process. It is thus possible to vary the color contrasts through the simple medium of printing, with the possible advantages that certain features of geologic significance, such as alteration zones, may be emphasized. Petrusevich and Kazik (1955, p. 5) noted that a greater contrast often can be obtained in a black-and-white print from a color negative than in a print from the corresponding black-and-white negative. Fischer (1958, p. 546) in turn stated that black-and-white positive prints from Ektachrome aero positive transparencies also show stronger tone contrasts between various rock units than the conventional black-and-white photographs.

TEXTURE

Texture was defined by Colwell (1952, p. 538) as "* * * the frequency of tone change within the image * * * [and] * * * is produced by an aggregate of unit features too small to be clearly discerned individually on the photograph." The scale of the photographs thus has an important bearing on this definition of texture. For example, a network of fine lines described as a texture on one scale of photographs may well be recognizable as a network of joints on a larger scale of photographs; this bears out Schulte's statement (1951, p. 697), made with regard to plant distribution, that at large scales photographic detail is more important, whereas at small scales tone becomes relatively more important. Such a texture, due to tone change within the image, may be called a "photographic texture" (figs. 43, 56, and 85). Photographic texture is therefore a comparative feature within any one general scale of photography. Although photographic tone is a fundamental element of photographic texture, the photographic conditions that affect tone may vary and yet permit such a texture to be a diagnostic recognition element. This is due to the fact that texture in the photographic sense is really a composite of several fundamental characteristics, namely photographic tone, shape, size, and pattern, and, of these elements, slight variations of tone would least significantly affect the recognition of a given texture.

Photographic textures have been described by various workers (Spurr, 1948; Raup and Denny, 1950) as coarse, fine, rough, and fluffy, but such descriptive terminology would seem to have very limited use unless accompanied by photographic illustrations. Furthermore, unless these descriptive terms are themselves clearly defined, comparisons of photographic textures with specific commonly known objects might be more useful. It may also be suggested that because photographic textures are normally considered as two dimensional, the use of a densitometer in conjunction with a coordinatograph-type instrument to determine tone changes per millimeter within the image might permit mathematical classification of such textures. However, such a classification might fail where a strong textural fabric prevailed, for two textures differing primarily because of shape or preferred orientations within the image might well be assigned to the same mathematical classification.

In addition to the use of the term "texture" as described above, texture has other meanings, as in reference to soils. The application of aerial photographs to soils and engineering geology studies has resulted in the introduction of "soil texture" in some photogeologic literature; the obvious distinction between photographic texture, which can be directly observed, and soil texture, which must be interpreted from other recognition elements, must of course be made. Texture also has been used in relation to the density of a drainage network; wide spacing of streams results in a "coarse" texture of drainage and close spacing of streams results in a "fine" texture of drainage (figs. 3, 42, 49, 51, 62, 63, 79, and 106). Unless quantitative meaning is given to drainage texture, the term must be used on a comparative basis within any one general scale of photography. Horton (1945, p. 283–284) defined drainage density in quantitative terms but little use has been made of this classification by geologists.

Topographic texture has been used to describe the degree of dissection of the land surface (see Smith, K. G., 1950, p. 655–668). Like texture of drainage, topographic texture may be described as fine or coarse (figs. 39, 51, 62, 75, and 106). Quantitative study of topographic texture, based on map study, has shown that the texture ratio, a mathematical expression of the dissection of the ground surface, bears a logarithmic function relation to drainage density (Smith, K. G., 1950, p. 667–668). Therefore, because drainage density can be determined readily, aerial photographs may be useful in a comparative study of erosional topographies.

When texture is used to designate drainage density or erosional characteristics of the terrain, rather than to designate a photographic texture, the use should be so qualified as to make the definition clear. Although textures are commonly considered in terms of the two-dimensional plan view, it is important to note that erosional texture may well be significant or at least more readily recognized when viewed from the third dimension of the stereoscopic model (see fig. 39).

PATTERN

Pattern, as used herein, refers to the orderly spatial arrangement of geologic, topographic, or vegetation features. The spatial arrangement of pattern is normally considered by interpreters to be a two-dimensional or plan-view arrangement of features, but it may also be a three-dimensional arrangement. If features that make up a pattern become too small to identify, as on small-scale photographs, they may then form a photographic texture.

Patterns resulting from particular distributions of gently curved or straight lines are common and are frequently of structural significance; they may represent faults, joints, dikes, or bedding. But a single line, or lineation, is also an illustration of pattern; it

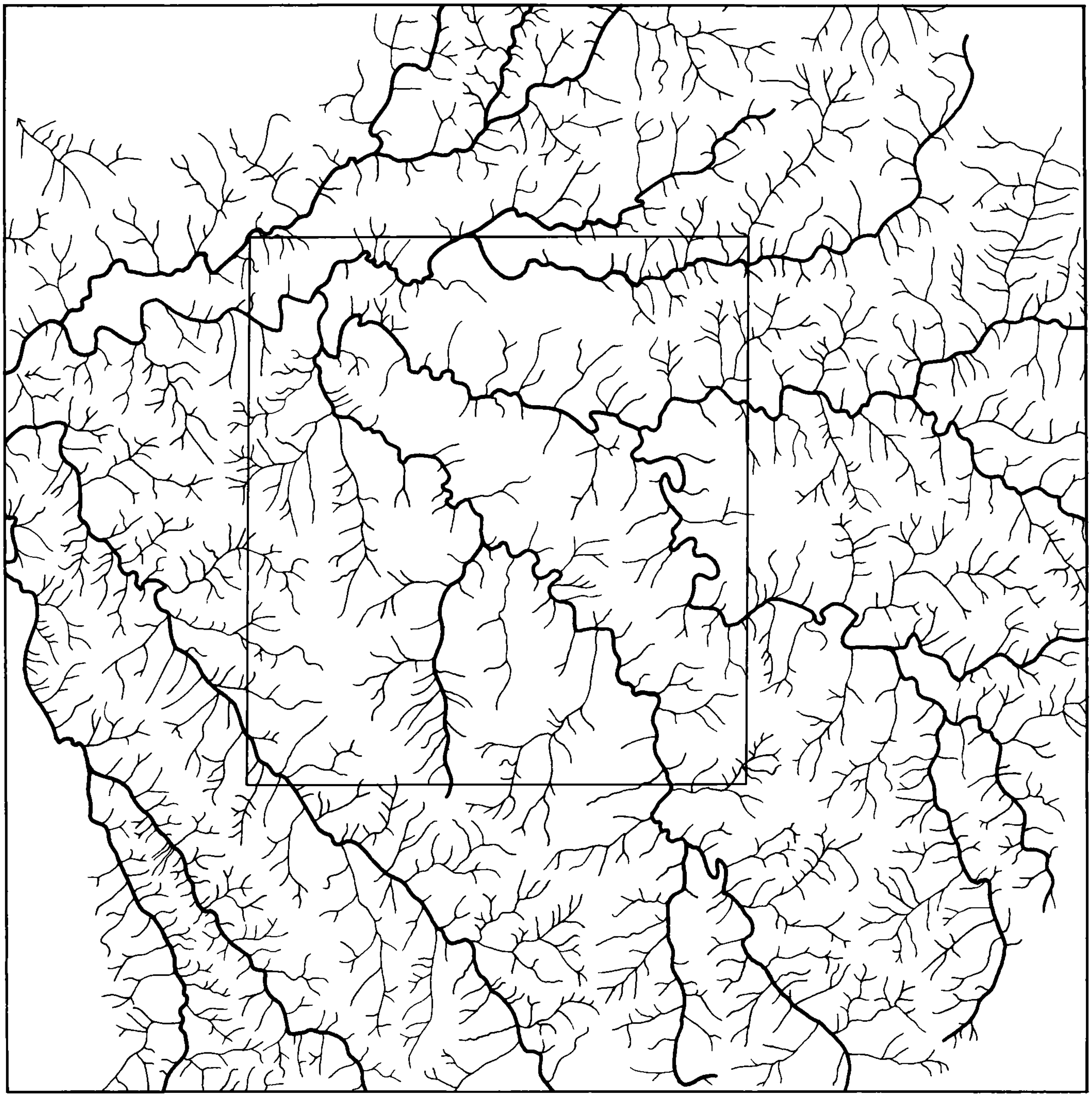

FIGURE 3.—Drainage map of large area in vicinity of ring dike shown in figure 54.

A separate tracing of drainage over a large area in the vicinity of the ring dike of figure 54 shows a marked decrease in drainage density within the ring-dike area. The contrast in drainage densities inside and outside of the ring dike is more readily seen on a separate tracing of drainage than in the stereoscopic model. (See also fig. 9.) Inset shows area of figure 54.

may result from an orderly arrangement of stream segments, trees, depressions, or other features (figs. 74 and 84). This arrangement may be a continuous alinement of geologic, topographic, or vegetation features, but more commonly it is a discontinuous alinement. Because lineations are especially important as expressions of fractures they may indicate areas of considerable economic significance.

Drainage patterns are an important element in geologic interpretation of aerial photographs (figs. 48, 94, and 96). In bedrock areas these patterns "* * * depend for the most part on the lithologic character of the underlying rocks, the attitude of these rock bodies * * * and the arrangement and spacing of the planes * * * of lithologic and structural weakness encountered by the runoff" (Tator, 1954, p. 412). Stream patterns thus reflect the control exerted by underlying structure and rock type. But stream characteristics may be influenced by thickness and kind of surficial material where structural control is at a minimum. Under these conditions the drainage may reflect differences in surficial materials that are significant to the engineering geologist. (See Belcher, 1945, 1948; Jenkins, Belcher, Greeg, and Woods, 1946; Frost, 1946; Frost and Woods, 1948; Hittle, 1949; and Parvis, 1947, 1950.) In areas where resistance to erosion may be more or less uniform, as in many surficial deposits or in bedrock without pronounced structure, the drainage pattern is commonly dendritic or modified dendritic (see figs. 70, 77, and 106). Where structures are well developed, as in folded mountains, characteristic trellis, annular, or other drainage patterns may develop (see fig. 64).

Because the sensitivity of drainage to strike and dip directions is pronounced, changes in a drainage pattern, or deviation from an established norm, may be as important or more important than interpretation of any one stream pattern. "It is therefore important that relatively large areas be examined so that local drainage patterns [or anomalies] may be readily differentiated from regional drainage patterns" (Alliger, 1955, p. 180). A change in drainage may thus have significant structural implications (see figs. 9, 94, and 96). But a difference in stream pattern may also suggest variations in lithologic character of the underlying rocks.

Patterns of vegetation are also commonly of geologic significance and may reflect structural conditions or lithologic character of rock types (see figs. 40, 43, 54, 72, and 85). Woolnough (1934a, p. 213) suggested that a distinction be made between two types of vegetation distribution which he called "blocks" and "alinements;" the former occurs on extensive outcrops of rock of uniform character, the latter along narrow rock bands, faults, or similar limited features. Alinements further may be subdivided as linear, parallel, and curved (see Woolnough, 1934a, p. 213). It is suggested that narrow linear or parallel alinements of vegetation may represent fractures (figs. 50, 60, 71, and 101), whereas wide, curved alinements may signify the distribution of outcrop of low, moderately or even steeply dipping beds (figs. 40 and 72); where curved alinements form closed loops they generally represent horizontal or nearly flat lying beds (figs. 61 and 77).

The term "pattern" has also been used in the literature in quite a different sense than described above. In the study of surficial materials the term "soil pattern"—a poorly chosen term—refers to the combination of surface expressions, such as landform, drainage characteristics, and vegetation, that are used in the interpretation of ground conditions (see p. 34–37). Thus pattern as defined above may be included as an element of the broad term "soil pattern," commonly used in engineering geology descriptions. Soil patterns may reveal information of direct use in engineering geology studies, as in the location of granular materials (figs. 52, 88, 104, and 108; and p. 34–37); in addition soil patterns may be important in suggesting the distribution of certain rock types; this distribution in turn may reflect geologic structures (see figs. 4, 48, and 81).

RELATION TO ASSOCIATED FEATURES

The relation of one feature to its surroundings is commonly important because a single feature by itself may not be distinctive enough to permit its identification. The significance of this relation may be spatial or genetic. For example, depressions may be identified as kettle holes because of their location near readily identified terminal moraines, and because of their genetic association with glaciated terrain. With regard to spatial association this recognition element has also been called the "site factor" (Colwell, 1952, p. 540); it may be particularly useful in determining the significance of vegetation with respect to the underlying geology. For example, certain tree groups growing on topographically high areas in interior Alaska suggest well-drained underlying materials. The landform, especially, in combination with the vegetation characteristics suggests stabilized sand dunes (fig. 56). The relation of associated features may thus permit specific identifications and inferences concerning surficial materials or rock types.

Photograph scale may be important in the interpretation of associated features; that is, a geologic feature on small-scale photographs may be interpreted because of its position with regard to other features,

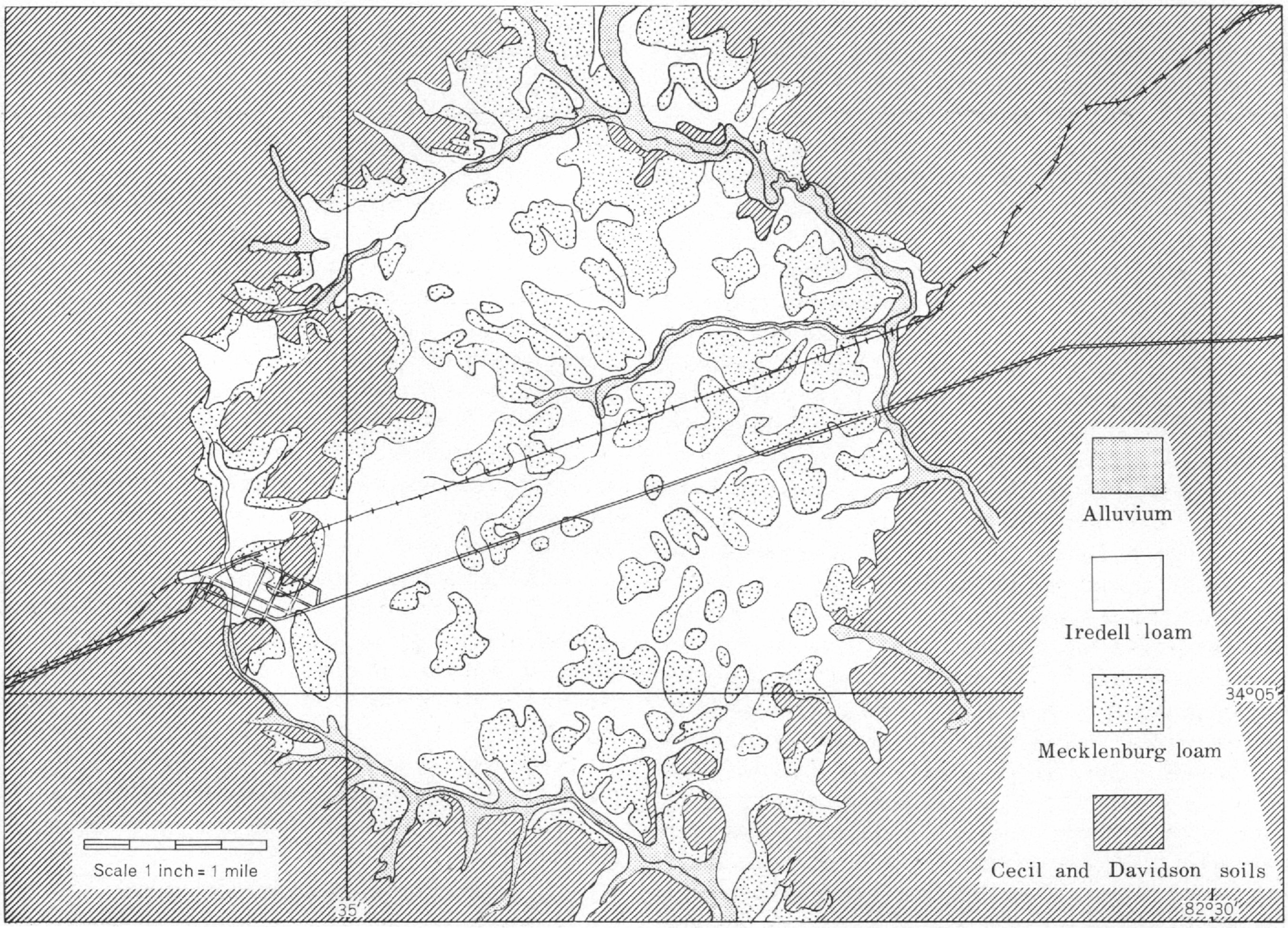

Figure 4.—Generalized soil map of area shown in figure 48 (modified from soil survey map of Abbeville County, South Carolina).

The circular area underlain by Mecklenburg loam and Iredell loam is conspicuous. These soils delimit an area of mafic intrusive rocks from a surrounding area of silicic rock types. Particularly where outcrops are sparse or lacking, soil maps may provide significant geologic information, especially in areas of residual soils. The soil maps may provide structural or lithologic data with respect to underlying rocks, or they may provide pedologic data concerning the surficial materials that is useful to the engineering geologist.

all of which can be seen at the same time (fig. 55), whereas on large-scale photographs direct identification might be made because photographic details are visible. The usefulness of association as a recognition element also will vary not only with photograph scale but with the objective of the study. The engineering geologist may be confronted with the immediate identification and location of kames as a source of gravel near a proposed highway route, whereas the geologist mapping the entire area would be interested in the identification, orientation, and distribution of all kames, with respect to geologic history of the area.

SHAPE

Shape as a recognition element in geologic interpretation is significant primarily only in its broadest definition, which involves relief or topographic expression. In this regard shape is very important in recognizing constructional landforms, such as volcanic cones, sand dunes, river terraces, and certain glacial features (figs. 41, 55–58, 60, and 104); it is also useful in differentiating rock units where one formation is expressed in bold cliffs and overlies a second formation that shows a lesser angle of slope (figs. 62, 84, and 91), or where adjacent rocks show significant differences in topographic relief (fig. 65). Rectilinear depressions may be expressions of faults (figs. 60, 85, 86, 99, and 103). The general surface configuration, as in the "beehive" weathering of some massive sandstones, also may be regarded as an expression of shape that is useful in recognition. According to Belcher (1945, p. 140–141) shapes of gully cross sections are important to the interpretation of surficial materials for engineering purposes. However, in its strictest definition, as "a spatial form with respect to a relatively constant contour or periphery" (Webster's New International Dictionary, 1950) shape has been of little importance as a recognition element because nature may reveal the same geologic feature in an infinite number of different shapes, and because common scales of photography (1:20,000) restrict an interpreter's ability to see details of shape. Where local field criteria have been established, shape may be useful, for example, in the interpretation of patterned areas (fig. 53) or in the study of gully cross sections, particularly when large-scale photographs are available (fig. 88).

Shadow as a recognition element is primarily a use of shape and photographic tone. Because vertical aerial photographs are commonly used for interpretation, shadows may permit an effective side view of some features. For example, shadows may be useful in interpreting tree types, such as conifers, which generally have pointed tops; the type of tree in turn may have a relation to underlying geologic materials and particularly to soil-moisture conditions (Stoeckeler, 1952, p. 4). For interpreting most natural features, however, the shape of shadows probably contributes little in direct identification. Insofar as shadows contribute to textures and patterns, they are of course of great importance. Even slight topographic breaks may be accentuated by shadows (figs. 88 and 97).

SIZE

The quantitative element of size, as it relates to surface or volume dimensions of an object, has been little used in recognition of geologic features from aerial photographs, although relative size has been useful as an interpretation aid. Size as an interpretation element is being used increasingly with the adoption of photogrammetry as a fundamental part of photogeology; it is most appropriately considered in relation to interpretations based on thickness of strata, amount of offset along faults, or other finite measurements (see p. 56–63). Geologically significant measurements may be directly related to topographic expression; that is, measurements between topographic positions may yield direct information such as stratigraphic thickness. But generally other influencing factors, such as dip of beds or other structural elements, must be considered just as in field measurement (see p. 56–58). If the thickness of a formation is known, it may aid in location of formation contacts on aerial photographs, because measurements may be made from known points that would permit the positioning of the obscured contacts (fig. 39); or it may aid in correlation of beds across fault zones. Determining the range of thicknesses over a broad area may be essential to understanding the regional geology of that area (see p. 59–60).

Studies in quantitative geomorphology suggest that size, in terms of finite measurements, may be an extremely important parameter of geologic interpretation of aerial photographs. Measurement of geologic data can be expected to become an even more important part of photogeology in the future as techniques of quantifying geologic information become more widely used.

COMBINATIONS OF RECOGNITION ELEMENTS

The usefulness of recognition elements, of course, is enhanced where they may be used in combination. Indeed, photographic tone, useful alone as a recognition factor under some conditions, is a fundamental photographic characteristic without which there could be no recognition elements at all on black-and-white photographs. As mutually supporting recognition elements an association of photographic tone, topographic expression, and texture may permit the interpretation of bedding, even in areas of sparse or no outcrops (fig. 40). Faults are commonly expressed as straight or gently curved lines; they may be further identified by an abrupt photographic tone change on opposite sides of these lines as well as by a pronounced offset of recognizable rock types (fig. 83). Surficial materials are commonly identified on the combined basis of stream patterns, shapes of gully cross sections, texture, and photographic tone as well as by their relation to associated features (see p. 34–37).

VERTICAL EXAGGERATION

In addition to those recognition elements that are based on factors, such as film and filter used and processing, that directly affect the photographic image, certain other factors are important in interpretation. Especially significant is vertical exaggeration—the exaggeration of vertical distances with respect to horizontal distances—which is characteristic of almost all stereoscopic models; this exaggeration makes slopes appear steeper than they are and objects seem taller than they are. Vertical exaggeration is generally present not only in viewing stereoscopic models formed from paper prints but also in viewing projected stereoscopic models formed from glass-plate diapositives in double-projection instruments.

An understanding of vertical exaggeration is fundamental in the study of stereoscopic models, not only because of the exaggerated heights and the somewhat unnatural view that results, but because in many geologic problems the interpreter relies on visual dip estimations rather than on any measuring devices (see p. 64). The amount of exaggeration of a dip angle in a stereoscopic model is fundamentally related to the tangent of the dip angle; that is, in a stereoscopic model exaggerated 3 times, for example, any true dip angle would be exaggerated to an angle whose tangent function was equal to 3 times the tangent of true dip. Exaggeration of low dips is generally an aid in structural interpretation and in detecting tilt from aerial photographs.

Minor topographic differences, which may reflect underlying geologic structure, are also exaggerated and in turn easily recognized (figs. 40, 88, and 97). The exaggeration of relief in a stereoscopic model of 1:20,000-scale photographs taken with a 6-inch-focal-length lens commonly permits an interpreter to distinguish differences in altitude as small as 1 foot. As a consequence vertical exaggeration then is most important where small but significant differences in altitude may be present in the stereoscopic model.

Vertical exaggeration results from the wide spacing of the camera positions at the time of exposure, as contrasted to the spacing of the human eyes with respect to normal viewing arrangement in examining stereoscopic models. Vertical exaggeration in normal viewing arrangement is fundamentally related to base-height ratio, which is the ratio of the air base distance to the flying height (see fig. 1). As this ratio increases, vertical exaggeration increases. Thus the greater the distance between camera stations (equivalent to air base distance), flying height remaining constant, the greater is the vertical exaggeration. The resulting photographs will have an increasingly smaller overlap area and consequently a lesser area within the stereoscopic model. It should be noted, however, that in normal photographing procedure when flying height is increased for any given focal-length lens, the air base distance is also increased so that a relatively constant base-height ratio is maintained. Under these conditions vertical exaggeration is not affected by flying height. When the base-height ratio is increased through the use of short-focal-length lenses, vertical exaggeration will also increase, the photographs taken with the shorter focal-length lens showing the greater exaggeration. Effective vertical exaggeration may also be increased by moving the two photographs farther apart at the time of viewing, or by increasing the viewing distance.

SCALE OF PHOTOGRAPHS

Small-scale photographs may be advantageous for interpreting some geologic terrains, particularly where reconnaissance information is desired. Small-scale photographs are normally taken at relatively high altitudes and have scales of 1:60,000 or smaller; their usefulness results chiefly from showing a large area in a single view (approximately 80 square miles on a single photograph having a scale of 1:60,000), which may reveal overall relations, as in geologic structures, drainage patterns, or other features, that could not be readily seen otherwise (figs. 48 and 55). Photomosaics commonly serve this same purpose (fig. 96). The association of features over a large area provided by the small scale is the significant factor to be considered. However, the reduction in image size due to high flying heights or short-focal-length lenses may be detrimental to the identification of some features, and hence make such photographs of little use for some interpretation problems. For example, details of jointing may be entirely lost on small-scale photographs. Also, use of small-scale photographs obtained by using extremely short-focal-length lenses, that is, 2 inches or shorter, may be undesirable, especially in areas of moderate to high relief, because many topographically low areas will be masked from view. Nevertheless, small-scale photographs have definite advantages in qualitative interpretation (Hemphill, 1958b) and may be especially useful if employed in conjunction with large-scale photographs or with instruments that enlarge the photography scale (see p. 47). Where quantitative study is involved, small-scale photographs are advantageous in that less control is needed within a given area than with large-scale photographs; but this advantage may be offset by the decrease in the reliability of measurements (see p. 72–74).

PHOTOGEOLOGY IN GEOLOGIC MAPPING

In geologic mapping maximum use of aerial photographs is attained by closely integrating field and photogeologic studies. It generally is desirable to precede the field phase of geologic study by a study of aerial photographs, which should include the compilation of a preliminary map on which all interpretations, however reliable or questionable, have been noted. Such a preliminary photogeologic study affords several advantages: it may point out areas that must be mapped primarily by field methods; it may eliminate or reduce extensive field surveys in certain areas; it may direct attention to anomalous areas where detailed field study is particularly warranted; and it commonly provides a basis for organizing the geologic plan of field study. In addition, attention is directed to those areas where field study will most likely result in establishing criteria that will permit a refinement of further photogeologic mapping. Also, a preliminary study of photographs gives a geographic familiarity of the area that would be useful in choosing camp sites, routes of traverse, and optimum locations of instrument survey stations.

Continuing use of aerial photographs during the field phase of geologic study permits a firsthand correlation of geologic features and photographic images, which corroborates or refutes preliminary interpretations and provides information for subsequent detailed photointerpretive study. Refinements in interpretation may be made in the field or in a followup photogeologic study.

The delineation of rock types and structures from aerial photographs may involve mere observation; or more commonly interpretation is involved. In some areas it is possible only to map similar photographic units, as no diagnostic or suggestive criteria as to rock type may be present. Such areas are usually poorly exposed because of heavy vegetation or surficial debris; relief may be very low. But in other areas, where wide expanses of rock crop out, specific formations or rock types may be easily delimited on the photographs; thus much of the routine work of mapping geologic contacts, as well as determining structural measurements, can be accomplished readily by photogeologic methods. Where geologic structures are small and complex, aerial photographs may provide only limited information as contrasted to areas where geologic structures are large and simple. Depending chiefly on factors related to geologic environment, climate, and erosional cycle, the extent to which photogeologic methods can be applied thus may vary widely.

KINDS AND AMOUNTS OF INFORMATION

Geologic information that can be interpreted from aerial photographs may be grouped broadly into two categories: lithologic and structural. In general or reconnaissance mapping the geologist is interested largely in determining the distribution of rock units, including surficial deposits, and in delineating geologic structures. Special studies may require a more rigorous application of photogeologic procedures, which includes quantitative as well as qualitative study of the stereoscopic models. But regardless of the objective of a particular study, the kinds and amounts of geologic information available from aerial photographs will depend primary on the type of terrain—whether igneous, metamorphic, or sedimentary—, the climatic environment, and stage of the geomorphic cycle.

It is generally believed that sedimentary rock areas will yield more information from aerial photographs than igneous rock areas, and that regions underlain by metamorphic rocks will reveal the least information. Putnam stated (1947, p. 560, 562) that "* * * geologic features * * * tend to be more recognizable where strong differences exist in the erosional resistance of adjacent rocks. Thus, sedimentary rocks, as sandstone, shale, and limestone, are likely to be more apparent than relatively homogeneous rocks like granite, especially if the sedimentary rocks have a moderate dip." Bentor (1952, p. 162), based on his work in Israel, was of the opinion that "As a whole, air-photographs are much less useful in regions of crystalline rocks than in those composed of sedimentary formations." With regard to igneous and metamorphic terrains, which are generally believed to be more difficult to interpret than sedimentary terrains, Melton (1956, p. 57) concluded that "Discovery of hitherto unknown or abnormal structures and [mineral] deposits, rather than detailed mapping, will probably be the most rewarding use of aerial photographs * * *."

Except for high mountainous areas where vegetative growth is restricted by altitude, arid and semiarid regions generally will have the largest areas of rock outcrop, and tropical regions the least; hence the arid and semiarid regions may be expected to yield the greatest amount of geologic information from aerial photographs. In addition to relatively wide areas of rock exposure, the arid and semiarid regions may be expected to show a greater number of significant plant-rock associations than other climatic areas, because weathered material in the arid and semiarid regions is not excessively leached and a close relation of soil to parent formation therefore persists. Where this close association of parent rock and residual soils exists the distribution of different vegetation, reflecting the effect of bedrock on the composition of the soils, may facilitate the mapping of different rock types (see Levings, 1944, p. 27–30). In areas of much precipitation, under temperate or tropical climatic conditions, soils tends to be leached of salts, and there is a further tendency for soils from different parent formations to become more similar at maturity (Murray, 1955, p. 104). Murray stated (1955, p. 104) that under tropical conditions where rainfall is abundant, the ratios of potassium, sodium, and calcium to aluminum, which are widely different in silicic and mafic rocks, become smaller on weathering and are nearly equal in mature soils. Thus differences in vegetation as related to specific formations might be less well developed in tropical areas, except for those plant associations that may depend primarily on physical characteristics of the soil rather than chemical. Grantham (1953, p. 329) noted that in semiarid areas of Africa the soils reflect geology through vegetation differences more strongly than in wet temperate areas.

Sedimentary terrains yield a greater amount of lithologic and structural information than igneous and metamorphic areas because of the generally nonhomogeneous nature of sedimentary terrain, which results in marked differential erosion characteristics that stand out on aerial photographs. Sedimentary rocks of strongly differing physical characteristics commonly crop out within short distances whereas plutonic rocks, particularly, are likely to be relatively homogeneous over wide areas. Locally, diagnostic landforms, such as volcanic cones, may be important in study of igneous terrains, especially where extrusive rocks prevail. Metamorphic terrains, on the other hand, may reveal the least amount of information from aerial photographs because of the very nature of the metamorphic processes, which tend to destroy the erosional and landform characteristics of sedimentary and igneous rocks from which the metamorphic rocks are derived.

In any area where vegetative cover is dense and where surficial debris is widespread, aerial photographs generally can be expected to yield more structural information than lithologic information. The amount of structural information in turn generally will be greater, for any one type of terrain and climatic environment, during the mature stage of the geomorphic cycle, at which time streams show their greatest adjustment to and reflection of structure, and at which time a greater third dimension of the terrain is visible for study in the stereoscopic model. Where the lithologic character of rocks is interpreted on geomorphic or landform expression, maturely dissected areas may reveal the greatest amount of information.

Although the extent to which photogeologic procedures contribute to the geologic mapping of an area depends on the climatic and geologic environment, as well as the stage of the erosional cycle, some generalizations may be stated with regard to differentiating and interpreting sedimentary, igneous, and metamorphic terrains. These generalizations are grouped into two categories: lithologic character of rocks and geologic structure.

LITHOLOGIC CHARACTER OF ROCKS

SEDIMENTARY ROCKS

Consolidated.—The presence of bedding in most sedimentary rocks is fundamental to their interpretation from aerial photographs. Because of differential resistance to erosion of sedimentary beds the typical banded patterns of these rocks are seen on aerial photographs. This is a result of what Rich (1951, p. 189) termed the "etching concept" wherein more resistant beds are brought into relief and less resistant beds lowered as a result of weathering and removal of materials largely by sheet wash and creep (figs. 87, 91, and 97). Back slopes of steeply dipping beds, especially, may contrast strongly because they commonly expose to erosion within a given area a wider variety of lithologic types than dip slopes of gently dipping beds. Although topographic expression is thus important in recognition of bedding, banding due to vegetation or soil differences, expressed by photographic tone may likewise delineate beds, in absence of topographic expression or in combination with it (figs. 40 and 81). Bedding is especially prominent in the mature stage of the geomorphic cycle, particularly in terrain underlain by interbedded hard and soft sedimentary rocks that are tilted. However, bedding may be masked by the massive character of some sedimentary rocks, such as certain sandstones, in which case the sedimentary rocks may appear to be homogeneous and similar to some metamorphic rocks or intrusive igneous rocks as seen on aerial photographs (contrast figs. 71 and 92). A notable exception is massive limestone in which sinkholes have developed (fig. 68).

As seen on aerial photographs shales and similar fine-grained sedimentary rocks tend to have relatively dark photographic tones, a fine-textured drainage, and relatively closely and regularly spaced joints (figs. 49, 62, 63, and 91). Coarse-grained clastic rocks, in contrast, tend to have relatively light photographic tones, a coarse-textured drainage, and relatively widely and regularly spaced joints (figs. 42, 91, and 92). These generalizations are probably most applicable to marine sedimentary rocks. However, some fine-grained clastic rocks may be light toned and some coarse-grained sedimentary rocks, such as the continental red beds, may be dark colored rather than light colored and be expressed as relatively dark photographic tones on aerial photographs. Drainage density in a given climatic area is related primarily to resistance of a rock to erosion; drainage density increases with decrease of resistance to erosion. Resistance to erosion in turn is fundamentally related to permeability; generally resistance to erosion is less in rocks of low permeability. Hence, fine-grained clastic rocks commonly have a fine-textured drainage (fig. 79).

Physico-chemical precipitates are in many places closely associated with fine-grained clastic sedimentary rocks; where these rocks are interbedded the drainage texture and joint pattern both may be fine, as with fine-grained clastic rocks alone, but photographic tone of physico-chemical precipitates may commonly be relatively light, as with some fresh-water limestone, rather than dark, despite the fine grain size.

Although fine-textured drainage commonly characterizes nonresistant fine-grained sedimentary rocks and coarse-textured drainage suggests resistant coarse-grained sedimentary rocks, drainage is probably more significant as an indicator of structure than it is of lithology. Drainage characteristics may suggest broad rock groupings, but no one drainage pattern is diagnostic of sedimentary rocks, although annular and trellis drainage generally suggest sedimentary rocks or close metamorphic equivalents. The association of specific drainage characteristics with rocks of certain lithologic or physical characteristics presents an interesting field of study; quantitative study of stream data measureable from aerial photographs, such as drainage density, may indicate certain drainage-lithology relations.

The type of vegetation may be useful in differentiating specific rock types (see figs. 43 and 61). Hemming (1937) noted that striking vegetation differences were exhibited by limestone and quartzite in northern Rhodesia where the trees *Acacia* and *Albizzia* grew on limestone and *Brachystegia* and *Isoberlinia* grew on quartzite.

Unconsolidated.—Most surficial deposits—the unconsolidated sedimentary rocks—are readily distinguished on aerial photographs from consolidated rock types, although thin veneers of surficial material may be difficult to identify. Many recognition criteria are used in identifying and interpreting surficial deposits from aerial photographs, but the most significant criterion is probably landform. Landform is significant because many surficial deposits, particularly those useful to the engineering geologist, are transported materials that have diagnostic topographic form. The importance of landform is seen in the identification of sand dunes, eskers, kames, alluvial fans, river terraces, and similar constructional geologic features (figs. 52, 55, 56, 58, and 104). On the other hand extensive deposits of surficial debris, such as the drift plains of north-central United States, may show little or no diagnostic landform, but their general makeup may be inferred from drainage characteristics, photographic tone, analysis of slope, and related criteria (fig. 107). These criteria are discussed more fully under uses of aerial photographs in engineering geology studies (p. 33–37).

IGNEOUS ROCKS

Extrusive rocks.—Extrusive igneous rocks commonly have diagnostic landforms (figs. 41, 60, and 76) in contrast to the intrusive igneous rocks, which are revealed on aerial photographs primarily by other recognition features such as drainage, texture, massive character of the rock, and crosscutting association with country rocks.

In addition to landform certain other criteria may be useful in identifying extrusive rocks, if the terrain is relatively undeformed. The structural relation of flows to associated rocks, for example, may be diagnostic in little-deformed areas, but where flows have been strongly tilted, folded, or otherwise disturbed, recognition and interpretation from aerial photographs may be extremely difficult or impossible. Only those relatively undeformed flows, mainly of Tertiary age and younger, are readily identified from aerial photographs without some knowledge from ground surveys. The ground plan of flows showing lobate patterns of vegetation and topography, especially at the terminations of suspected flows, is commonly diagnostic (figs. 76, 85, and 113), and association with volcanic cones makes misinterpretation difficult (figs. 41, 60, and 76). Locally flow channels may be visible. The surface of a flow may be rather hummocky and irregular, in contrast to surfaces of sedimentary strata, and where several flows have piled up, present topography may show several terracelike forms with irregular surfaces. The unconformable contact between flows and underlying rocks may aid in recognizing extrusive rocks (fig. 87), and where flows cascade down over older topography their identity is obvious (fig. 60). The basaltic or mafic flows may show dark photographic tones on conventional photographs, particularly in well-exposed areas, whereas rhyolitic or silicic flows may have light photographic tones. Locally distinctive patterns are present on mafic flows (fig. 53), and in some areas erosional characteristics permit differentiation of flows and associated rocks (fig. 69).

Where flows have been extruded over deformed igneous and metamorphic terrains, a low-dipping surface associated with lobate patterns of vegetation and topography is suggestive of extrusive rocks, and in some areas faults in the underlying rocks are seen to terminate abruptly at the edge of a lava flow (fig. 85).

Intrusive rocks.—Intrusive igneous rocks have a wide variety of structural relations to surrounding rocks that commonly aid in their identification from aerial photographs. Dikes may be revealed on aerial photographs as rectilinear or curved ridges that stand up because of greater resistance to erosion than surrounding rocks (figs. 81, 82, 87 and 90); they may also contrast in photographic tone with the surrounding rocks either because of the difference in rock types (fig. 90), or because of distinctive vegetation that covers dikes in some areas (Mogg, 1930, p. 662 and 668, pl. 5). Dikes may follow fractures in other igneous rocks and contrast in photographic tone with the host rock. Where dikes are less resistant than the country rock, they may be expressed as rectilinear depressions that appear similar to fault expressions.

Because sills occur parallel to bedding in sedimentary rocks, they may be difficult to interpret as igneous from aerial photographs, even though strong tonal contrasts of the sills and sedimentary rocks are present. Mogg (1930, p. 656) pointed out that the diabases of Pretoria, South Africa, although relatively hard rocks, weather easily to deep soils that support distinctive deep-rooted vegetation, but the vegetation type differs from area to area. The tree *Kirkia wilmsii* grows conspicuously and exclusively on diabase sheets in the sedimentary rocks of the Pyramid Hills area of Pretoria (Mogg, 1930, p. 658), but in the Magaliesberg area *Acacia caffra* characteristically marks the diabase (Mogg, 1930, p. 662). Vegetation thus may be important locally as an indicator of rock types, but commonly it must be interpreted with caution because the same rock type may carry a different flora in different areas.

Igneous plugs, laccoliths, stocks, and batholiths, by nature of their mode of origin, commonly tilt the sedimentary rocks which they intrude, and in areas where plutonic rocks are exposed the pattern of dips in surrounding rocks may support other criteria suggestive of igneous rocks. Domal areas due to intrusion may also be reflected in radial drainage patterns (fig. 48), just as are certain folds in sedimentary rocks. But if areas of plutonic rocks are large, the characteristic homogeneous nature of such rocks may result in a dendritic drainage pattern, unless drainage is controlled by a fracture system (figs. 51, 70, 71, and 86). Because of the generally homogeneous nature of plutonic rocks as contrasted to sedimentary rocks they will have a massive appearance on aerial photographs, and banding typical of sedimentary and some metamorphic rocks will generally be lacking (figs. 59, 70, and 71). Also because of the homogeneous character of many igneous bodies, elements essential to plant growth may be distributed more or less uniformly throughout the mass (Murray, 1955, p. 103) and significant differences in vegetation can be expected to be absent from any one plutonic rock mass (fig. 70), except for those differences controlled by altitude or by structural conditions, such as faults that may trap an abundance of moisture (fig. 71).

In addition, topographic and erosional characteristics may aid in the interpretation of some igneous terrains. Granite at low altitudes in some tropical areas is expressed in hummocky, rounded topography on which a uniform type of vegetation is present; dendritic drainage may characterize this terrain. Similar rounded topography may also be present at high altitudes, but where glaciers have been active all rocks may stand out in sharply angular topography. Regardless of surface expression, however, a crisscross pattern of joints, nearly always present in igneous rocks, commonly can be seen not only in the well-exposed areas (see figs. 70, 71, 100, and 103) but also in many vegetation-covered areas (fig. 72). Topographic expression of most plutonic rocks, as with other rock types, is dependent in large part on climate and stage of the erosional cycle, although within an area underlain by different igneous rock types difference in resistance to erosion may be significant and specific rocks may stand topographically high (see fig. 82). The homogeneous character of many intrustive rocks and characteristic jointing, on the other hand, are related primarily to the rock type and its mode of occurrence, and are independent of climate and erosional cycle.

METAMORPHIC ROCKS

The identification and interpretation of metamorphic rocks from aerial photographs is commonly difficult because large-scale distinguishing characteristics are generally lacking. Bedding, so necessary to structural interpretation, may be difficult or impossible to recognize because of physical changes brought about by metamorphism, including the superposition of metamorphic structures of small scale. Indeed, many structural trends that can be interpreted from aerial photographs represent foliation rather than bedding (figs. 73 and 74). Where exposures are good, differences in photographic tone offer the best clue to recognition of bedding, especially where the metamorphic rocks are derived from thin-bedded sedimentary rocks of contrasting lithologic makeup (fig. 103). Thick formations of quartzite and marble might readily retain the photographic characteristics of the original sedimentary beds, however, because the metamorphic changes of induration of sandstone and recrystallization of limestone would likely have little effect on the gross physical appearance of these rock types as seen on aerial photographs. It is possible, however, that talus from quartzite ledges might take the form of large blocks in contrast to smaller chunks of rubble at the base of sandstone cliffs. The preference of vegetation for one rock type such as limestone, as a result of its chemical makeup, might well persist, even if the formation were metamorphosed to marble; but vegetation that might show a preference for sandstone because of its physical makeup, especially its high porosity, might well be lacking on its metamorphic equivalent, quartzite.

Strong parallel alinements of ridges and intervening low areas may be due to regional cleavage, foliation, or fold axes, and thus the "topographic grain" of an area may suggest underlying metamorphic rocks (figs. 73, 76, 100, and 102), but in glaciated areas this evidence must be used with caution (fig. 67). In an area where a pronounced regional trend, or "topographic grain," is shown on the aerial photographs, the likelihood that metamorphic rocks are present is supported by the occurrence of widely spaced lineations at right angles to the regional trend. These lineations commonly represent regional cross joints and may be reflected in abrupt deflections of drainage along conspicuous straight stream segments of major streams (fig. 74) or in the development of tributary streams along these joints (figs. 73–75). Where bedrock is well exposed the profuse fractures in certain metamorphic rocks may be visible (figs. 46 and 99). Cady (1945) pointed out that in some areas in central Alaska talus slopes are developed much more extensively where the peaks are of metamorphic rocks rather than of granitic rocks; this distinguishes these two rock types locally (fig. 103).

STRUCTURE

FLAT-LYING BEDS

Flat-lying or nearly horizontal beds are most easily recognized where different sedimentary rock types exhibit contrasting photographic tones expressed as bands that extend along the topographic contour (figs. 77 and 78). Where both resistant and nonresistant rocks are present slope characteristics commonly are suggestive of horizontal strata—the resistant rocks have steep slopes or vertical cliffs, and the nonresistant rocks have a lesser angle of slope; the significant changes in slope between two beds extend generally along the topographic contour (figs. 77 and 78). Photographic tone and slope characteristics are associated in many places as mutually supporting evidence of flat-lying beds.

Because of the uniform resistance of one rock type to erosion, particularly in a horizontal direction, the drainage on flat-lying beds is generally dendritic unless controlled by joints or faults (figs. 42, 61, and 77). However, dendritic drainage alone, although suggestive, is not necessarily diagnostic of flat-lying sedimentary rocks; other rock types, such as granite, also may be uniformly resistant to erosion and may also exhibit dendritic drainage.

DIPPING BEDS

Numerous expressions of dip of sedimentary beds may be seen on aerial photographs. Dip direction is readily apparent where topographic surfaces coincide with bedding surfaces (figs. 87, 90, 92). Even in heavily vegetated areas the direction of dip commonly stands out as a result of the overall view afforded by the aerial photograph, which shows the tree crowns to fall in a dipping plane (fig. 89). In those areas where dips are very low, the aerial photographs are advantageous, if the beds are clearly expressed, because vertical exaggeration, which is present in most stereoscopic models, permits low dips to be readily interpreted (see fig. 91 and p. 64). The degree of dip may be estimated from the stereoscopic model by experienced photointerpreters or it may be measured photogrammetrically.

Where bedding is expressed by bands of differing photographic tone or by topographic breaks in slope due to resistance of beds, the rule of V's may be applied to determine the direction of dip; that is, where the trace of a bed intersects a stream valley a V in the outcrop pattern will point in the direction of dip (figs. 80, 81, and 98) unless the direction of dip and direction of streamflow are the same and the stream has a gradient greater than the amount of dip (fig. 59).

In many areas, particularly those of low relief, where beds are obscured by surficial materials or vegetation the direction of dip may be inferred from drainage characteristics. Where dips are gentle the relatively long tributary streams commonly flow down the dip slopes (Lattman, 1954, p. 361–365), whereas short tributary streams will characterize back slopes (figs. 5, 7, and 74). It is interesting to note that the relation of short and long tributary streams may be reversed where dips are steep, that is, about 45° or more (fig. 6). Other photorecognition criteria, such as distribution of photographic tones, should be sought to indicate whether dips are gentle or steep; or scattered field observations may provide sufficient information for making an analysis of dip direction based on stream characteristics. In such an analysis it may be desirable to trace all streams, however small, on a separate overlay (fig. 7). This is best done from the stereoscopic model. Exact positioning of tributaries is not essential to this technique of determining dip direction, but lengths of tributaries must be sketched carefully as the length relations of updip to downdip tributaries is significant. Viewing the stereoscopic model pseudoscopically (fig. 95) may be helpful in delineating the drainage.

FOLDS

Folds are commonly expressed as obvious features on aerial photographs especially where a fold is shown in its entirety within a single view and an orderly structural arrangement of beds is discernible (fig. 90) or where erosion has exposed a cross section of the

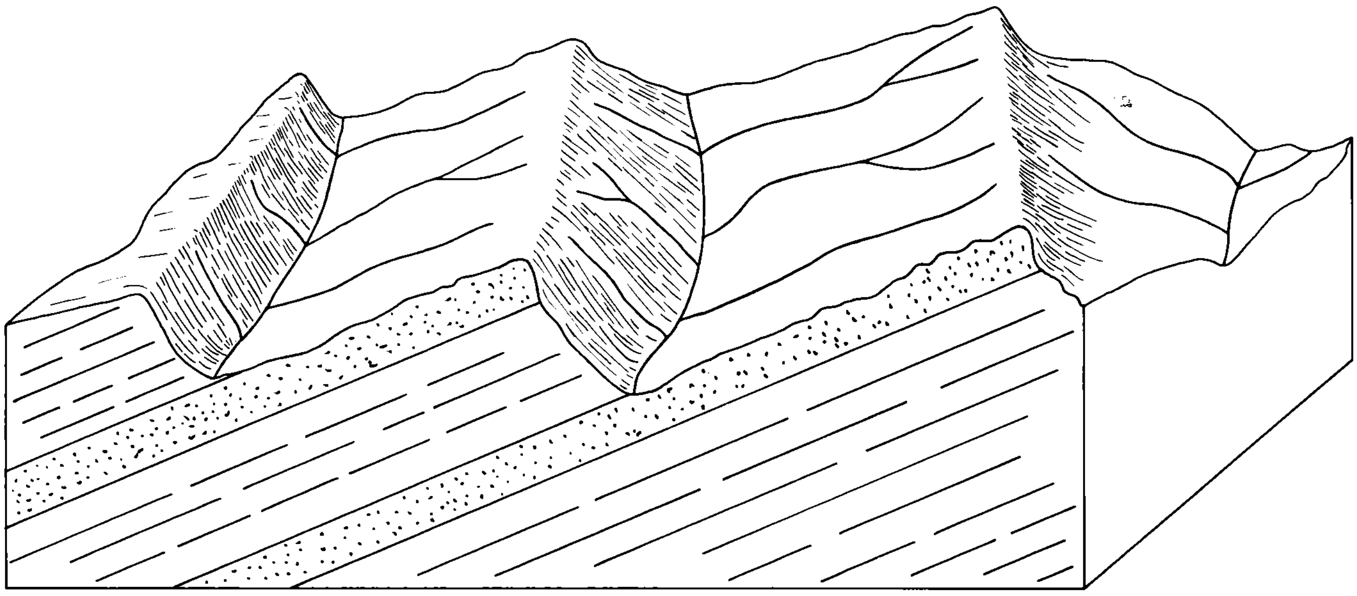

FIGURE 5.—Sketch showing long tributary streams on updip side of strike valley in area of low dips.

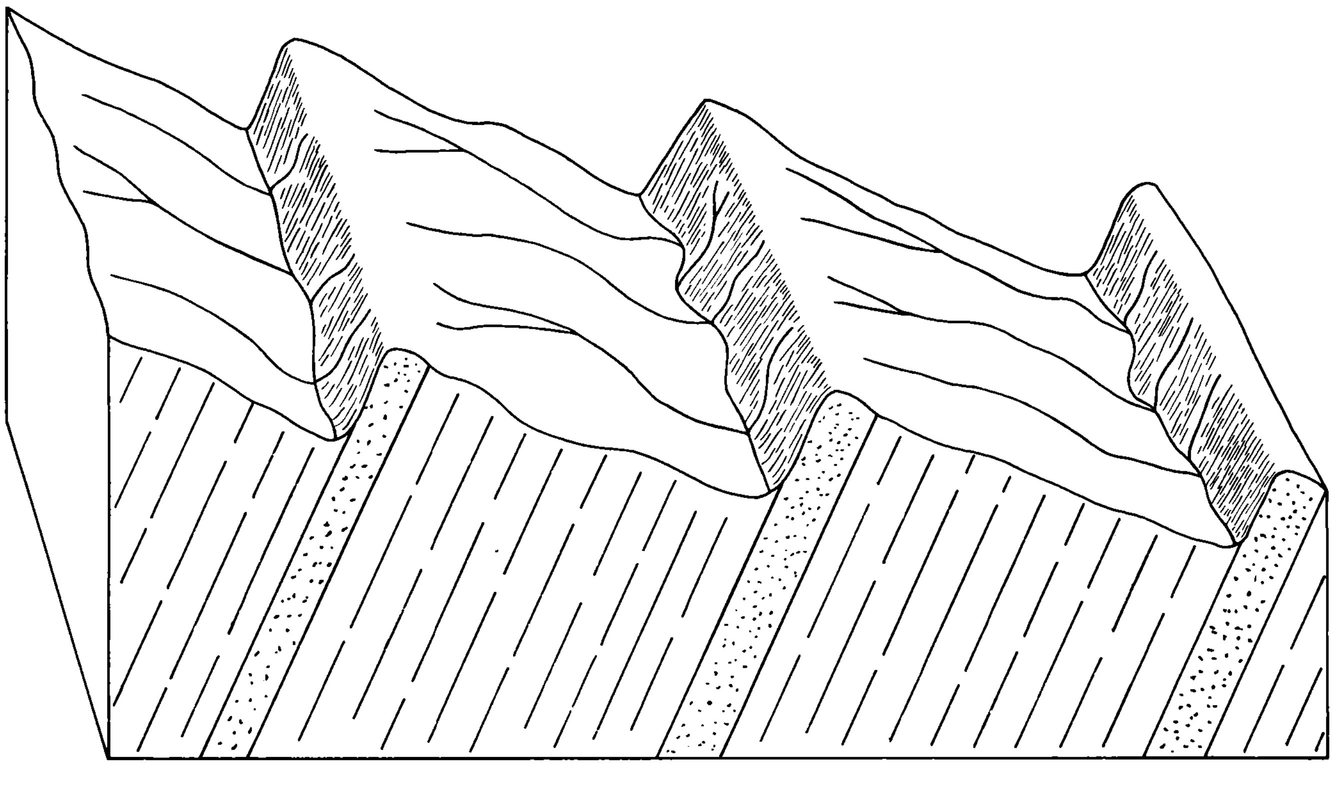

FIGURE 6.—Sketch showing long tributary streams on downdip side of strike valley in area of steep dips.

structure (fig. 91). Drainage characteristics may also aid in recognizing and delimiting the fold. Wengerd (1947, p. 596) noted that in parts of northern Alaska streams flowing in synclinal valleys were sluggish and meandering, and had low banks and swampy border areas with meandering tributaries; in contrast, streams flowing in anticlinal valleys were steep walled and less meandering. Wengerd also noted that dip slopes and back slopes in some areas commonly exhibited different drainage densities (fig. 79).

Where folds are plunging, major streams commonly curve around the nose of the fold; the convex side of the curve indicates the direction of plunge of anticlinal folds (figs. 81, 89, and 90). However, in areas where relief is low or bedrock is obscured by vegetation or surficial materials, drainage patterns or drainage anomalies may be the primary expression of folds (see figs. 9, 94, and 96; and p. 26–27). Drainage patterns or anomalies generally are best seen on small-scale photographs or mosaics where segments of streams combine to form significant patterns when observed in a single view (fig. 96). The significance of drainage characteristics may not be immediately apparent when large-scale photographs are viewed.

FAULTS

One of the advantages in study of aerial photographs is that of delineating high-angle faults or suspected faults. This advantage is a direct result of the aerial view, which allows a large area and the gross features within it to be seen at one time. For example, many alinements that are inconspicuous on the ground are readily seen on aerial photographs (figs. 74 and 83). Although many alinements are conspicuous because of their independence of stream valleys or ridges and uplands which they cross (see Barton, 1933, p. 1198), alinements of stream segments and small drainage courses are probably the most common indicators of faults. Most high-angle faults are expressed on photographs as straight or gently curving lines, and this characteristic is probably the most important clue that a fault may exist. All linear features should be examined with care even though other criteria are needed to prove the existence of faults.

Lines indicative of faults may be expressed as alinements of vegetation, straight segments of stream courses, and waterfalls across streams; alinements of lakes, ponds, and springs; conspicuous changes in photographic tone or drainage and erosional texture on opposite sides of a linear feature, or tone change along a linear feature because of vegetation which may appear darker; alinements of topography, including saddles, knobs, or straight scarps; rectilinear depressions; or any combination of these. Faults may also be expressed by horizontal or vertical offsets of beds or recognizable rock units (figs. 50, 60, 62, 74, 79, 80, 82–84, 86, 98, 99, 101, and 114). Where bedrock is well exposed the actual physical break may be seen. In some places a lineament, or broad linear depression, may be conspicuous but not distinct. Where such areas of possible faults occur, beds on one side of the general lineament should be examined for change of dip and strike as well as abnormal stratigraphic position with respect to beds on the other side (see fig. 80). Commonly in sedimentary terrain, offsets on opposite sides of a linear feature are easily detected, owing to the vertical exaggeration which is inherent in most stereoscopic models and which generally assists in the identification of correlative beds (figs. 83 and 84).

Suspected faults should be examined carefully because other features may be represented, at least in part, on aerial photographs in the same manner as faults, particularly if a single photograph is being viewed. In some areas jointing in one direction within a formation may be prominent and where an apparent offset is present owing to the occurrence of an erosion scarp along a joint plane, the scarp line may be misinterpreted as a fault trace. Where channels have been cut in sedimentary formations, and a rock type of different lithologic character now occupies the channels, a distinct lineation between the channel filling and the original sedimentary rock, now truncated, may suggest a fault trace. A line between two distinct types of vegetation, although possibly reflecting the presence of a fault, may well be due to differences in underlying rock types in normal sequence, or to the moisture content of the soil, or even to manmade features. In some areas the simple erosion of dipping strata may result in an alinement of topographically high points that suggests a fault. Or vegetation and drainage alinements may be present along easily eroded dikes. The need for caution in interpreting faults from aerial photographs is thus dictated by the very presence of numerous other geologic features that are expressed photographically in a similar manner.

Low-angle faults are more difficult to interpret from aerial photographs than high-angle faults. Discordance of structures within different rock types combined with strongly curving or irregular traces of the fault contact of the rocks involved offer the best clue to the presence of low-angle faults. Angular unconformities may show similar photographic expression.

In a study of azimuth, frequency, and length measurements, Gross (1951) demonstrated that in some covered areas of the Canadian Shield certain lineations very likely represent faults. The study involved the

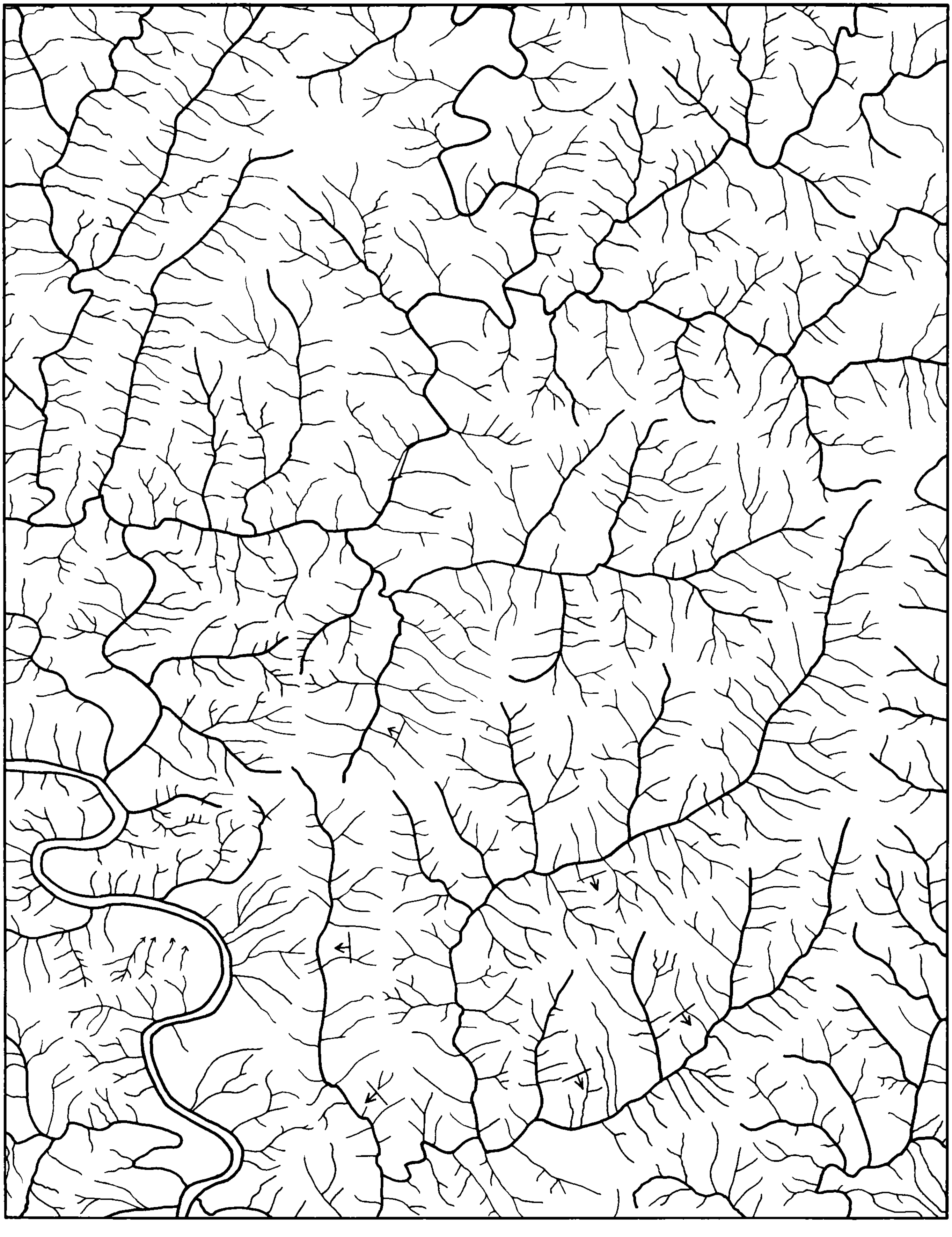

FIGURE 7.—Drainage map of area shown in figure 74 and vicinity. (Strike and dip positions based on analysis of stream-length relations.)

The separate drainage tracing allows a study of drainage characteristics divorced from the abundant imagery of the photograph. Patterns and tributary stream-length relations, for example, are readily observed on the separate tracing. Relative lengths of tributary streams at many places might easily be overlooked in the stereoscopic model. However, a study of the planimetric disposition of streams must be considered a supplement to a study of the stereoscopic model in which significant features in the third dimension, such as elongate hills or other features that may represent structure, are seen.

construction of histograms in which the length and frequency of topographic lineations as seen on aerial photographs were plotted against geographic orientation within 10° segments of the compass. Similarly, histograms were plotted from a sampling of field data of strike of strata, schistosity, dikes, glacial striae, faults, and other features considered to have a bearing on the configuration of the topography. One peak on the histograms compiled from aerial photographs was found to represent a direction of prominent faulting.

JOINTS

Joints, like faults, are most commonly expressed on aerial photographs as linear features. In flat-lying or gently folded sedimentary rocks, most joints are steeply dipping or vertical, evenly or regularly spaced, and commonly consist of two prominent sets that are expressed on aerial photographs as lines intersecting approximately at right angles, which gives a blocky appearance to the topography (fig. 42); however, joints may be well developed in only one direction, which gives a strong linearity to the fracture plan (fig. 92). In fine-grained clastic rocks the joints are generally more closely spaced than in coarse clastic rocks. Joints may become widened through weathering and erosion processes and appear as particularly conspicuous linear features; the similarity of these joints to faults is superficially striking, especially where well-developed regional cross joints have formed in metamorphic rocks and other criteria of faulting are lacking. Identification of many joints is enhanced by the presence of vegetation along them, due perhaps to greater moisture along these lines. Lattman and Olive (1955, p. 2087) described the use of solution-widened joints in Texas as a guide to indicate steepening of dip and to locate changes in dip direction. Joints more nearly parallel to the dip direction were widened by solution of meteoric water. Rubble, soil, and water trapped in these joints gave rise to dense vegetation expressed on aerial photographs as conspicuous, even-spaced parallel lines. A good clue to the identification of joints in relatively undisturbed sedimentary rocks is the general abundance of short lineations on a photograph, and a more or less uniform trend of these lineations within a given area of a few square miles extent.

Lattman and Nickelsen (1958) described azimuth-frequency measurements from aerial photographs in a study of fracture traces in western Pennsylvania. The fracture traces are expressions of natural linear features that consist of topographic, vegetation, or soil alinements exposed continuously for less than 1 mile. The term "fracture trace" is used by Lattman (1958, p. 569) to differentiate these alinements from natural linear features exposed continuously for at least 1 mile or more, called "lineaments." A histogram of frequency and orientation of the fracture traces showed maximums closely corresponding to those of prevailing directions of joints as seen in the field, with the exception of one fracture-trace maximum which had no counterpart in exposed rocks of the area (Lattman and Nickelsen, 1958). This one maximum of frequency and orientation of traces, however, was found to correspond with joints in underlying coal beds; the joints apparently were reflected through an overlying thickness of shale and sandstone to be expressed at the surface in a manner discernible on aerial photographs but not in routine field-mapping procedure. The close correspondence of fracture traces and joint directions in the test area suggest that aerial photographs may be used to extend mapping of joints into nearby areas of no outcrop.

Joints in igneous rocks are likely to be seen readily on aerial photographs (figs. 70, 71, 100, and 103). Commonly three and sometimes four prominent joint sets are developed. Where these joints are primary joints, dips may be low, moderate, or steep, depending on the orientation of flow structures within the igneous mass; this contrasts with the generally steep dipping joints of little-disturbed sedimentary rocks. Because of the wide range of dips of joints in igneous rocks, and because at least three joint sets are almost always developed, the surface traces of these joints, shown as lineations on aerial photographs, intersect at widely varying angles. The resulting crisscross pattern is distinctive of intrusive rocks in many areas. Joints in igneous rocks also may be irregularly spaced in contrast to those in sedimentary rocks.

Joints in metamorphic rocks may not be as conspicuous on photographs as joints in sedimentary or igneous rocks. Joints previously formed in igneous or sedimentary rocks may be destroyed by metamorphic processes and much of the energy of metamorphism spent in development of schistosity, fracture cleavage, or other small-scale metamorphic structures, rather than conspicuous joints. This is particularly true of metamorphic rocks formed from fine-grained clastic rocks, which comprise more than 50 percent of the sedimentary rock group. Where metamorphic rocks are recognizable by strong lineations that represent fold axes or trend of foliation, widely spaced regional cross joints perpendicular to the fold-axes direction may be prominent; streams developed along the cross joints accentuate these structures (figs. 8, 73, and 74).

CLEAVAGE AND FOLIATION

Cleavage or foliation, which is almost universally present in metamorphic rocks, especially in those that were originally shale or other thin-bedded clastic rocks, is difficult to differentiate on most aerial photographs. The "grain" of metamorphic terrain as expressed on aerial photographs by stream and vegetation patterns, as well as by parallel ridges and gullies, however, may well reflect pronounced cleavage or foliation (figs. 76 and 100). Turner (1952) pointed out that prominent topographic alinements in the schists of central Otago, New Zealand, are clearly expressed on aerial photographs. These alinements, generally parallel to the trend of *b* lineations, are believed to have resulted from differential weathering controlled by cleavage, foliation, and other elements of the schist fabric.

UNCONFORMITIES

Unconformities are generally difficult to interpret from aerial photographs. An angular unconformity may be inferred from the discordance of bedding, either in strike, dip, or both, at a contact line that has an irregular trace across a wide area. But discordance alone does not prove the presence of a stratigraphic unconformity since a discordance of bedding may be due to faulting, or locally to crossbedding. The areal distribution of rocks or structures as seen on small-scale photographs or mosaics, or after plotting geologic data over a large area, may also suggest the presence of an unconformity. On a local scale, the separation of unconsolidated, nearly horizontal, river gravel from the truncated, underlying strata is a good example of an unconformity (fig. 88). Pediment gravel that overlies truncated bedrock (fig. 45), or channel-fill deposits that truncate the underlying bedrock (fig. 44), may be clearly expressed on aerial photographs.

INTERPRETATION OF AERIAL PHOTOGRAPHS IN PETROLEUM GEOLOGY

Aerial photographs have been widely used by geologists of the petroleum industry particularly in the mapping of many large-scale geologic structures, which are readily recognized on aerial photographs because of direct surface expressions of dipping beds. The use of photogeologic techniques in the search for structures that may contain oil is continuously increasing. However, as the obvious and well-exposed structures in many areas have long been discovered, considerable attention is now being given to indirect, or geomorphic evidence of subsurface structures. In addition, photogrammetric methods for making measurements needed to compile structure contours and to

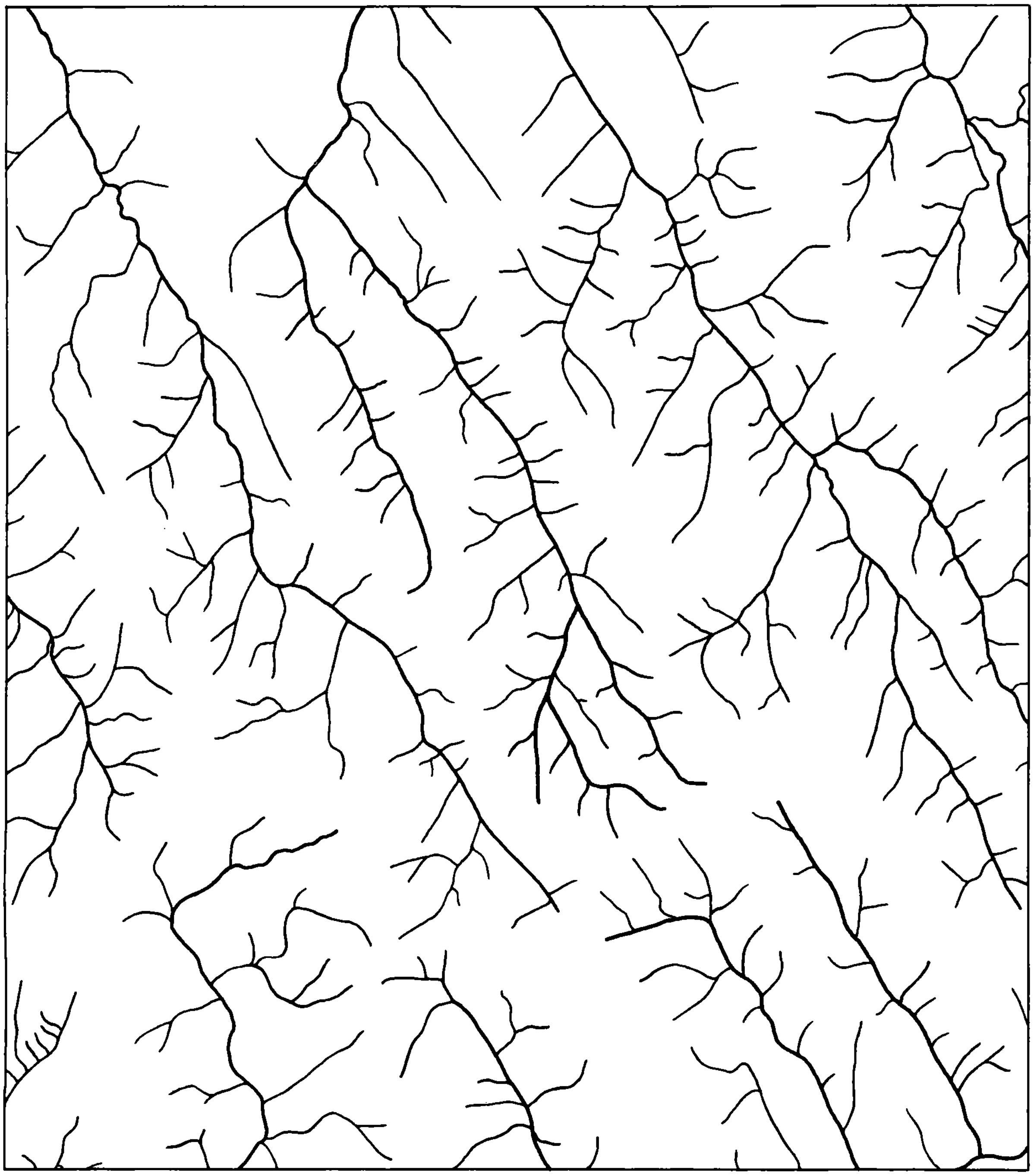

FIGURE 8.—Drainage map of area shown on left half of figure 73.

The regional cross-joint trend, expressed by the main streams on figure 73, is strongly brought out on the drainage map. Note tributary streams flowing at right angles to the main streams. Stream trends are obscured commonly by the abundant imagery of the photograph and it may be desirable to compile separate drainage maps when stream characteristics are used to interpret lithologic or structural features of an area.

determine strike, dip, stratigraphic thickness, and closure are being used increasingly.

The indirect evidence yielded by photointerpretive studies is based on the premise that subsurface structures may be reflected in surface expressions of various kinds, such as stream or vegetation patterns or anomalies. Indirect evidence is particularly useful in the interpretation of areas of few or no outcrops, such as areas of low relief, or areas of dense vegetation. Commonly in such areas, the evidence points not directly to a structure, but to an anomaly, such as a variation in drainage characteristics from the norm established for a local region. The anomaly in turn suggests a possible subsurface structure. Thus even though surface evidence alone may not be conclusive in the interpretation of subsurface structure, it may provide clues and stimulus for exploration (Alliger, 1955, p. 183). However, Wheeler and Smith (1952, p. 112) cautioned that "* * * strong deformation, periodically rejuvenated, is restricted to the mobile belts * * *," and structures farthest away from maximum deformation are "* * * therefore more difficult to infer from physiographic abnormalities at the surface * * * that without the genetic background of those events in the geologic history of the tectonic province responsible for surface and subsurface indications of structure, photogeology may be unfavorably speculative."

FOLDS

Folds may be expressed on aerial photographs by the distribution of bedding, by drainage characteristics, by topography, by distribution of soils, or by combinations of these criteria. The surface manifestations of folded or domed structures thus may range from obvious, where direct surface expression of dipping beds is present, to subtle, where subsurface structures are reflected only indirectly by physiographic criteria.

BEDDING

Many folded structures can be delineated readily because bedding is clearly expressed at the surface. Particularly in areas where rocks are well exposed and structural deformation has been mild, beds may be clearly defined by photographic tone together with topographic relief or hogback landform (figs. 90, 91, and 92); strike and dip of beds are easily determined and the structure delineated from the distribution of beds (see also p. 19).

In areas where bedding may be obscured by low plant and grass vegetation, differences in vegetation together with slight topographic relief changes, enhanced by vertical exaggeration of the stereoscopic model, may permit bedding to be delineated and structures to be structure contoured (see fig. 40 and p. 6).

DRAINAGE

In areas where bedding is largely obscured, for example by vegetation or surficial materials, stream patterns, anomalies, or textures may be helpful in determining dip slopes and outlining folds. In some areas dip-slope streams have a coarse-textured arrangement in contrast to the fine-textured arrangement of back-slope streams (fig. 79). These textures probably reflect coarse-grained and fine-grained rocks, respectively. The distributions of such textures in turn may suggest the location of structural axes.

In many areas stream adjustment to structure will result in a sweeping curve of the stream particularly across a structural axis and around the nose of a plunging fold; the convex side of the curve indicates the direction of anticlinal plunge (figs. 81 and 90). But such curves may also develop on dip slopes and thus not be indicative of the location of a structural axis. This situation may prevail where anticlinal structures are breached into softer material. Streams developing on the more resistant dip slope of the structural flank may curve on that flank and along soft interbeds, and not across the axis of the structure (fig. 93). Such a condition would probably be most pronounced during the mature phase of the geomorphic cycle. In geomorphically young areas streams may not have had sufficient time to adjust to folded structures, and may have a tendency to follow joints or preexisting faults (Howard, 1940, p. 195). In areas where stream pattern or anomaly is the primary surface reflection of underlying structure, as in some jungle-covered areas, other criteria, such as vegetation pattern, should be sought to corroborate the location of a structural axis suggested by stream characteristics.

Stream patterns or anomalies are undoubtedly the most useful indirect evidence of subsurface structures in many areas. This is especially true for coastal areas of low relief, many interior basins, or areas of dense vegetation or other surficial cover. Tator (1951, 1954) and DeBlieux (1949) discussed the structural significance of drainage anomalies in the coastal region of the Gulf States; in these low, swampy areas of aggradation it is important to establish the drainage norm by studying the drainage characteristics over a large area. Deviations from this norm may give the first indication of a structural anomaly. DeBlieux (1949, p. 1259) described abrupt locally restricted changes in drainage considered to be the result of subsurface structure. Over the Lafitte field in Louisiana a relic distributary of the Mississippi River forms two sharp meander bends, although for miles upstream and downstream from this area, the stream channel is simple and straight. Over the Scully dome "* * * two relic distributaries of Bayou Lafourche followed simple courses, but suddenly changed to an anastomosing pattern over the dome, then resumed simple courses south of the structure." (DeBlieux, 1949, p. 1259.)

Structural implications of stream pattern or anomaly may be corroborated by other geomorphic evidence. Over the Lafitte field the presence of distinct remnants of natural levees on either side of the channel, the only such ridges over the length of the relic course of the stream, was considered significant supporting evidence of underlying structure (DeBlieux, 1949, p. 1259). The levee-ridge remnants presumably were held up by subsurface structure as surrounding areas subsided.

In a study of tonal and textural anomalies in west-central Texas DeBlieux and Shepherd (1951) described anomalous compressed meanders over structural highs. In the same area annular and radial drainage patterns and stream deflections in the flank areas were important criteria that supported an interpretation of subsurface structure (fig. 94). The importance of abrupt changes in direction of streamflow in relation to possible subsurface structures has recently been emphasized by Buttorff (1958) and Elliott (1958), based on work in the Powder River Basin, Wyoming. Such deviations from the norm for an area commonly stand out when a separate drainage map of an area is studied (see fig. 9) or when stereoscopic models are viewed pseudoscopically (see p. 5 and fig. 95).

In areas of aggradation and active subsidence it is to be expected that abnormal drainage characteristics rather than any specific drainage pattern might be indicative of subsurface structure. The combination of emergence, due to recent rise of salt plugs, and subsidence of the general coastal-plain area is responsible for many of the anomalous drainage characteristics of the coastal area of the Gulf States; such characteristics are anastomosing stream segments, abruptly widened levee ridges, or abrupt changes in direction of streamflow.

In areas of active degradation, patterns of drainage rather than abnormal drainage characteristics can be expected to be indicators of structure. However, Wheeler and Smith stated (1952, p. 82) that the analysis of stream pattern with regard to structure—which they called "creekology"—is somewhat outmoded as a photogeologic procedure; they implied that anomalies in drainage characteristics may be far more important than specific drainage patterns. However, drainage pattern may actually be anomalous with respect to the drainage norm for an area; such examples of drainage patterns have been found along the northwest coast of Alaska on the Arctic coastal plain. Here, in an area of northward-flowing streams, slight topographic highs have resulted in radial-dendritic drainage patterns, which outline areas of subsurface structure (fig. 96). Commonly no other surface expression of structure is present. Because of low relief, outcrops are few.

TOPOGRAPHY

The presence of topographic highs has been significant in locating subsurface folds or domal structures even in many areas where relief is very slight. Many of the "islands" of the coastal area of the Gulf States are surface expressions of salt domes. Topographic features such as natural levees, which represent areas of higher ground only a few feet or tens of feet above the delta or flood plain, are also significant interpretation criteria in the search for subsurface structure (Tator, 1951). Tator reported (1951, p. 717) that "* * * cheniers and natural levees * * * provide linear patterns of higher ground supporting distinctive vegetation growths." These higher areas are also favored for cultivation. According to Tator (1951, p. 717) "Tonal contrasts in the photographs are the major keys used for recognition of landscape features of extremely low relief, such tonal variations being largely the result of soil and vegetation differences." The significance of low relief, is shown by DeBlieux's description (1949, p. 1254) of Felicity Island, a 2-mile-long natural levee ridge separated by several miles of marsh from the area where the levees normally could be expected to die out. The preservation of the "island" in an area of active subsidence has been attributed to local subsurface structure. Abrupt widening of levees on one or both sides of a channel, in areas of subsidence, also has been noted over subsurface domal structures (DeBlieux, 1949, p. 1254, and fig. 2, p. 1255); widening of levees may be due to other causes, such as coalescence of two levees, however, and this feature of the flood plain must be interpreted carefully.

In a study in northern Alaska, Fischer (1953) used topography as the principal interpretation criterion in locating the Square Lake anticline. The area is a treeless waste of low relief that is underlain by permafrost; tundra grasses cover the region, and no bedrock is exposed. Fischer (1953, p. 208) reported that the original photogeologic study showed small hills in the area elongate in the same direction as the regional

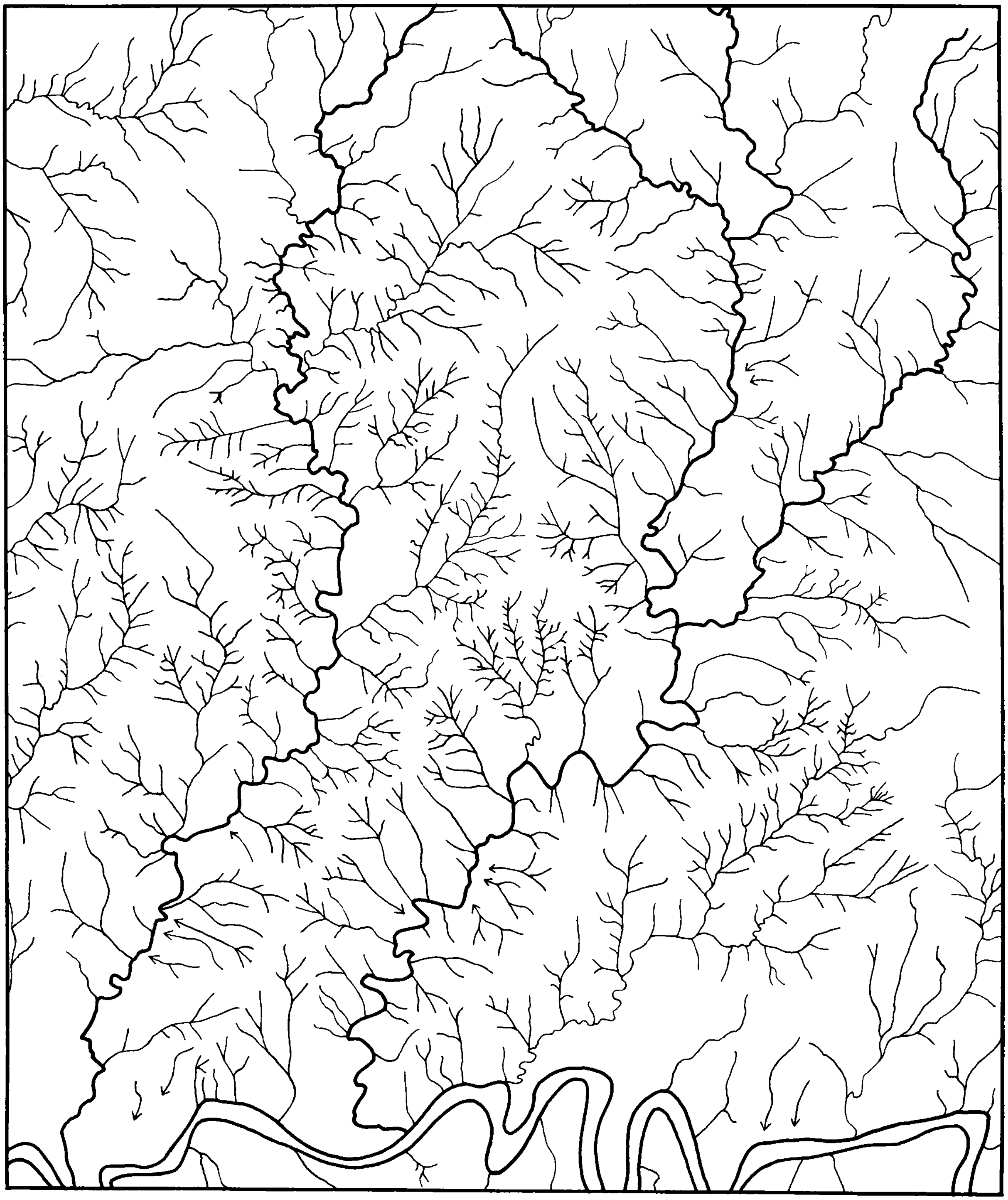

FIGURE 9.—Drainage map of area shown in figure 94.

Radial drainage over structure, *A* of figure 94, stands out on the drainage map which is unobscured by the abundant details of the photograph. Note that the radially draining streams flow into larger streams that have an annular pattern around the structure. Stream deflections, as at *D* in figure 94, are commonly more readily observed on the separate drainage map or in pseudoscopic view of the model (see fig. 95).

structural trend. Normal to this trend other elongate hilltops sloped in the direction of the inferred dip of beds. Also, streams flowing in the dip direction had a slightly less well developed dendritic pattern than those flowing opposite to the dip direction. There also appeared to be a correlation between slopes of the tops of cut banks and the direction of dip. Plotting of all such data gave a consistent apparent structural pattern —a plunging anticline—of unknown reliability. A subsequent seismic survey corroborated the photogeologic interpretation.

SOILS

In some areas devoid of outcrops, soil patterns or soil distributions may be useful in delineating or suggesting structures. Both Woolnough (1934b, p. 221, 224) and Christensen (1956, p. 858–859) cited examples of the usefulness of aerial photographs in this regard. Wheeler and Smith (1952, p. 106) stated that contrasts in soil tone accentuate unusual drainage relations on the northern flank of a structure in the southwest Maysville area, Oklahoma; and in southwestern Alabama differences in cultivation pattern reflect relief and soil characteristics by which geologic units of Tertiary age beneath younger unconsolidated materials can be differentiated.

DeBlieux and Shepherd (1951, p. 98) described tonal and textural anomalies in west-central Texas that resulted from differences in soil types, soil-moisture content, and erosional characteristics. They cited an anomaly at Salt Fork on the Brazo River where "* * * dark and coarsely hummocky surface strongly contrasts with the lighter color and finer texture of the surrounding surface * * *" (DeBlieux and Shepherd, 1951, p. 98). The anomaly was strikingly similar to that of a reef producer in Scurry County. DeBlieux and Shephard (1951, p. 88) emphasized that how a structure forms is unimportant in a study of tonal, textural and other anomalies, because the surface evidence is identical, whether the structure has resulted from upward movement, differential downwarping, reef or residual topography, or combination of these features; it is important initially that a surface anomaly can be recognized.

FAULTS

Faults are significant in the geologic interpretation of petroleum areas because they may be deep seated and of major importance in localizing oil accumulation. Where faults are genetically related to structures that may be oil bearing the distribution pattern of faults may be of considerable use for interpreting the locations of those structures. The many surface expressions of faults are described above (p. 21).

Desjardins (1952, p. 82) stated that surface fault and fracture lines, expressed as lineations on aerial photographs, form patterns that bear a definite relation to deep-seated salt domes and to subsurface faults of the Gulf Coastal Plain. Disturbance centers, believed to be underlain at depth by salt domes, may be indicated by the fault patterns, shown on photographs as "Sharply curving lines which are strikingly concentric" or as "Prominent transverse lines radiating usually from some marginal point rather than from the center of the structure" (Desjardins, 1952, p. 82). Desjardins believed that such fault patterns were the result of continuous application of small stresses caused by rising salt masses rather than an accumulation of stresses that would produce large amounts of movement; he also felt that faults probably would form in interdome areas as well as over the domes. The genetic significance of the fault pattern is thus critical if distribution of faults is used as a basis for locating the dome itself. Desjardins (1952, p. 83) made a strong distinction between surface expressions of faults, which he associated with deep-seated domes, and other criteria, such as topographic expression, widening of natural levees, and looping of stream channels, which he associated with shallow-seated domes.

Although most interpretations of faults are based on qualitative characteristics of observed data, such as the dislocation of correlative beds, or the contrast in light and dark photographic tones on opposite sides of a straight line, a quantitative approach to such studies may provide additional useful data. On the basis of azimuth-frequency studies Blanchet (1957, p. 1748) suggested that structural and stratigraphic anomalies in some areas may be located by a statistical analysis of fractures, which he defined as the generally abundant, natural lineations discernible on aerial photographs. The basis for analysis is a comparison of local deviations in the statistical mean direction of fracture sets with regional norms for each fracture set. Regional norms are first established by plotting fracture-azimuth frequency diagrams of the region involved. Then statistical mean directions of fracture sets are determined by analyzing samples within circular areas centered at relatively small horizontal intervals of a few miles. These local mean directions are in turn studied for local deviations which are entered into empirical equations that yield structure-intensity values. These structure-intensity values are then contoured, to form a structure-intensity map, which may reflect structural anomaly. The structure-intensity map is supported by a fracture-incidence map, prepared in contour form, and by an analysis of drainage characteristics of the area in question. Blanchet applied this method to a study of petroleum structures.

FACIES

Although the widest application of aerial photographs in petroleum geology has been with regard to structural traps, a study of aerial photographs may contribute to the location of stratigraphic traps, particularly if photogrammetric measurements of formation thicknesses can be made at many points within the streoscopic model (see p. 59–60). From a qualitative standpoint it can be seen in figure 97 that a rapid loss of sandy section can sometimes be detected on aerial photographs. Such "shaling" or loss of sandy section due to facies change may be important in the search for stratigraphic traps and in some areas it may be measured photogrammetrically. In other areas well-defined formational units may thin or thicken without facies change, but this also may be significant in regional studies with regard to stratigraphic traps (Christensen, 1956, p. 861, fig. 6). Measurements of stratigraphic sections needed in such studies commonly can be made from aerial photographs.

REGIONAL STUDIES

The significance of aerial photographs in regional petroleum studies is widely recognized, but very little information is present in the literature with regard to this phase of photograph use. Not only may measurements be made from aerial photographs with regard to strike, dip, stratigraphic thickness, and closure, but the regional view of the mosaic or small-scale photographs permits a continuity of photographic criteria that may be of structural or stratigraphic significance. Overall geologic relations are brought together, and areas where detailed study is needed may be indicated. However, the limitations of the photogeologic technique must be constantly borne in mind. As Wheeler and Smith (1952, p. 112) pointed out, the validity of the technique "* * * depends a good deal upon the human element and the utilization of all applicable geologic data." They warned that "* * * the student of photogeology may * * * become overly impressed with geometric design of lines, masses, and tones so that, in the absence of understanding of the tectonic history he may find compatible alignments of stream courses, structurally inexplicable lineations or shapes and soil patterns that are not consistent with the known or expectable products of diastrophism" (1952, p. 112). An emphasis on regional study is indeed justified, however, if maximum use is to be made of aerial photographs, and this is true whether photographs are used in long-range exploration programs, as in reconnaissance mapping of broad basin areas, or in the ultimate study of local structures.

INTERPRETATION OF AERIAL PHOTOGRAPHS IN SEARCH FOR ORE DEPOSITS

The search for ore deposits, similar to that for petroleum, requires favorable host rocks or structures, or both, and it is therefore necessary to determine the general lithologic character and distribution of rocks and associated structures as a basis for carrying out a mineral survey of an area. Aerial photographs may contribute geologic data not only with regard to the fundamental guides of lithology and structure in ore search, but they also may reveal details of physiography, which may be an important ore guide in the search for placer deposits. Botanical guides to ore bodies may also be detected on aerial photographs of some areas, although little work has been done in this field.

STRUCTURAL GUIDES

Where fractures have been significant in localizing ore deposits aerial photographs may reveal significant structural data relating to trends and offsets of fractures, even in areas where surficial cover is extensive. This is due in large part to the great variety of criteria suggestive of fractures (see p. 21). In many areas it is possible to determine spatial relations of sets of fractures, and to infer the relative ages of the fractures from the aerial photographs, although results of field study are necessary to determine the significance of the patterns.

Aerial photographs are presently most useful in study of those ore deposits associated with fractures. In many mining districts where mineralized fractures form a vein pattern that is repeated throughout the district, an analysis of the fracture pattern and distribution may provide significant data in the search for new ore bodies. Reed (1940) described the use of aerial photographs in a mineral-deposits study of the heavily timbered Chichagof mining district of Alaska where gold-bearing quartz veins are associated with faults and shear zones (see fig. 99). There the faults are commonly expressed as depressions owing to greater erosion of soft material from fault zones (see also Twenhofel and Sainsbury, 1958, p. 1433). Reed (1940, p. 44) stated that many faults of moderate surface expression would probably have been overlooked on the ground, and that many faults of weak surface expression were seen only on aerial photographs. Joliffe (1945, p. 604), in a discussion of photogeologic prospecting in the Yellowknife area of Canada, noted that some of the largest gold-ore bodies "* * * lie in strong shear zones that are marked by rather distinctive gullies in relatively massive, resistant volcanic rocks." Many of these shear zones and other lineaments are conspicuously shown on aerial photographs.

Gross (1951) pointed out that in the glaciated Drysden-Kenora area of northern Ontario and the Goldfields area of northern Saskatchewan, Canada, there are many linear features seen on aerial photographs but that only certain ones represent faults. He devised a scheme of statistical analysis to show the likelihood that certain linear trends were faults (see p. 21). Concentration of prospecting along these linear features in the Goldfields area resulted in discovery of pitchblende deposits.

Because faults commonly are interpreted readily from aerial photographs, photogeologic study may aid in locating extensions of faulted ore bodies. Faults that offset an ore body may show an orderly spatial arrangement, and information regarding direction of displacement may be extrapolated to similar faults whose displacement is masked by vegetation or surficial debris. Willett (1940) found that aerial photographs provide significant information on the location of faults cutting the Invincible Lode, a gold-quartz deposit in the Glenorchy district of New Zealand. The photographs strikingly show the offset of a lode east of the Invincible Lode by a series of parallel faults, which suggest that similar conditions exist at the Invincible Lode where the evidence is not as readily observed because of surficial debris. In the Invincible Lode area one major stream flows parallel to the strike of the faults, and a second stream is deflected along a fault for about 1,000 feet, then bends back to its old course; the direction of deflection also indicates the horizontal direction of displacement of the quartz lode. The pattern of displacement, based on photogeologic evidence together with ground evidence, suggests the location of faulted extensions of the lode.

Major anticlinal and domal structures, readily interpreted from aerial photographs of many areas on the basis of drainage characteristics or strike and dip patterns, are with notable exceptions of relatively little importance in ore search. Where folds have been a factor in localizing ore, as in some metamorphic rocks, they commonly are too small or the geology too complex for existing aerial photographs to provide useful guides in prospecting.

LITHOLOGIC GUIDES

Lithologic guides may be considered from the standpoint of the parent and host rocks, or from the standpoint of mineralized or altered zones, which are more appropriately termed mineralogic guides. Photogeologic interpretation of rock types (see p. 16–19) may outline broad target areas of favorable parent and host rocks (fig. 100). Lueder (1953, p. 823) suggested that various locations can be rated on the basis of favorable photogeologic evidence; the most favorable area would become the prime target area for further investigation. Where some local field criteria are available, specific ore-bearing formations may be traced on photographs (fig. 98). At Ross Lake, Canada, the fact that rare-earth-bearing pegmatites of small areal extent were recognizable on photographs was a major factor in the discovery of certain tantalite deposits (Joliffe, 1945, p. 604).

The use of color aerial photography will increase many times the amount of lithologic information that can be obtained from a photogeologic study. This additional information will contribute not only to the reliable interpretation of host or parent rocks, but may permit local guides, such as alteration zones, to be readily recognized. In a study of the hydrothermally altered volcanic terrain near Tonopah and Goldfield, Nevada, information obtained from reversible-type color transparencies was contrasted with data obtained from thin sections of rock types. Kent (1957, p. 868) stated that "In both areas a general correspondence between coloration and alteration was observed. Zones of different coloration within a lithologic unit represent different stages of alteration. Colors of rocks in early stages of alteration are useful in recognizing lithology, but highly altered rocks have the same color within several different lithologic units. The colors associated with highly altered rocks are easily recognized on color aerial photographs; thus their distribution and their relationship to structural features can be studied." In addition Ray (1958, p. 37) wrote that "In one area of altered andesites a pale green color on color aerial photographs was found to represent an intermediate stage in the alteration resulting from partial silicification, with pale green chalcedony, and deuteric alteration and later oxidation of iron opaques. A light color in another zone was found to result from brecciation of dacite and attendant alteration to carbonates. A rather intense orange color was indicative of highly altered zones in all localities observed. However, the orange coloration did not indicate the rock type involved nor the type of alteration present, but rather was the result primarily of weathering of iron minerals following their partial breakdown by deuteric alteration."

PHYSIOGRAPHIC GUIDES

Some ore deposits are topographically expressed or are related to structures, rock types, or surficial deposits that are so expressed (fig. 102). Hence, topography may be considered a guide in ore search, although it does not by itself indicate the presence of ore. Because fractures commonly are topographically ex-

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pressed as rectilinear depressions, a possible physiographic guide to ore as interpreted from aerial photographs may be said to exist in many areas. Where fractures have been mineralized, and the vein filling stands in relief, topography may be a useful guide in ore search. However, many mineralized veins are poorly resistant to weathering and erosion, and occur as topographically low areas.

Where topography results in a photographic texture it may be possible to delineate areas of favorable host rocks, as the paraschists in Surinam (Zonneveld and Cohen, 1952, p. 155). Grantham (1953, p. 336) pointed out that in the wet Sierra Leonne area of Africa, the "* * * sharp change in topography from linearly arranged hills, controlled by schist and migmatite, contrasts with the irregular features of structureless granite."

An analysis of the physiography of an area may provide significant information, particularly in relation to placer deposits. As many placers have a complex history, it may be necessary to work out the alluvial history of a valley or valley system for maximum information in locating placer pay streaks. The arrangement and positions of old stream channels may be interpreted from meander scars, oxbow lakes, and different terrace levels that are commonly seen on aerial photographs. Photographs also may provide gradient measurements of present or past streams; this information may be significant inasmuch as placer concentrates occur especially where stream gradients flatten.

Buried stream channels, also the site of some ore deposits, may be interpreted from photographs of some areas on the basis of topographic expression (fig. 101). In many parts of the western Sierra Nevada, Tertiary stream valleys have been filled and gold-bearing gravel buried by younger lava flows. The greater resistance of the lava flows compared with the surrounding rocks has resulted locally in sinuous cappings of volcanic rocks that stand above the present-day stream system. Table Mountain, California (Loel, 1941, p. 384, 386–387), is an outstanding example of basalt capping auriferous gravel of a buried channel.

The location of stream-channel deposits recently has received wide attention in the search for uranium deposits on the Colorado Plateau in Western United States. There the Triassic Shinarump member of the Chinle formation is thicker in channels cut in the underlying Moenkopi formation, which is also of Triassic age. Some channels can be observed directly on aerial photographs (fig. 44); others may be inferred from isopach measurements, which in some areas may be obtained from aerial photographs. (See p. 58–59). The uranium is associated with carbonaceous materials, largely plant remains, scattered throughout the channels.

BOTANICAL GUIDES

Much field and laboratory work has been accomplished with regard to plant distribution and plant concentration of certain elements as indicators of ore. Little has been done, however, on plant characteristics or associations that may be observed or interpreted from aerial photographs, and herein lies a field of research that has much potential. There appear to be three aspects of botanical study from aerial photographs that may contribute to the location of ore deposits. These involve (a) color differences in vegetation brought about by concentration of certain chemical elements, (b) species differences or absence of vegetation owing to concentration of certain chemical elements, and (c) distribution of vegetation suggesting favorable structures or rock types. Color differences in vegetation, due to mineral and chemical concentrations, that may be reflected on aerial photographs have received almost no attention, and offer an interesting field of study. Species differences or lack of vegetation has likewise received little attention in ore search, although Walker (1929, p. 50–51) noted that air search was made for "dambos" as indicators of copper deposits in central Africa. Dambos are open spots in the bush cover, where vegetation does not grow because of the concentration of poisonous copper salts in the soils. Walker noted that the Roan Antelope copper deposit was marked by such a dambo, although the deposit extended beyond the limits of open area. Identification of species from color differences due to concentrations of certain chemical elements may be particularly amenable to detection on color or other special aerial photography.

Plant and tree distribution may be useful indicators of structures or of rock types favorable to ore deposition; vegetation distribution may reflect physical characteristics of the rocks, such as porosity or presence of fractures, although some rocks, such as limestone, may be preferentially covered by a certain type of tree because of chemical concentrations in those rocks (see fig. 72) rather than because of physical properties. Or vegetation may grow preferentially or trees grow higher and be alined along a fault or shear zone, which might in turn be a favorable site for ore deposition (see fig. 71). Such indirect guides in ore search contrast highly, however, with color or species differences, which might suggest more strongly the presence of ore minerals.

Levings and Herness (1953, p. 456–457) stated that heavy timber growth in the Corbin-Wickes area of Montana shows a preference for unaltered quartz monzonite, which has a darker photographic tone than the surrounding andesite and dacite; ore occurs in the volcanic rocks. Zonneveld and Cohen (1952, p. 153) mention that vegetation differences permit photographic differentiation of the clay savannahs and sand savannahs of Surinam, South America. Bauxite production at Surinam's Billeton mine (Hemphill, oral communication, 1958) is from a clay area, and hence it is important to know the distribution of such clay areas.

INTERPRETATION OF AERIAL PHOTOGRAPHS IN ENGINEERING GEOLOGY

Aerial photographs have been used for many years to provide topographic and land-use information in locating routes for pipelines, highways, or other rights-of-way, but only in recent years have photographs attained wide recognition as a source of geologic information for engineering purposes. Many kinds of geologic information for engineering use may be obtained from aerial photographs. These include (a) identification and location of soil materials, particularly granular materials, which would provide suitable foundation sites for industrial and airport developments, or highway rights-of-way; (b) identification and location of clay and clayey silt soils, which would have detrimental properties with regard to building, airport, and highway sites; (c) location of aggregate materials; (d) delineation of areas that may be underlain by permafrost; (e) interpretation of distressed conditions in landslide areas; (f) analysis of structural geology in areas of tunnel, dam, and reservoir sites; and (g) location of sample areas for detailed investigation of soil and rock materials.

SURFICIAL MATERIALS

Surficial materials generally are interpreted in terms of gross physical characteristics, rather than the detailed physical characteristics used by the pedologist. Knowledge of the gross physical properties is sufficient for many reconnaissance studies in engineering geology. Indeed, it is the grouping of several pedologic soil types into a few classifications that permits aerial photographs to be of significant engineering use. In the preparation of soil-engineering maps from agricultural reports of an area in Illinois, Thornburn (1951, p. 91) was able to reclassify 99 different pedologic soil types into 13 engineering groups. Lueder (1951) described the use of aerial photographs as a major tool in preparing soil-engineering maps.

The inability to interpret fine details with regard to physical characteristics of the soil thus does not preclude the use of aerial photographs in many engineering geology studies. From the standpoint of engineering significance a granular material, for example, which exhibits certain diagnostic photographic characteristics such as coarse-textured drainage, will generally react favorably to drainage, compactability, and other engineering tests, regardless of whether it is a residual granular material that has resulted primarily from weathering in place or whether it is a transported gravel derived from different rock types. However, Jenkins, Belcher, Greeg, and Woods (1946) pointed out exceptions to the general thought that photographic characteristics common to granular materials always signify suitable granular materials for engineering purposes. For example, the soil profile of well-drained limestone has a granular texture due to aggregation of clay particles into lumps. The surface drainage may be coarse textured; but the soils break down on compaction and react as plastic soil material, and not as a granular material (Jenkins, Belcher, Greeg, and Woods, 1946, p. 80).

Where pedologic data are already available they may be very useful to the engineer when interpreted in terms of engineering test data (fig. 4). Indeed, certain soil mechanics tests by the engineer, such as plasticity or soil-texture tests, are similar to those used by the pedologist. Greenman (1951) suggested that the pedologic method can become the nucleus around which aerial photo interpretive and field geologic information can be accumulated. But Eardley (1943, p. 567) pointed out that "In many places conditions unfavorable for the development of a normal soil, such as rugged mountains, wide sandy plains, or swampy basins may cover rather large areas. The important construction materials in such places may be better interpreted as a result of geological processes than from the standpoint of a soil classification * * *."

GROUND CONDITIONS

The interpretation of ground conditions probably has received more attention in recent years than any other engineering geology application of aerial photographs. Much of the literature concerns reconnaissance studies of soils in general and granular materials in particular; granular materials are essential for building sites and highway and airport development (Jenkins, Belcher, Greeg, and Woods, 1946; and Purdue University, 1953). Special attention also has been given to photointerpretation of permafrost conditions in northern latitudes.

With regard to highway engineering, Belcher (1945, p. 144) stated that "* * * the soil problem resolves itself into two parts, one in which the soil in place is satisfactory as subgrade, and the second, where the soil is unsuitable. In areas of unsuitable soils some form of improvement, by stabilization or insulation, is required. Insulation involves the economic location of granular materials in the form of rock to be crushed, cinders (volcanic), or sand and gravel * * *. Inasmuch as sand and gravel or other granular deposits exist to some extent in nearly every county in the country the significance of soil patterns indicating granular materials is of considerable economic importance to engineers." In fact, a large percentage of construction and maintenance expenses are in the costs of sand, gravel, crushed rock, and similar materials. As a tool for interpreting areas of gravel, sand, silt, and clay, aerial photographs offer an inexpensive and rapid method of reconnaissance, and according to Schultz and Cleaves (1955, p. 370) "* * * planning and exploration for large engineering projects should almost never be undertaken without a thorough study of aerial photographs of the region * * *."

Photointerpretation of surficial materials must consider not only the surface expressions of these materials but also the geologic factors reflecting the origin of these materials. A knowledge of the origin of materials permits inferences as to what kind of materials can be expected in an area, and in what locations with respect to other geologic features. Field-sampling programs also could be based on the analysis of the photogeologic data, and subsequent mineralogic and related studies by the engineering geologist could provide the soils engineer with information that would eliminate the need for many of the soil mechanics tests now performed as part of the routine laboratory analysis of all soil samples.

ELEMENTS OF SOIL PATTERN

The surface expressions of granular and other soils materials have been termed collectively the "soil pattern." The soil pattern consists of several elements of which the most important ones for nonpermafrost areas are considered to be landform, drainage, erosion, relative photographic tone, and color; vegetation cover and land use may also be significant (Belcher, 1944, 1945, 1948; Jenkins, Belcher, Greeg, and Woods, 1946; Frost, 1946; Mollard, 1947; Hittle, 1949; and Purdue University, 1953). Schultz and Cleaves (1955, p. 371) considered that "interpretation of soils by means of aerial photographs rests largely on the interrelationships of soils and geomorphic features"; consequently landform is considered by some to be the most important element in photointerpretation of soils. Landform, however, is only one element of the soil pattern and it is clearly evident that the association of several elements of the soil pattern will provide the greatest amount of information from aerial photographs.

Landform

Identifying the landform commonly identifies the natural process that formed it, and commonly limits the type of soils or soil characteristics that can be expected. The emphasis on landform is probably valid in reconnaissance soils investigations where broad areas of several different landforms are studied and mapping is at a small scale. But where detailed engineering information is needed, as in foundation studies, it is likely that the area of study will be within one landform, mapping will be on a large scale, and other elements of the soil pattern, such as differences in relative photographic tone, which may reflect soil-moisture content, will be of prime importance.

In small-scale mapping the emphasis on landform is probably warranted particularly for constructional landforms of transported materials, such as sand dunes, river terraces, alluvial fans, and many glacial landforms, all of which have distinctive shapes, although not necessarily unique (see figs. 52, 55–57, and 104); here the transported soil materials make up the landform. In contrast residual soils associated with destructional landforms may be more difficult to interpret from aerial photographs, for here the parent rock makes up the landform, and the significance of soils rests in part on the subjective interpretation of rock types. However, the interpretation of other elements of the soil pattern with regard to physical characteristics of soils are just as valid for residual as for transported materials; the engineering significance of many residual soil areas can be interpreted readily from aerial photographs on the basis of these other elements, such as drainage and erosional characteristics (figs. 63 and 65).

Drainage characteristics

Highly permeable soils will have good drainage regardless of their origin, provided that topographic positions will permit draining. In well-drained soils surface drainage normally will be coarse textured or even absent (figs. 49, 52, 66, 104, 106, and 108); in soils of low permeability drainage will normally be fine textured (fig. 63) or ponds may be numerous (figs. 57 and 66). The presence of fine- or coarse-textured drainage in surficial materials, like that in bedrock (p. 16), is primarily related to the relative resistance of the different materials to erosion, and hence related to permeability and grain size. Coarse materials characteristically are resistant to erosion, are permeable, and have a coarse-textured drainage; fine materials commonly are less resistant to erosion, are impermeable, and have a fine-textured drainage. These relations are significant in the interpretation of engineering soils from aerial photographs because drainage texture can be readily observed. However, exceptions to these relations may exist, as with loess, which is commonly characterized on aerial photographs by a relatively fine-textured drainage (see figs. 105 and 106); yet, loess in its natural environment is generally considered well drained internally.

Flow or channel markings, for example on terraces, indicate that the material was deposited by running water and further suggest that the material may be granular. Frost (1946, p. 121) described flow markings in an area in the midwest as consisting of light and dark streaks usually parallel to the direction of flow. The light streaks are ridges of sand or fine gravel that are probably sand and gravel bars; the dark streaks are fine clay or organic material deposited in depressions that once contained standing bodies of water. Frost (1946, p. 121) stated that "The chief significance of such markings lies in the fact that they suggest stream deposition and in order to have stream deposition at such elevated positions and occurring on * * * a large scale, there must have been large volumes of swiftly flowing water. Since swiftly flowing water allows only coarse material to settle, the terrace must contain a large percentage of gravel." It may be debatable that channel markings always indicate swiftly flowing water, but where some doubt exists other elements of the soil pattern may reveal the character of the terrace material.

In broad areas of aggradation, such as the Mississippi embayment, drainage characteristics revealed by aerial photographs are significant to the engineering geologist, as different soil characteristics are associated with the several features of valley alluviation. For example, backswamp areas contain clay and silty clay of high organic content, whereas natural levees consist of silt, silty sand, and some silty clay (Fisk, 1944, p. 18, 20). The levees commonly "* * * provide linear patterns of higher ground supporting distinctive vegetation growths" (Tator, 1951, p. 717). Low areas may be swampy and also contain distinctive vegetation. Graveliferous deposits fill the old valleys and in turn are covered by various other deposits; sandbars contain permeable sand that grades downward into the gravel. The distribution of features of the flood-plain drainage may be significant in analyzing ground conditions and locating favorable engineering materials in highway, railroad, and airport development.

Erosional characteristics

Closely related to the drainage characteristics of a soil are its erosional characteristics; these are important in photointerpretation studies chiefly from the standpoint of gully erosion, which is controlled largely by the physical properties of the soil and especially by cohesion. The usefulness of gully erosion characteristics in photointerpretation primarily involves the shape of transverse profiles, although longitudinal profiles may provide additional information. According to research workers at Purdue University (1953, p. 15–16) "* * * there are three basic gully characteristics which are associated with three major soil textural groups." Granular soils commonly develop sharp, V-shaped gullies that have short, steep gradients. Nongranular cohesive and plastic soils are generally indicated by uniform gentle gradient of gullies that extend well back into the upland, and by broadly rounded shallow V-shaped transverse profiles. The loess soils and sandy-clay soil exhibit U-shaped cross sections of gullies that have flat bottoms and low gradients.

Although there may be a general adherence of gully characteristics to the major soil textural groups, exceptions are not uncommon. For example combinations of the basic gully characteristics "* * * occur in 'layered soils' or in soils exhibiting a 'strong profile' ". (Purdue University, 1953, p. 16), and compound gradients may develop. In addition to the steep or vertical slopes in deep gullies, windblown silt may develop silt pinnacles and catsteps or terracettes (Purdue University, 1953, p. 45). It has been pointed out (Purdue University, 1953, p. 27) that climatic environment under which gullies form is an important consideration; for example, soft clay shale in an arid region where flash floods may occur commonly exhibit abnormally steep slopes in contrast to clay shale in areas of uniform rainfall where such slopes are usually softly rounded. Under certain conditions, such as gravel capping on clay soils in the New Jersey coastal plain (fig. 108), gullies in the underlying clay soils may be steep and deeply incised, in contrast to the usual broad shallow transverse gully profile of the clay soil group in humid regions.

In permafrost areas different materials may yield the same cross-sectional profile. Gravel deposits cemented by ice may have vertical gully walls, or may have gullies that are asymmetric in cross section if one side is preferentially exposed to the sun and thaws at a faster rate than the shadow side. The insulating materials overlying frozen deposits also affect the rate of thawing and hence the erosional characteristics of gullies. Interpreted carefully, however, the erosional characteristics—gully cross section and gradient—may reveal useful information on texture and other engineering characteristics of the soil.

Photographic tone

On black-and-white photographs the significance of color must be interpreted in terms of relative gray photographic tones. Belcher stated (1948, p. 486) that

"Light color tones (grays) are usually associated with well-drained soils, while clays, principally because of their water-retention capacity, appear dark." Frost (1946, p. 122), in describing the mottled soils in Indiana, stated that mottling nearly always indicates gravel. The mottling is due to "dark areas" which are "* * * small clay-like pockets that have been formed by the normal weathering processes of the gravel-sized material" (Frost, 1946, p. 122). These pockets are depressions that "* * * act as small infiltration basins which result in a higher moisture content and a darker color pattern" (Frost, 1946, p. 122). This mottled soil pattern contrasts with that of the drift plains in other areas where light-toned patches of slightly higher and dryer silty soils adjoin lower areas of wet plastic silty clays. Somewhat similar mottled patterns have been described by Gwynne (1942, p. 202–205) from the drift plain in Iowa (see fig. 107). But light photographic tones also may result from lack of moisture, owing to lack of precipitation as in many arid regions, rather than because of good drainage, and thus tone may be of little significance in evaluating soil texture in some areas. Or light tones may be the result of topographic position, and it is probable for example that a "* * * sand dune on a sand plain in a humid region will photograph light in color against a dark background" (Purdue University, 1953, p. 26) not because of differences in soil textures but because of topographic position. Climatic conditions also influence the colors of soils, especially the residual soils, and dark color rather than light color may be associated with well-drained materials, as certain red soils developed from limestone (Jenkins, Belcher, Greeg, and Woods, 1946, p. 84). Yet, provided climatic conditions are considered and provided relative photographic tone is borne in mind, the generalization that light photographic tones suggest good drainage and dark tones poor drainage may be useful in the overall interpretation of soils with regard to moisture content. Where tone is due to moisture, infrared photography will result in strong tonal contrasts between soils of different moisture content.

Color

Color has been cited as a principal element of the soil pattern that may yield information on the texture and drainage character of the soil profile, but to date very little interpretive work has been done with color photography. Belcher (1945, p. 138) briefly mentioned experimental color photography taken in different parts of the United States and stated that "The value of color * * * lies in the added detail that it furnishes with respect to these two elements of the soil pattern" (that is, soil color and details of vegetative cover). It would seem that color photography would reveal pedologic information significant in engineering evaluation of soils, especially the residual soils, which may be more difficult to interpret in general than transported soils, particularly from black-and-white photographs.

Vegetation

Vegetation as an element of the soil pattern has been considered one of the most difficult to interpret. It is known, for example, that certain trees, such as aspen, are tolerant of many different soils and soil conditions, but some types of vegetation are strongly influenced by soil type. Furthermore, vegetation may be influenced significantly by climatic factors. Where permafrost is close enough to the surface to affect tree and shrub roots the kind of vegetation that will grow may be restricted (see p. 37). Species identification may be difficult in any area unless large-scale photographs are available or unless pure stands are present. Nevertheless, vegetation may reveal significant information in engineering studies provided valid interpretations are made with regard to how vegetation is associated with soil textures, soil-moisture content, and topography; thus a knowledge of plant ecology is necessary if maximum information on soil conditions is to be obtained from aerial photographs. Willows, for example, indicate wet ground, poplar indicates dry ground, and jack pine implies sand and gravel beds (Belcher, 1945, p. 139). However, where abrupt changes in soil conditions exist, it is likely that vegetation changes will also occur (figs. 56 and 72), and areas needing further ground surveys may be easily delineated by inspection of aerial photographs without any basic knowledge of plant ecology. For example, stabilized sand dunes in interior Alaska can be easily delineated because they are marked by stands of dark-toned spruce (see fig. 56), in contrast to light-toned brush and grass of the interdune areas. This relation may be found where the topographically higher, well-drained sand of the dunes contrasts with frozen silty deposits of the interdune areas.

Where phreatophytes—plants and trees that obtain water from the water table—can be delineated (see p. 40), aerial photographs may provide significant engineering data because phreatophytes may choke overflow channels and thus increase the flood potential of some areas. Information pertaining to the downstream de-silting effect of phreatophytes with regard to dams and reservoirs may also be obtained from aerial photographs of some areas (see Robinson, 1958, p. 28–29). However, little interpretative work in this field has been done.

Land use

Land use may also reveal information on the soil conditions of an area. Belcher (1945, p. 142) reported that "Orchards thrive in well-drained locations and therefore, when observed on level ground, good subdrainage is implied." Shallow drainage ditches in areas of little relief commonly signify plastic, poorly drained soils. Schultz and Cleaves (1955, p. 378) stated that in eastern France and western Germany "* * * rugged topography and associated sandy soils developed on sandstones are generally left in forest; the comparatively level topography and associated clayey soils developed on shales and limestones are cultivated * * *." On the flood plain of the Mississippi River the silty sand of the natural levees is cultivated primarily because of its topographic position above the lower backswamps. In parts of the Valley and Ridge province of Eastern United States the limestone areas commonly are farmed whereas shale areas may be left in forest.

PERMAFROST

Permafrost has a significant effect on engineering characteristics of soils of the far northern latitudes and has received considerable attention in recent years, particularly from the standpoint of photointerpretation (Cabot, 1947; Woods, Hittle, and Frost, 1948; Benninghoff, 1950; Frost and Mintzer, 1950; Frost, 1951; Sager, 1951; Black, 1952; Hopkins, Karlstrom, and others, 1955). Considerable disagreement exists, however, on the significance of photointerpreted data in the study of permafrost areas (see Black, 1952, p. 126–127, 129), although it is generally agreed that aerial photographs can be particularly useful in such studies. The following discussion of ground conditions in permafrost areas is taken from the work of Hopkins and Karlstrom (Hopkins, Karlstrom, and others, 1955), except as noted by specific references.

Muller (1947, p. 219) defined permafrost as "a thickness of soil or other surficial deposit or even bedrock, at a variable depth beneath the surface of the earth in which a temperature below freezing has existed continuously for a long time (from two to tens of thousands of years)." Muller (1947, p. 30) also stated that "From the standpoint of engineering, the content of ice in frozen ground is of paramount importance * * * [because] * * * thawing of this ice produces excessive wetting and undesired plasticity of the ground and renders it unstable and susceptible to settling, caving, and even flowing." Building foundations, highways, railbeds, and airport runways may be considerably damaged unless the presence of permafrost is taken into consideration and measures taken to eliminate or minimize the effect of the thawing that results from the disturbance of the natural thermal regimen. Where bedrock or thick frozen gravel deposits that contain local drainage channels are the primary foundation materials, permafrost is not normally detrimental to construction.

Although aerial photographs are useful in the interpretation of areas that may be underlain by permafrost, criteria used for interpreting soil conditions of nonfrozen areas apply only to a limited extent to permafrost zones. Gully characteristics of an impermeable gravel deposit cemented by ice, for example, will not necessarily be the same as the characteristics of gullies in impermeable nonfrozen soils. Because of the altered permeability and porosity of soils owing to permafrost, erosional characteristics, as applied to the interpretation of nonpermafrost areas, may have little significance in the perenially frozen regions. Other criteria, such as the common landforms, although suggestive of type of material present, are of limited use in determining the presence or absence of permafrost. Few diagnostic indicators of permafrost appear to exist. More often than not the criteria are suggestive rather than indicative; they include distribution and type of vegetation, polygonal relief patterns, pingos, and features resulting primarily from thawing.

Distribution and type of vegetation

Distribution patterns of trees and shrubs commonly supplement topographic expression in recognizing landforms; these patterns may contribute indirectly to the interpretation of probable permafrost conditions based upon inferences concerning the age of the land surface, climate, and character of the underlying material. In addition, the type of vegetation may be useful in delineating areas where permafrost is likely to be present. Hopkins and Karlstrom (1955) reported that recognition of shallow-rooted species on aerial photographs aids in delineating the areas where permafrost is most likely to occur at shallow depth, and that recognition of deep-rooted species helps delineate areas least favorable for the formation or preservation of permafrost. Thus, black spruce may suggest areas underlain by permafrost at shallow depth, whereas tall willow shrubs and isolated pure stands of balsam popular on river flood plains generally indicate unfrozen ground. The distribution patterns of trees and shrubs, however, are most significant only when evaluated together with other information, such as type of landform, concerning permafrost distribution in the region under study.

Polygonal relief patterns

Polygonal relief patterns commonly can be identified on aerial photographs, but as they may be present in both permafrost and nonpermafrost areas this criterion is not, by itself, always diagnostic in evaluating permafrost conditions; however, in conjunction with other features it may be very significant. Polygonal patterns may be divided into two broad groups: those formed by frost-stirring and those formed by contraction. The formation of frost-stirred polygons is favored by the presence of permafrost at shallow depth, but these polygons are not necessarily an infallible indicator of shallow permafrost as they are also known to occur where permafrost is absent or is at a considerable depth.

Contractional polygons are subdivided into low-center, high-center, and frost-crack polygons. Low-center polygons, one of the most dependable indicators of permafrost, are commonly found in poorly drained depressions. The presence of pools of water in the centers of some polygons is a diagnostic recognition feature, and it is common to find low-center polygons expressed on aerial photographs as dark-toned centers surrounded by light-toned marginal ridges (figs. 109–112). High-center polygons occur in slightly better drained areas than those in which low-center polygons are found; generally, the centers are relatively level, although they may be domed where frost is extremely active. In contrast to low-center polygons, drainage around high-center polygons is commonly concentrated in marginal trenches, and pools of water are present at trench intersections. Because of the high centers, these polygons are commonly expressed on aerial photographs as light-toned centers surrounded by dark-toned margins (figs. 40 and 109–112). Frost-crack polygons may be difficult to distinguish on aerial photographs, as they are similar to high-center polygons; they may be present in some areas where permafrost is absent.

Other relief patterns in conjunction with vegetation distribution result in striped slopes that are commonly present in permafrost areas (fig. 40).

Pingos

Pingos are rounded or elliptical steep-sided hills formed by the "downward freezing of a body or lens of water or of semi-fluid mud" (Muller, 1947, p. 59). They may be as much as 300 feet high. Fissures may develop along the axis of a pingo or radiate from the crest. Pingos usually are found in poorly drained areas and normally are readily distinguished on aerial photographs by their distinctive local landform (figs. 110 and 111); they are almost always a reliable indicator of permafrost, although locally they may be confused with erosional knolls or hills.

Features resulting from thawing

Two features associated with thawing are suggestive of the presence of permafrost. These are thaw lakes (sometimes called thermokarst lakes) and beaded drainage. Thaw lakes occur in frozen fine-grained sedimentary deposits that generally contain clear lenses and masses of ice whose volume is greatly in excess of the porosity of the unfrozen material. As this ice melts the ground subsides and forms a basin in which a thaw lake may accumulate (figs. 110 and 111). When caving is progressing, banks are ragged and steep or overhanging. Tilted trees known as "drunken forests," along the margins of such lakes are indicative of active caving. In treeless areas active caving may be indicated by tension cracks parallel to the banks. Other indications of thawing, such as serrated margins of lakes, also may be present (figs. 109–111). The usefulness of thaw lakes as permafrost indicators, however, is limited by the difficulty of distinguishing on aerial photographs between active thaw lakes, relict thaw lakes, and similar-appearing lakes that are in no way related to permafrost.

Beaded drainage occurs particularly in perennially frozen peat and silt containing ice wedges; it is characterized by small pools connected by short water-courses that may be sharply incised (figs. 40 and 112). The pool banks commonly are steep as a result of thawing and caving of frozen materials.

Absence of permafrost

In areas of discontinuous permafrost it is not only desirable for the engineer to know where permafrost is present, but it may be equally important to determine where permafrost is absent. Certain hydrologic phenomena and elements of the soil pattern commonly indicate or suggest the absence of permafrost. For example, subterranean drainage in unfrozen zones within permafrost may be detected on aerial photographs of some areas. The recognition criteria are in part similar to those applied in evaluating soil conditions in nonpermafrost areas of the world. That is, streams may disappear into the bottoms of closed depressions or by percolating into a gravel-covered surface. In addition, the presence of dry depressions in permafrost areas may indicate locally well-drained areas, inasmuch as there is generally a source of water during the summer months. Such areas contrast with other areas of the earth's surface where dry depressions may be due to absence of precipitation or other immediate source of water. Locally unfrozen zones within permafrost areas may also be suggested by springs, which are commonly indicated by flood-plain icings, shown as flat, white surfaces on some aerial photographs, or indicated by more luxuriant vegetation along a pronounced lineation or within a dark-toned area on low hill slopes. These unfrozen zones may be favorable as a source of ground water. In addition, because permafrost generally causes soils to be impermeable, drainage characteristics indicative of permeable materials (see p. 34) may be interpreted to mean lack of permafrost, at least in the immediately underlying materials. Certain tree species may also suggest absence of permafrost (see p. 37).

EROSION, TRANSPORTATION, AND DEPOSITION

LANDSLIDES

Natural movement or potential movement of materials is a significant consideration in many construction engineering problems. Foremost in this regard is the movement of soils and rock materials by landslides. Ritchie (1958, p. 67) stated that "All landslide investigations must start with recognition of a distressed condition in the natural or artificial slope * * *." Distressed conditions are commonly interpretable from aerial photographs. "The evidence for distressed conditions that may be present, or that may be induced, lies chiefly in evidence of movements, minor or major, that have already taken place or of geologic, soil, and hydrologic conditions that are likely to cause movement in the future" (Ritchie, 1958, p. 67). Geologic, soil, and hydrologic conditions signifying potential landslide areas include the presence of unfavorable geologic structures and rock type, prevalence of fine-grained materials, and an abundance of water or conditions that would permit access of water to fine-grained materials.

Because remedial measures for landslides or prevention of landslides are generally not only difficult but costly, avoidance of landslide areas is important in highway route layout. Existing landslides are commonly identified on the basis of landform (figs. 46 and 113). Liang and Belcher (1958, p. 70) stated that some landforms are more susceptible to landsliding than others, and thus identifying the landform is highly important. "Potential slides of the rockfall and soilfall type can commonly be foreseen simply by recognizing geologic conditions that are likely to produce overhanging or oversteepened cliffs" (Ritchie, 1958, p. 51). Basalt cappings underlain by easily eroded shale (figs. 53, 87, and 113) illustrate a condition where rockfalls may occur as a result of failure and slump in the underlying materials.

Movement of unconsolidated materials by flowage is likely to produce the most damaging landslides. Existing flows and slides (figs. 46 and 113) commonly have a "hummocky" surface. Landslide scars, where soils and vegetation have been stripped off the bedrock, may be easily recognized on aerial photographs by the light photographic tone of the bedrock in contrast to darker tones of surrounding areas. Areas of potential flow of unconsolidated materials may be revealed by tension cracks or crevices, or suggested by the presence of seepage zones or springs, shown by dark tones of dense or luxuriant vegetation or by dark tones of the soil.

Ritchie (1958, p. 50) warned, however, that although aerial photographs are of significant help in developing the setting for detailed studies, they seldom contain the detail needed by the engineer to carry out preventative or remedial measures. The prime application of aerial photographs in landslide studies appears to be in interpreting ground conditions to determine areas that should be avoided in highway route layout and similar problems.

BEACH EROSION

In a shoreline study in California, Munk and Traylor (1947) showed that variation in wave height and refraction of waves along the shore was controlled in part by sea-floor topography. Where refraction causes a convergence of waves the rate of shoreline erosion may increase. Krumbein stated (1950, p. 203) that "Refraction diagrams are becoming an essential part of any study concerned with shore processes, and graphic methods have been developed for preparing them from hydrographic charts or aerial photographs." Photographs taken periodically of shoreline areas would also provide information, both qualitative and quantitative, in studies of erosion and deposition, which might thus be useful in planning remedial action against the eroding currents. In a study of shoreline erosion by the U.S. Army Corps of Engineers (U.S. Beach Erosion Board 1946, p. 13) aerial photographs taken in 1941 were compared with land surveys of 1836 to obtain rates of erosion along the shore of Lake Michigan. The rate of erosion plays a significant part in planning corrective measures for eroding currents.

BEDROCK

GEOLOGIC STRUCTURE AND TYPE OF ROCK

Because of the influence that faults may have on construction design and costs, it is important that faults be located and studied in the beginning stages of an engineering project. Aerial photographs may provide significant information in this regard as some faults are recognized from subtle expressions on photographs but are identified only with difficulty on the ground. The usefulness of photographs in mapping a proposed damsite in southeastern Alaska is shown in a study of the Swan Lake area (fig. 114) where faults stand out in aerial view as conspicuous lineations, which are primarily reflections of rectilinear depressions on the ground. In a damsite study in Malaya, Alexander and Proctor (1955) used large-scale aerial photographs taken 750 feet above the ground. These photographs showed clearly the attitude and distribution of faults and joints in granitic country rock. In connection with the San Jacinto tunnel project in California, Henderson (1939) noted that aerial photographs revealed indications of unsuspected faults and corroborative evidence of those previously suspected. Fault locations underground were found to be close to that predicted from study of photographs.

In addition to showing faults, aerial photographs commonly shown dipping beds that are important in some foundation studies for pier and abutment location. Or dipping beds may indicate potential rockslide conditions where the dip is in the same direction as the hill slope.

Lithologic characteristics of bedrock materials are also significant in many engineering problems, as in foundation work, or in locating road metal sources. Criteria useful for interpreting the general lithologic character of rock types from aerial photographs are discussed on pages 16–19.

INTERPRETATION OF AERIAL PHOTOGRAPHS IN HYDROLOGIC STUDIES

LOCATING POTENTIAL GROUND-WATER SOURCES

Little has been written on the interpretation and uses of aerial photographs specifically in hydrologic studies, although photogeologic techniques offer both practical and research applications in this field. Practical application of aerial photographs in hydrologic study are at present confined largely to assisting the geologic mapping in ground-water investigations, particularly in areas covered by surficial materials. As an aid in ground-water mapping, elements of the soil pattern are evaluated in terms of ground conditions, just as in many engineering geology studies (see p. 34–37). Thus, for example, coarse-textured drainage or absence of drainage may signify highly permeable materials (figs. 52, 66, 88, 104, and 105*B;* and p. 34–35) or the landform (figs. 52 and 104) may suggest the kinds of materials that compose it, which permits an evaluation of permeability and porosity and potential as a water reservoir. In addition, aerial photographs may reveal information directly suggesting the presence of water, such as a preferential distribution of vegetation at the margins of a gravel cap (see figs. 104 and 108). The type of vegetation in turn may permit inferences with regard to the general quality of water. For example, salt cedar is tolerant of relatively high content of salt in water, whereas cottonwood trees are intolerant. Howe (1958) described briefly the use of aerial photographs with specific reference to locating possible water-bearing formations.

WATER-LOSS STUDIES

In a study of water loss caused by phreatophytic plants and trees, which take their water from the water table, Turner and Skibitzke (1952) used aerial mosaics and contact prints for delineating areas of different densities of phreatophytes. The areas were then measured by planimeter and used in conjunction with vertical foliage density, determined by field methods, to arrive at volume density to which water loss by transpiration for specific species could be equated. Data pertaining to tree species and heights were determined by ground methods. Turner and Skibitzke (1952, p. 67) stated that "The comparison between results obtained by air and by ground mapping led to the conclusion that the former offers a much faster and more accurate method, particularly in areas of dense growth." Further use of aerial photographs in collecting basic data for studies of water loss by phreatophytes could probably be made. For example, it may be possible to determine tree or plant species, especially when large-scale black-and-white photographs are available or where color photographs have been taken. In addition, for many areas where the ground surface can be observed through the trees, photogrammetric measurements may provide rapidly those height measurements needed in water-loss studies. For areal measurements of differing vegetation types or densities a simple dot-templet method may be useful (Wilson, 1949). Like many other studies, however, where vegetation and ground features must be observed, measured, and plotted, maximum use of aerial photographs will result from combined use of field and photogeologic methods.

OTHER APPLICATIONS

Aerial photographs as a tool in hydrologic studies provide a medium for obtaining basic data, such as cross-section profiles, linear, areal, slope, and volume measurements. Some of the suggested uses of photogrammetric techniques in hydrologic studies are: (a) for definition of channel size and shape of cross section to be used in studies of the effect of channel geometry in flood characteristics of streams; (b) for determining channel storage capacity used in flood-frequency correlations; (c) for definition of the three-dimensional sinuosity of natural channels to be used in studies of the rate of energy loss; (d) for definition of the geometry of bed roughness of alluvial channel models (Thompson, 1958); (e) for measuring topographic characteristics of drainage basins such as stream slopes and drainage density; and (f) for determining areas of lakes and swamps in water-storage studies.

INSTRUMENTATION

Instruments in photogeologic study serve three objectives, namely, interpretation, measurement, and plotting of data. The instruments used thus may be photogrammetric or nonphotogrammetric—photogrammetry is the art of making reliable measurements from photographs. Usually different instruments are used for attaining each of the three objectives, as, for example, in using a stereoscope, parallax bar, and radial planimetric plotter, respectively. But all three operations may be combined in a single piece of equipment, such as the Kelsh plotter (fig. 18). Whether interpretation is done with a simple stereoscope and paper prints or with a precision stereoplotting instrument using glass-plate diapositives, the criteria of recognition, described in the first part of this paper, remain the same except insofar as scale and resolution of photographic details are involved. Both measurement and plotting are here considered as mechanical aids that provide quantitative information to be further used in geologic interpretation of an area, and instruments are discussed primarily with this objective in mind.

Measurement involves (a) the determination from aerial photographs of vertical and horizontal distances, which in turn are used to compute stratigraphic thicknesses, angles of dip, and other quantitative data of geologic use; (b) the direct determination of inclined distances, commonly the stratigraphic thickness of a formation; (c) the direct determination of angles of slopes or beds; and (d) other quantitative determinations of possible significance in geologic interpretation, such as light-transmission measurements.

Plotting primarily involves the orthographic positioning of geologic data from aerial photographs to base maps or compilation sheets. It also involves direct plotting of geologic data in cross-sectional views, and may include positioning data such as geologic contacts, which are not directly recognizable in the stereoscopic model, by use of the floating dot or spatial reference mark that is found in many photogrammetric instruments.

KINDS OF INSTRUMENTS

Many different photogrammetric instruments are available for making measurements and plotting geologic data to base sheets or cross-sectional profiles (see Fischer, 1955; Ray, 1956; Pillmore, 1957; and Hemphill, 1958a). Certain instruments permit only the measurement of altitude differences, others permit only the orthographic positioning of geologic data, but many instruments are used for both measuring and plotting. Most measuring and plotting devices are designed to accommodate standard 9- by 9-inch photographs; enlarged photographs can be used with only a few instruments, such as the overhead projector, in transferring data to a base sheet.

MEASURING DEVICES FOR USE WITH PAPER PRINTS

One of the most commonly used and widely available types of instrument for determining altitudes from paper prints of aerial photographs is the stereometer or parallax bar. Several varieties of stereometers are available for use with either the lens or mirror-type stereoscope (see fig. 10); they consist of two small plates, usually of glass or plastic, that have inscribed dots, or other targets, that can be centered over conjugate image points in a stereoscopic pair of photographs. The plates are attached to a supporting bar along which they may be separated horizontally. The supporting bar generally has graduated readings in millimeters or inches and a slow-motion adjustment drum that permits readings of hundredths of millimeters or thousandths of inches. All stereometers are based on the "floating-dot" principle, where two target dots, one seen with each eye, are fused stereoscopically into a single dot that appears to float in space within the stereoscopic model. The apparent height of the single fused dot, used as a reference mark in determining altitude differences, is related to the horizontal separation of the individual dots being viewed. Thus by measuring the horizontal separation between individual dots when the fused dot in the stereoscopic model is placed at the top of an object (such as a hill or cliff) whose height is to be determined, and subtracting from it the measurement of the horizontal separation between individual dots when the fused dot is placed at the bottom of that object, a measure of the height, called differential parallax, is obtained. Differential parallax is converted to feet by simple mathematical calculations (see p. 53). Stereometers are thus merely devices that permit reliable measurement of differences of horizontal distances between two or more pairs of conjugate image points as seen on two photographs that form a stereoscopic pair.

Parallax ladders also may be used for determining differences in altitudes from aerial photographs. Like the stereometer, the parallax ladder is based on the floating-dot or floating-line principle. The instrument may consist of two diverging rows of dots on plastic or glass arms; thus, a series of pairs of dots exist with different horizontal separations, and this in turn results in several floating dots all at different altitudes within the stereoscopic model (see fig. 12). Or the instrument may consist of two diverging lines with intercepts of specific horizontal separations ticked off; thus a single plunging line would be seen in stereoscopic view. The instrument, oriented at right angles to the flight line, is used by sliding it over the stereoscopic model until a pair of dots or line intercepts—seen stereoscopically as a single dot or cross in space—appears to fall on the base of the object whose height is to be determined. A reading of the horizontal separation of the two dots or intercepts is then made. The parallax ladder is moved until a different pair of dots or intercepts—also seen stereoscopically as a single dot or cross in space—appears to fall on the top of the object whose height is to be determined. Again a reading of the horizontal separation of dots or intercepts is made. The difference in readings obtained is then used in a simple formula to determine the difference in altitude of the two points (see p. 53). A direct-reading parallax ladder that eliminates the need for most of the mathematical computation has also been devised. The differences in horizontal separation of pairs of dots has been calculated by the manufacturer in terms of heights in feet for different flying heights and photobases, and this permits a direct reading of relative altitudes within the stereoscopic model.

Also for use with paper prints is a stereo slope meter, designed primarily for determining degrees or percentage of slope. The instrument consists of two transparent disks each scribed with eccentric circles of specific diameters (fig. 11). These disks are mounted in a frame so as to be movable horizontally in a fashion similar to the dots of the stereometer. In stereoscopic view the two sets of eccentric circles appear as a cone that is divided into several zones. By proper horizontal spacing of the two disks, the resulting cone seen stereoscopically can be raised or lowered so that some two circles will rest on the slope or grade to be determined. By appropriate simple calculations the slope can be determined. Center dots present on each of the transparent disks also permit relative altitudes to be determined just as with a stereometer.

PLOTTING DEVICES FOR USE WITH PAPER PRINTS

Instruments have been designed specifically for plotting information from paper prints to base maps or control sheets. An instrument widely employed in the past is the sketchmaster (fig. 13), which uses the camera-lucida principle in transferring data from the photographs to the base sheet. The sketchmaster allows the operator to view a single photograph image superposed on the base map. Adjustments for scale changes in the perspective photograph permit coincidence or near coincidence of photograph control points and base-map control points. Geologic detail is sketched directly on the base map. This instrument can be adjusted to remove small amounts of tilt inherent in some vertical photographs, but like any direct-reflecting projector, large amounts of radial displacement due to relief cannot be effectively removed.

The radial planimetric plotter has been devised especially for transferring photographic detail to a base map or control sheet. Unlike the sketchmaker, this instrument is designed to eliminate displacement due to relief. The plotter consists of a mirror stereoscope mounted above two photograph tables (fig. 14). A transparent plastic arm with a centrally scribed line extends from and pivots around the center of each table. These arms are linked to a pantograph attachment. Because the plastic arms radiate from different centers they cross each other in stereoscopic view to form the so-called plotting cross.

In operating the radial planimetric plotter a pair of vertical photographs is oriented on the photograph tables for proper stereoscopic viewing, and control points on the photographs are oriented to control points on the base manuscript by means of the radial arms and pantograph. Movement of the pantograph attachment moves the plotting cross over the stereoscopic model and permits tracing of photograph detail on the base manuscript. Inasmuch as the radial arms that intersect a terrain feature on each photograph represent azimuth lines from known points on the base manuscript, the intersection of these two arms will represent the true map position of that feature, just as will the intersection of two azimuth lines shot from different instrument stations in the field. Thus the relief displacement of a feature on a photograph is effectively removed; this is one of the chief advantages in using the radial planimetric plotter. However, the radial lines do not intersect along the principal line—or flight-line direction—between photographs, and the photograph tables must be shifted to their alternate centers before the central area of stereoscopic model can be delineated. Because the photograph tables are mounted in a horizontal position, the instrument does not permit removal of tilt that may be present in the photographs, but tilt is usually small in present-day photography and generally does not cause significant errors in horizontal positioning of geologic data.

The multiscope is a combination of mirror stereoscope and camera lucida that has received limited use

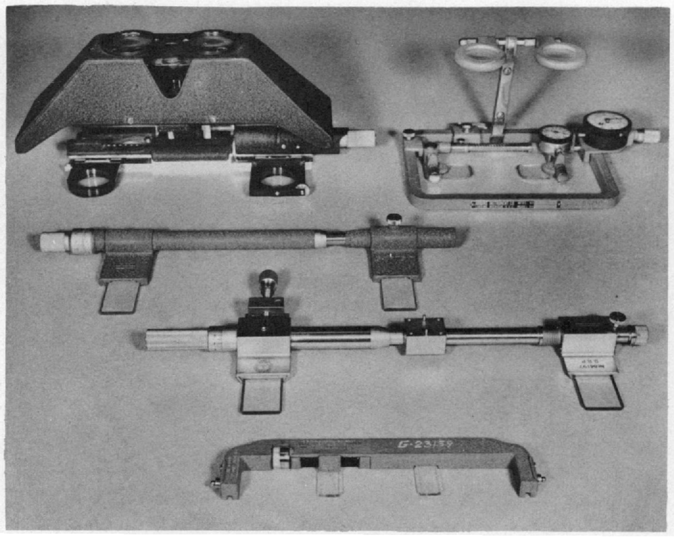

FIGURE 10.—Stereometers.

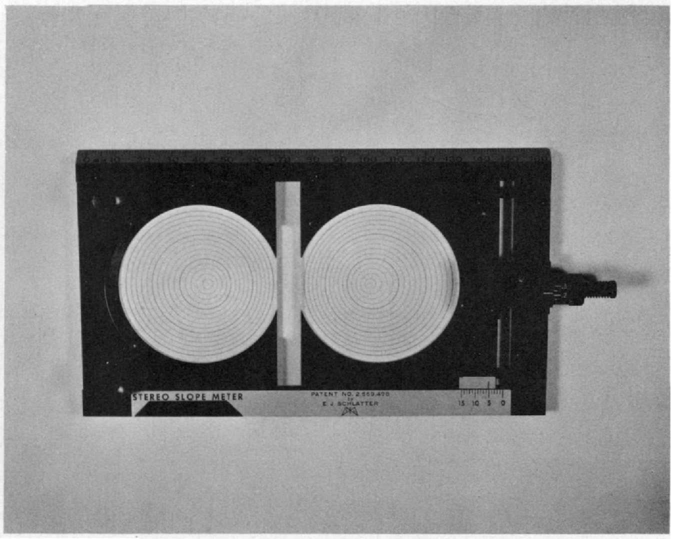

FIGURE 11.—Stereo slope meter.

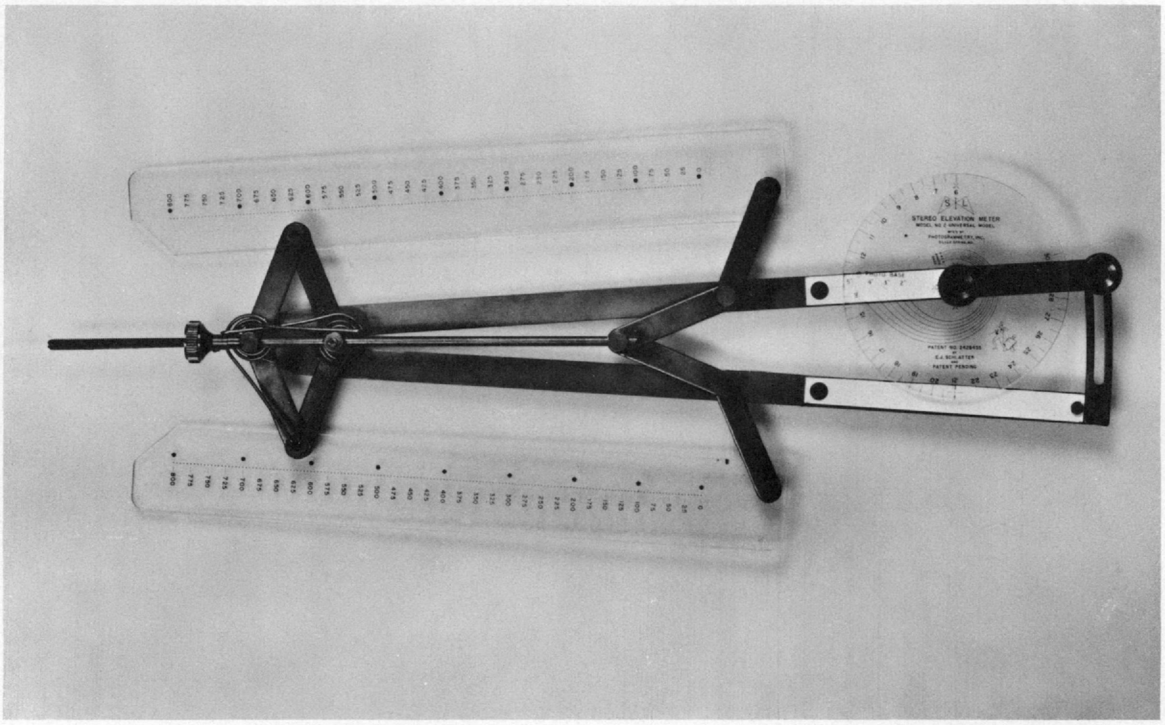

FIGURE 12.—Parallax ladder.

MEASURING INSTRUMENTS FOR USE WITH PAPER PRINTS

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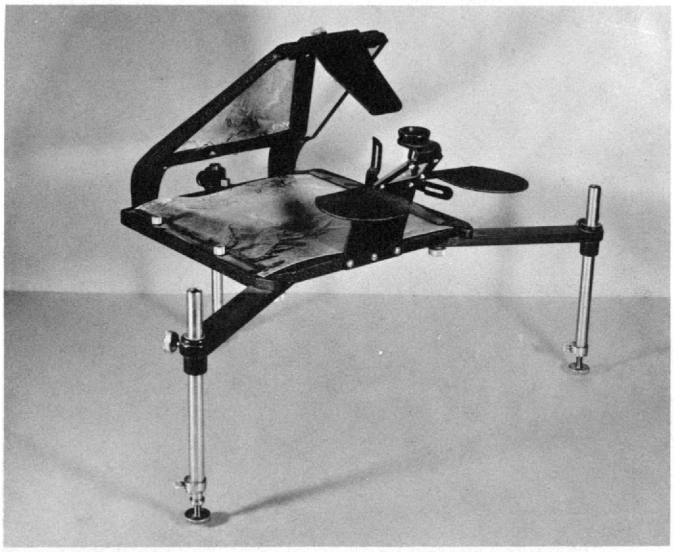

FIGURE 13.—Sketchmaster.

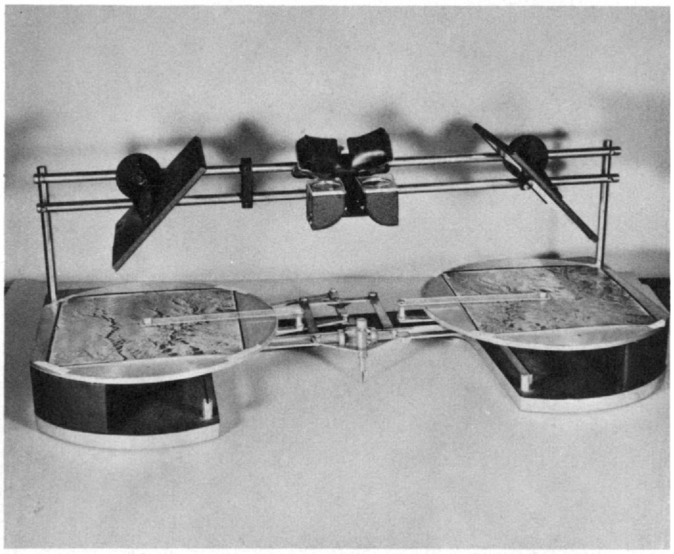

FIGURE 14.—Radial planimetric plotter.

PLOTTING INSTRUMENTS FOR USE WITH PAPER PRINTS

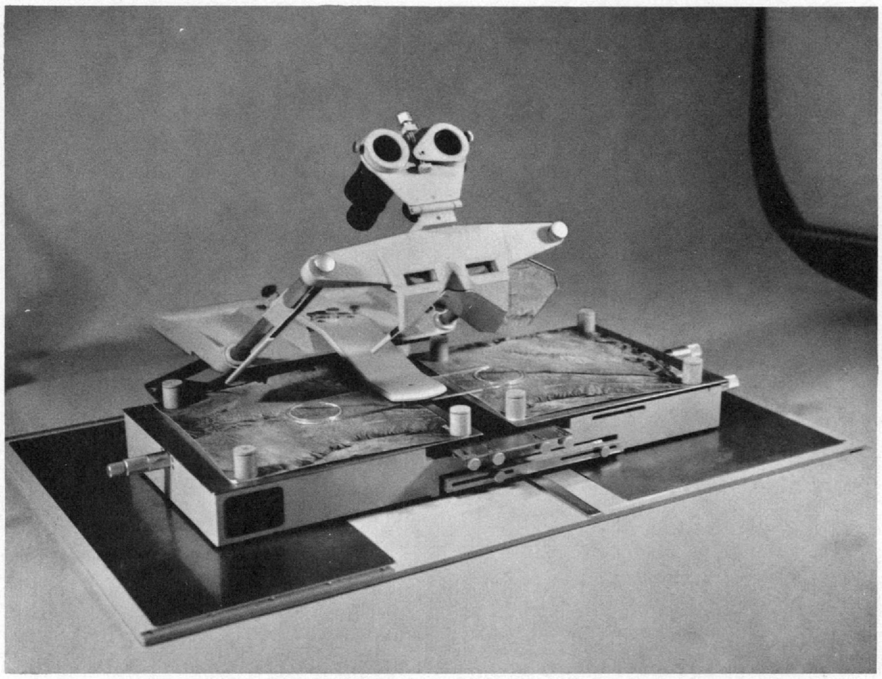

FIGURE 15.—Stereotope.

COMBINED MEASURING AND PLOTTING INSTRUMENT FOR USE WITH PAPER PRINTS in plotting geologic data from photographs to base maps or control sheets. Photographs are mounted on movable photograph plates that permit small adjustments for tilt. The viewing assembly is constructed to allow the insertion of one or two half-silvered mirrors in the eyepiece, so that in operation either the image of a single photograph or the stereoscopic model may be superposed optically on the map or control base. Although the stereoscopic model may be seen at all times, use of only one half-silvered mirror permits the eye to see only the image of one photograph superposed on the map base; the resulting plot is similar to that from the sketchmaster—or reflecting projector—no errors due to relief displacement are removed. If, however, two half-silvered mirrors are used, appropriate manipulations permit true orthographic plotting of detail from the stereoscopic model. Scale adjustments between photographs and map base are made by interchanging special lenses in the viewing assembly together with changing manually the distance of the viewing assembly above the map base. The instrument is said to permit measurement of altitudes when coupled rotary prisms are inserted under the half-silvered mirrors, or when a device similar to the multiplex tracing table is placed in the field of stereoscopic view (Spurr and Brown, 1945, p. 177).

MEASURING AND PLOTTING DEVICES FOR USE WITH PAPER PRINTS

Some instruments have been designed both for measuring altitudes and for plotting data from paper prints of aerial photographs. These instruments are commonly termed "paper-print plotters" and include the KEK plotter, the Mahan plotter, and the stereotope.

The KEK plotter consists of a stereoscope, two photograph tables, floating-dot assembly, and drawing attachment. The plotting cross of the radial planimetric plotter is replaced in the KEK plotter by the fused dot floating in space. By raising or lowering the photograph plates the fused dot is positioned on the ground in the stereoscopic model. Vertical motion of the photograph plates is linked to a drum scale on which relative altitudes can be read directly in feet. Movement of the pantograph drawing attachment allows geologic detail to be sketched directly on the map base, but during this sketching the fused dot must be held on the ground in the stereoscopic model by simultaneous vertical movement of the photograph plates. The photograph plates may be tilted to make an approximate correction for tilt that may be inherent in the photography. Because the floating-dot assembly lies above and is physically separated from the photograph tables, small amounts of extraneous parallax and significant amounts of horizontal shift in the map position of a point may result by moving one's head in viewing the stereoscopic model.

The Mahan plotter is generally similar in principle to the KEK plotter but differs slightly in operation. The floating dot is positioned on the ground in the stereoscopic model by vertical motion of the disks on which the dots are scribed, whereas in the KEK plotter the position of the disks containing the scribed dots is fixed and the photograph plates are moved vertically in order to position the floating dot at a particular level in the stereoscopic model. The stereoscope of the Mahan plotter is adjustable, which permits very nearly the recovery of the perspective from photography ranging in focal length from about 8.25 to 12 inches. As with the KEK plotter, a shift of the viewer's head when viewing the model may cause horizontal positioning errors and the presence of small amounts of extraneous parallax. The stereoscopic model of the KEK and Mahan plotters may be effectively leveled, in absence of vertical control, by visual reference to certain physiographic features of the terrain (see p. 55).

A somewhat different paper-print plotter is the stereotope. The instrument consists of a stereoscope with binoculars of × 4 magnification mounted over a photoholding assembly that contains a parallax bar and attachments for pantograph hookup, as well as a mechanism, when vertical control is available, for effectively leveling tilted models, for correcting errors of horizontal position, and for orthographic plotting of geologic data (fig. 15). The stereotope is an elaborate instrument that corrects for tilt by mechanical linkages within the photoholding assembly. No physical tilting of the photoholders takes place and thus the instrument differs significantly from the KEK and Mahan plotters. In addition, the targets of the stereometer attachment for altitude determinations are in contact with the paper prints, and no extraneous parallax can be introduced by movement of the operator's viewing position. In the absence of vertical control, which permits tilt correction through mechanical linkages, the stereotope as a measuring device must be used as a simple parallax bar.

MEASURING AND PLOTTING DEVICES FOR USE WITH GLASS-PLATE DIAPOSITIVES

The Kelsh plotter, multiplex, and ER-55 plotter, all of which require glass-plate diapositives, are used in the United States both to measure quantitative geologic data and to plot geologic detail to base maps or control sheets (figs. 16–18). These double-projection precision-plotting instruments are designed to accom-

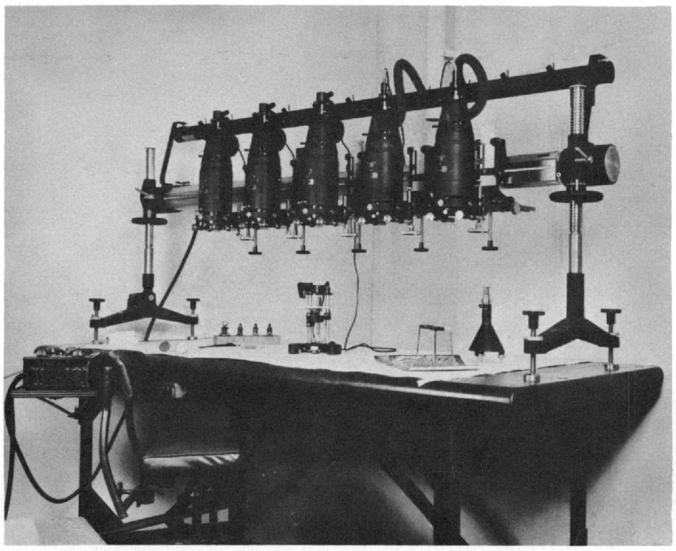

FIGURE 16.—Multiplex.

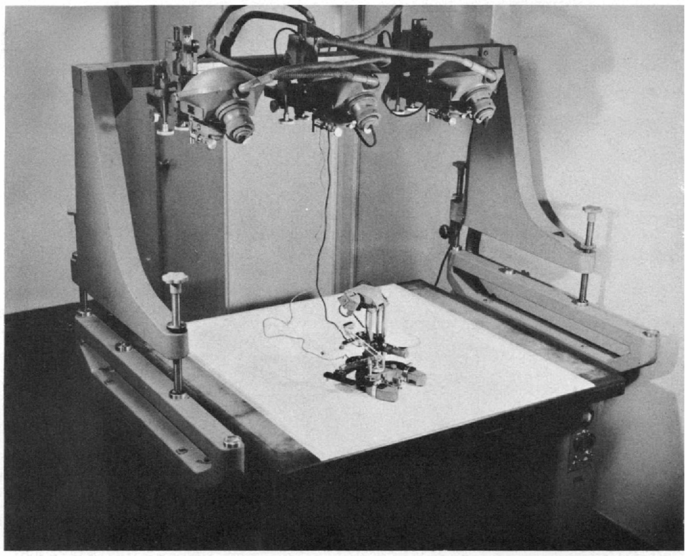

FIGURE 17.—ER–55 plotter.

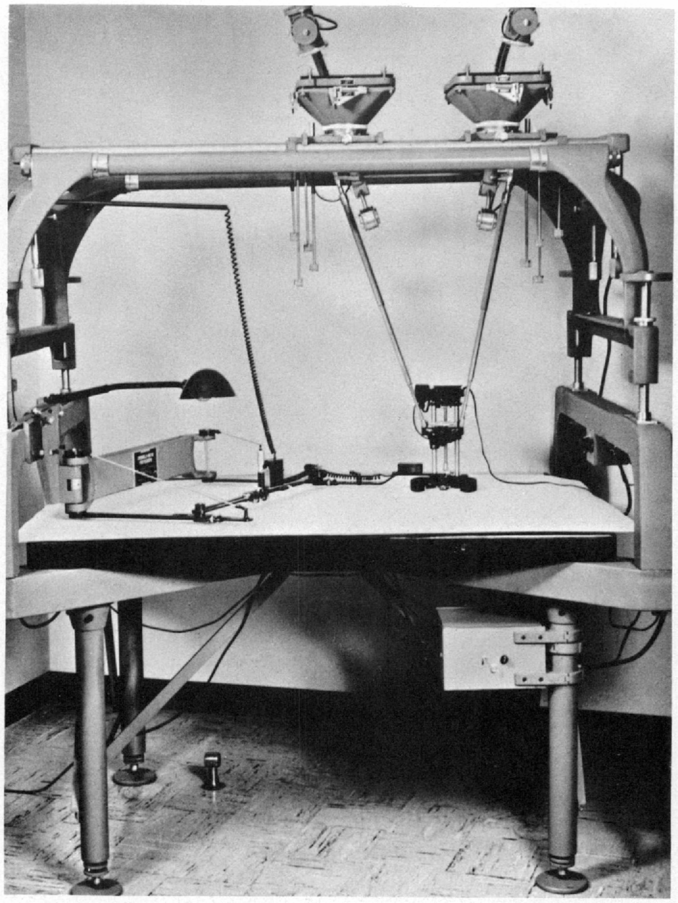

FIGURE 18.—Kelsh plotter.

COMBINED MEASURING AND PLOTTING INSTRUMENTS FOR USE WITH GLASS-PLATE DIAPOSITIVES

modate photography of specific focal lengths, usually 6 or 8.25 inches. All utilize the anaglyph principle of projection of light of complementary colors, red and blue-green, through glass-plate diapositives to create the third dimension. The stereoscopic model is viewed through glasses of the same color as the filters used in the light-source projectors. Because double-projection, or anaglyphic-type, stereoplotting instruments simulate in miniature the spatial relations of the camera stations at the time the photographs were taken, all features of the terrain are optically re-created in the stereoscopic model in essentially true relation with respect to the measuring mark or floating dot. Where sufficient vertical control is available any tilt inherent in the photography can be removed so that accurate measurements of altitudes can be made and true orthographic positioning of detail obtained. Without vertical control the stereoscopic model of many terrains commonly can be leveled within 1° of the horizontal datum by visual reference to certain physiographic characteristics of the terrain (see p. 55); under these conditions approximate orthographic positioning may be obtained, but significant errors in vertical measurements may result (see p. 69–75).

The stereoscopic model is usually viewed on a small white-surfaced table called a platen, which may be raised and lowered so that an illuminated floating dot in its center is kept in contact with the surface of the ground, as seen in stereoscopic view. Vertical motion of the platen is transmitted to a scale reading in millimeters of vertical measurement, or, on some instruments, to a scale that converts readings directly to heights in meters or feet. Geologic features are traced orthographically on the base map by a pencil located directly beneath the illuminated dot on the platen, or by a reduction pantograph attached to the tracing table. Interpretation, measuring, and plotting can be carried out in one continuous operation.

The Kelsh plotter is designed to accommodate glass-plate diapositives the same scale as the original photography. For many geologic problems film positives may be substituted for the more expensive glass-plate diapositives. The scale of the projected stereoscopic model is usually about 5 times that of the original photography. Only that part of the stereoscopic model appearing on the platen is illuminated; this results in a concentration of light and a brightly illuminated model but prevents viewing of the entire model at one time. Because the glass-plate diapositives are the same scale as the original photography the resolution of the stereoscopic image is excellent.

The multiplex uses glass-plate diapositives on which the original 9- by 9-inch negative is reduced about 5 times. The small diapositive image is then enlarged approximately 12 times in projection of the stereoscopic model. The projected stereoscopic model is about 2.5 times the original photography scale. As a result of the large amount of reduction of the original photograph negative, some of the photographic detail is lost and fine details of terrain, important in geologic interpretation, may not be visible. In multiplex projection the entire model area is illuminated, and if the terrain being viewed has only low or moderate relief the stereoscopic model may be observed in its entirety by substituting a large white surface for the platen. This overall view of the stereoscopic model is often of considerable use in geologic interpretation, because of the association of geologic features that can be seen at one time. The overall view is generally accomplished by projecting the stereoscopic model to the multiplex table slate; no plotting or measuring can be done when the model is viewed on this surface.

The ER–55 plotter uses glass-plate diapositives on which the original 9- by 9-inch negative is reduced about 2.8 times; this amount of reduction does not seriously affect image resolution. The projected stereoscopic model is about 3.5 or 5 times the scale of the original photographs, depending on the projector model. Ellipsoidal reflector-type projectors result in a brightly illuminated model in which terrain detail has a high degree of resolution. Like the multiplex, the ER–55 plotter permits viewing the entire stereoscopic model at one time. In addition to accommodating vertical photography the ER–55 projectors are adaptable to twin low-oblique photography taken with the camera axis inclined 20° from the vertical position.

Geologic study of stereoscopic models in double-projection plotters has numerous advantages over the study of paper prints. The ability to interpret, measure, and plot in one continuous operation has already been cited. In addition, the geologist works with an enlarged stereoscopic model that ranges from about 2.5 times to 5 times the original photography scale, depending on the instrument used; thus small-scale photography commonly may be used. A higher degree of image resolution is maintained on glass diapositives than on paper prints, and results in more detail that can be observed in the double-projection stereoscopic models, except for the multiplex, in which some resolution needed in qualitative and quantitative interpretation is lost in the projected model. Because all features of the terrain are optically re-created in essentially true relation, reliable measurements for structure contouring, for drawing isopach lines, for computing strikes and dips, and for determining fault displacements can be obtained for many areas with stereoscopic plotters; measurements can be made rapidly and hence economically (see Pillmore, 1957).

OTHER INSTRUMENTS

Other photogrammetric instruments such as the stereoplanigraph and autograph permit precise measurements from aerial photographs, but these heavy plotters are generally unavailable to the geologist. Beside permitting precision of measurement, these instruments are designed to accommodate different sizes of diapositives and photography taken with different focal-length lenses.

Certain modifications or additions to existing instruments have been made specifically for geologic purposes; and some new instruments, described below, have been designed expressly for geologic study.

EXAGGERATED-PROFILE PLOTTER

The exaggerated-profile plotter is a device attached to the tracing table of double-projection plotters, such as the Kelsh, multiplex, and ER–55 plotters, for drawing terrain profiles. As the tracing table is moved along the line of profile and as the platen of the tracing table is moved vertically a pencil attachment records the profile on a vertical tracing board. Profiles exaggerated as much as 5 times may be plotted. An arm on the tracing table slides in a groove along the base of the tracing board so that a selected cross-section direction is maintained. Two models of the exaggerated-profile plotter have been developed. One is based on the lever and fulcrum principle (fig. 19); the other is based on the pantograph principle (fig. 20). The exaggerated-profile plotter was first developed to aid in solving a specific geologic problem in correlating thin and closely spaced intraformational sandstone beds in rocks of Cretaceous and Jurassic age in Wyoming (Pillmore, C. L., oral communication, 1958). The plotter may be very useful also in quantitative geomorphic studies or in studies involving the qualitative correlation of shape characteristics of terrain.

INTERVAL-MEASURING DEVICE

A floating-dot instrument that permits the maintenance of a desired vertical interval between two floating dots in a stereoscopic model from paper prints, as well as serving as a conventional stereometer, also has been developed in the course of photogeologic study (Hackman, R. J., oral communication, 1959). Two floating dots, representing different altitudes in the stereoscopic model, may be useful for example in positioning an obscured formation contact when other contacts are readily observed and formation thicknesses are known. The instrument consists of two transparent circular disks mounted on a frame with two worm screws, one of which permits separation of the disks in the x direction, and the other of which permits both disks to be rotated equally but in opposite directions (see fig. 21). A series of dots, evenly spaced, are arranged in a straight line so as to pass through the center of each disk. One dot coincides with the center of each disk and can be moved only in the x direction, as in most stereometer-type instruments. The other dots may also be moved in the plane of the disk by rotating the disk, thus providing a parallax ladder as seen stereoscopically. By proper adjustment a pair of dots, one on each disk, can be separated by rotation of the disks to provide a direct-reading parallax ladder, or the dot separation may be referred to millimeters of parallax and differences in altitude calculated in the usual manner (see p. 53). The center dots of each disk can be floated in the stereoscopic model at a desired point and the distance above or below this point measured merely by rotation of the disks. Scales graduated to record hundredths of millimeters of parallax permit readings of separation of the center dots of the disks as well as reading of total x parallax resulting from rotation or x motion of the disks.

UNIVERSAL TRACING TABLE

Some research in development of instruments carried out to date has centered around the modification of existing instruments. Important in this group is the universal tracing table (fig. 22), which is a multiplex tracing table that has been modified in design by R. H. Morris and C. L. Pillmore of the Geologic Survey. It is used for direct measurement of inclined distances, such as stratigraphic thickness of dipping beds, in stereoscopic models from double-projection plotters. The platen and underlying assembly can be tilted as much as 45°. A separate worm-screw drive on the tilted assembly distinct from the conventional worm-screw drive for vertical movement, permits movement of the platen in an inclined direction perpendicular to the surface of the platen. A scale on this auxilliary worm-screw-drive assembly permits the reading of measured intervals in hundredths of millimeters; conversion to feet is made in the usual manner for double-projection stereoscopic models (see p. 54–55). A series of holes drilled through the platen to the underlying light source provides a plane of floating dots in the stereoscopic model.

MEASUREMENT

PRINCIPLES OF VERTICAL MEASUREMENT

Vertical measurements of altitude differences provide by far the greatest amount of quantitative information in geologic interpretation from aerial photographs. Differences of altitudes are generally deter-

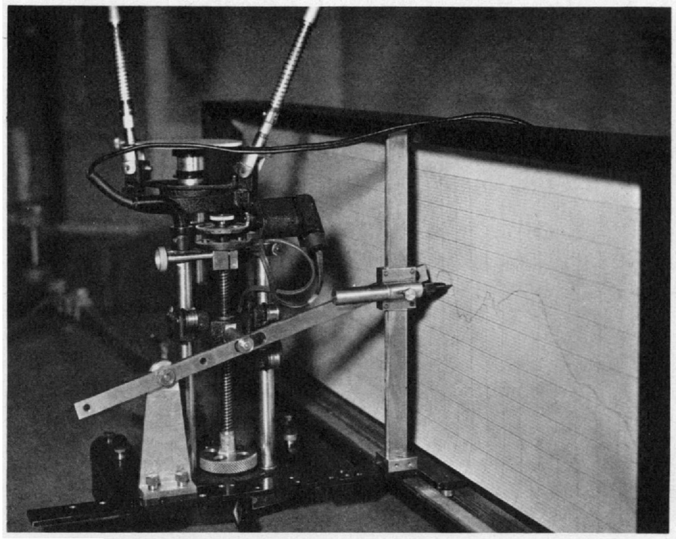

FIGURE 19.—Lever and fulcrum type of exaggerated-profile plotter.

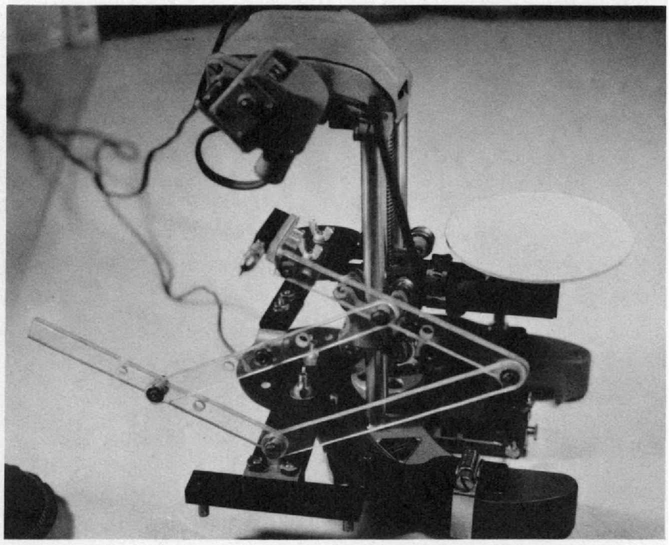

FIGURE 20.—Pantograph type of exaggerated-profile plotter.

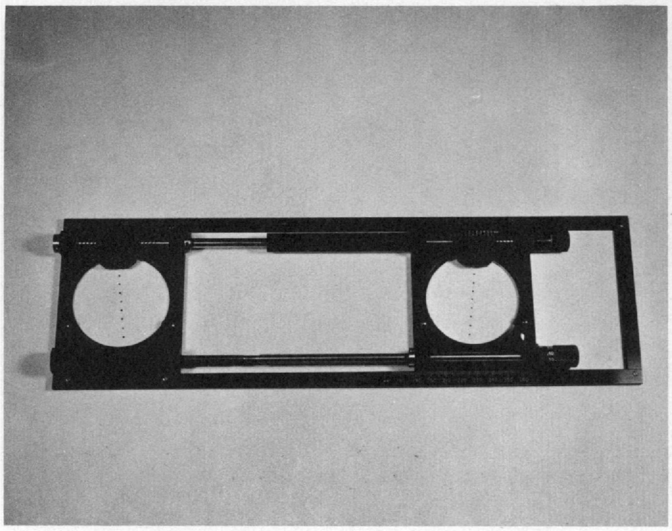

FIGURE 21.—Interval-measuring instrument.

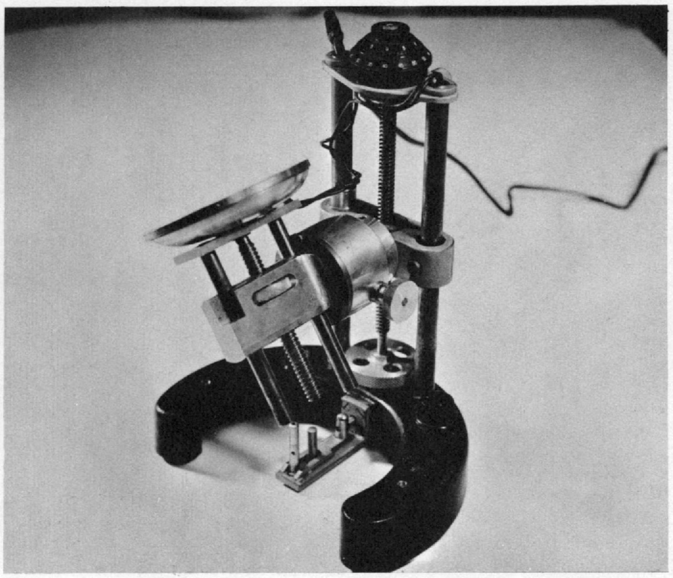

FIGURE 22.—Universal tracing table.

INSTRUMENTS DESIGNED OR MODIFIED FOR GEOLOGIC USE mined from overlapping aerial photographs, although they may under special circumstances be determined from a single photograph. When overlapping prints are used, the altitude difference between any two points is determined by measuring the horizontal linear parallax difference between the two points and relating it to appropriate geometry of the stereoscopic model. Altitude determinations from glass plates in double-projection plotters require the measurement of actual vertical distances within the stereoscopic model. In the uncommon circumstance when a single photograph may be used, altitudes are determined by measuring relief displacement and relating it to appropriate geometry of the aerial photograph.

DETERMINATION OF ALTITUDE DIFFERENCES BY THE PARALLAX METHOD

When an object is viewed or photographed from two different positions, as on two overlapping vertical aerial photographs, an apparent shift in the position of that object takes place, which is known as parallactic displacement. On overlapping aerial photographs this is a measurable linear distance that is directly related to the height of the object. In photogrammetric terms parallax of an image point appearing on two overlapping photographs is called absolute stereoscopic parallax and is represented by the algebraic difference, parallel to the flight line, of the distances of the conjugate image points from their respective principal points (see fig. 23). The difference in absolute stereoscopic parallaxes between two different image points is a measure of the distance one point is above the other. On overlapping paper prints the parallax difference may be measured reliably by using a stereometer-type instrument, based on the floating-dot principle; parallax difference may also be measured with a ruler, although this procedure is rarely used because of inaccuracy of measurement.

In double-projection stereoplotting instruments (Kelsh, multiplex, and ER-55 plotters) an actual vertical measurement of altitude difference is made within

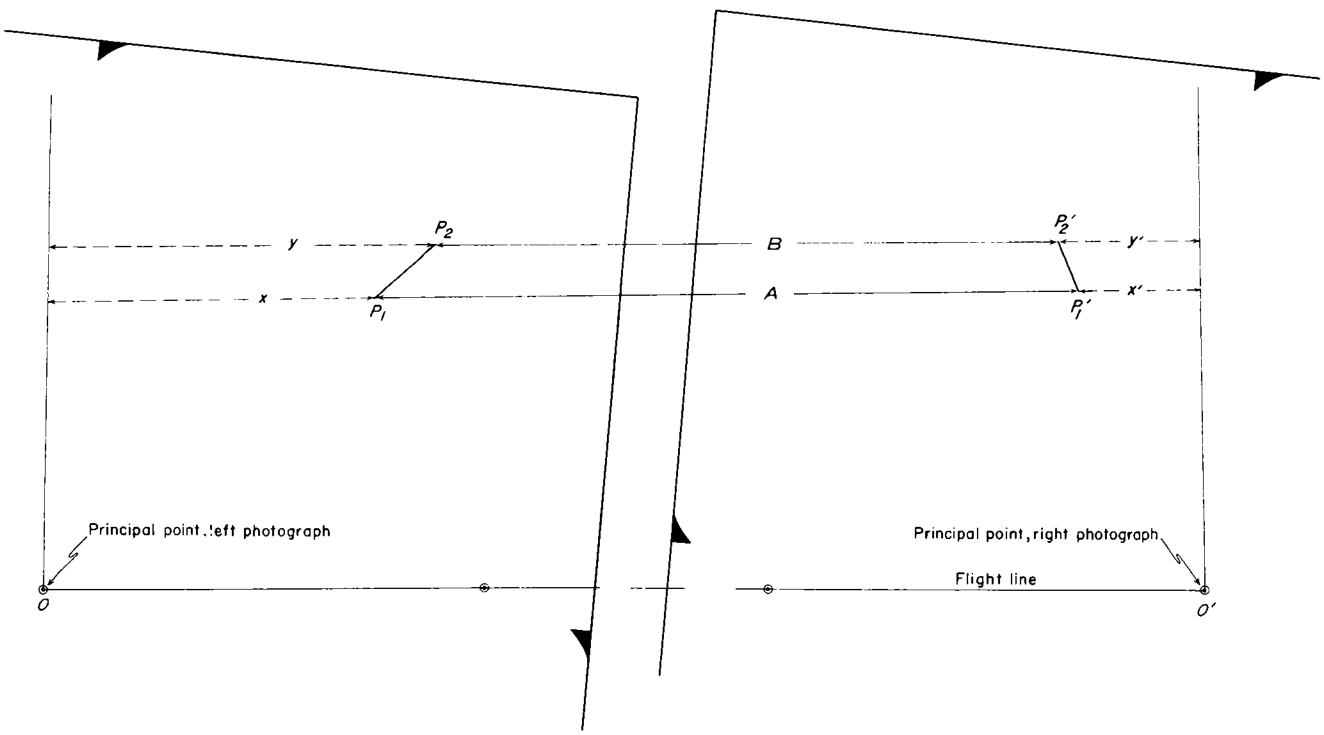

FIGURE 23.—Diagram showing relation between absolute stereoscopic parallaxes and horizontal distances actually measured with stereometer-type instruments in determining differences in altitude from paper prints.

Let images $P_1 - P_2$ and $P_1'-P_2'$ represent the photographic expression of a pole on the left and right photographs of a stereoscopic pair. The absolute stereoscopic parallax of the base of the pole is $x-(-x')=(x+x')$. The absolute stereoscopic parallax of the top of the pole is $y-(-y')=(y+y')$. (Distances measured to the right of the principal point are positive, to the left, negative). The parallax difference between the top and bottom of the pole then is $(y+y')-(x+x')$.

From the figure:

$$y+y'+B=x+x'+A$$
$$y+y'-x-x'=A-B$$
$$(y+y')-(x+x')=A-B.$$

Thus the difference in absolute stereoscopic parallaxes is equal to $A-B$. The distances A and B are the actual distances measured with stereometer-type instruments, generally in hundredths of millimeters, in determining altitude differences from paper prints.

the stereoscopic model; the linear parallax recorded on the photograph is translated into a vertical distance as a result of angular parallax in the viewing arrangement. Figures 23 and 24 show diagrammatically the distances that are actually measured when stereometer-type instruments and double-projection instruments are used respectively in altitude determinations.

USE OF STEREOMETER-TYPE INSTRUMENTS

When paper prints of aerial photographs are used in conjunction with a stereometer-type instrument and a stereoscope, two linear horizontal distances must be measured to obtain the parallax difference between two different image points. These distances are simply A and B as shown on figure 23. They can be measured with a finely graduated ruler but more commonly a

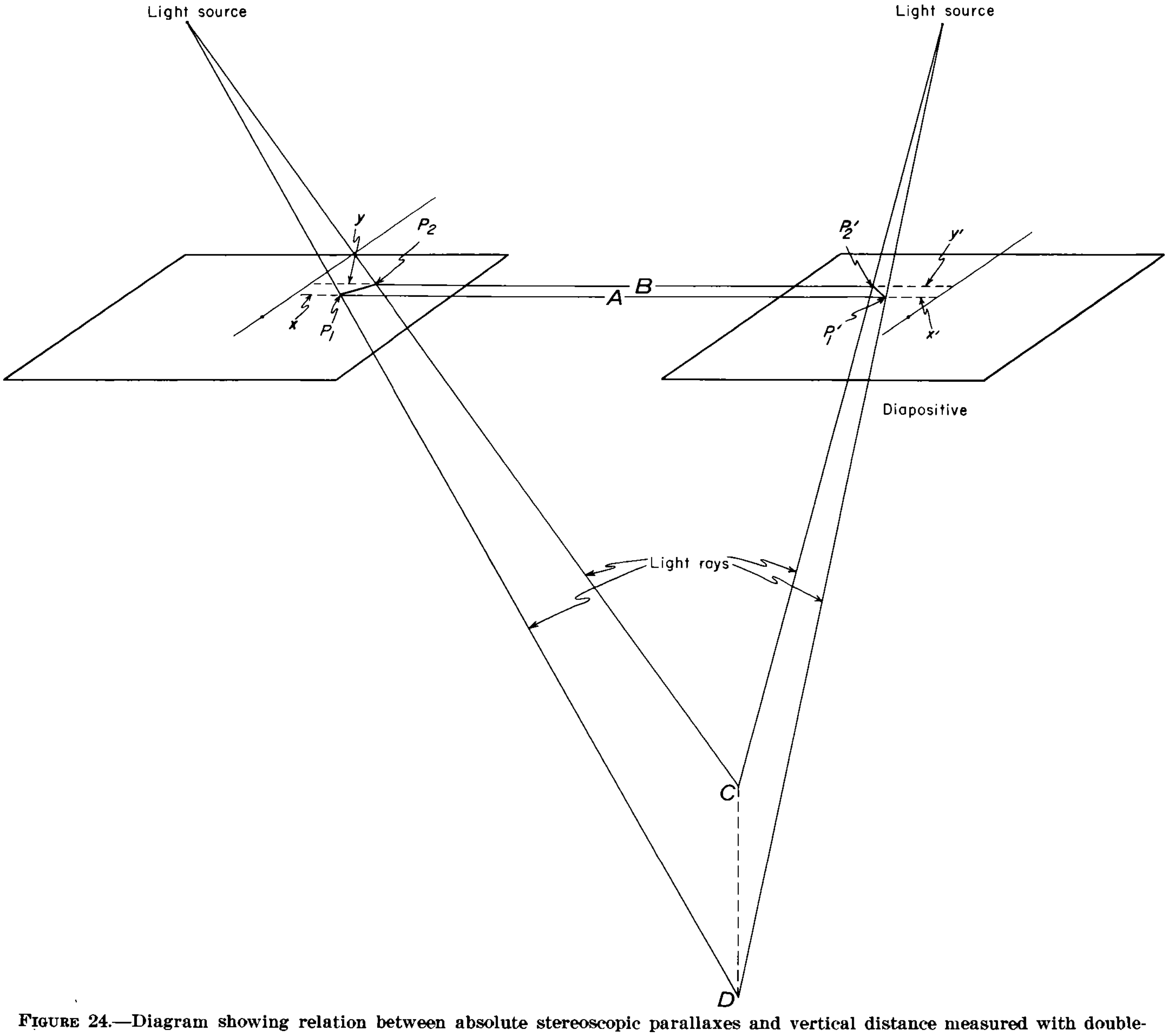

Figure 24.—Diagram showing relation between absolute stereoscopic parallaxes and vertical distance measured with double-projection type instruments in determining differences in altitude from glass plates.

The absolute stereoscopic parallaxes of the top and bottom of a pole represented on the left photograph by P_1–P_2 and on the right photograph by P_1'–P_2' are $(y + y')$ and $(x + x')$, as in figure 23, and differential parallax between the top and bottom of the pole is $(y + y') - (x + x')$ or $A - B$. With double-projection instruments the vertical distance CD is actually measured, rather than the horizontal distances that are measured on paper prints. The distance CD, measured generally in tenths of millimeters, is converted to feet by multiplying by the K factor, which represents the number of feet on the ground per 0.1 millimeter in the stereoscopic model. Points C and D represent the intersections of those light rays that pass through the top and bottom of the pole respectively.

stereometer-type instrument or parallax bar is used because it permits more consistent readings of smaller increments of length than a ruler. Stereometers are generally constructed with a principal scale graduated in millimeters and a subordinate drum scale calibrated in hundredths of millimeters for recording parallax measurements; a few instruments are designed to record in inches.

To make parallax measurements from aerial photographs it is first necessary to orient the photographs properly for stereoscopic viewing. This is accomplished by alining the photograph centers and conjugate centers along a straight line—the equivalent of the flight-line direction—and separating the photographs for comfortable viewing (fig. 25). Photograph centers are located by marking the intersections of lines drawn between fiducial marks at the opposite sides of each print. Each center is then transferred stereoscopically to the other photograph of the stereoscopic pair and its conjugate image point marked. Parallax measurements are then made in the so-called x direction, parallel to the flight line. Measurement is accomplished by adjusting the separation of the dots of the parallax bar until a single fused dot, seen stereoscopically, appears to rest on the ground at the first point selected. The instrument reading is recorded and the procedure is repeated for the second point selected. The difference in readings is the parallax difference between the two points. In making parallax measurements the fused dot will be seen readily when it floats above the apparent ground surface of the stereoscopic model but will appear to split into its two component dots as it is lowered below the ground surface. If the fused dot, as it is being lowered, appears to split at some point just above the ground surface, a slight change in the separation of the photographs may be necessary to permit simultaneous viewing of the floating dot and the stereoscopic model.

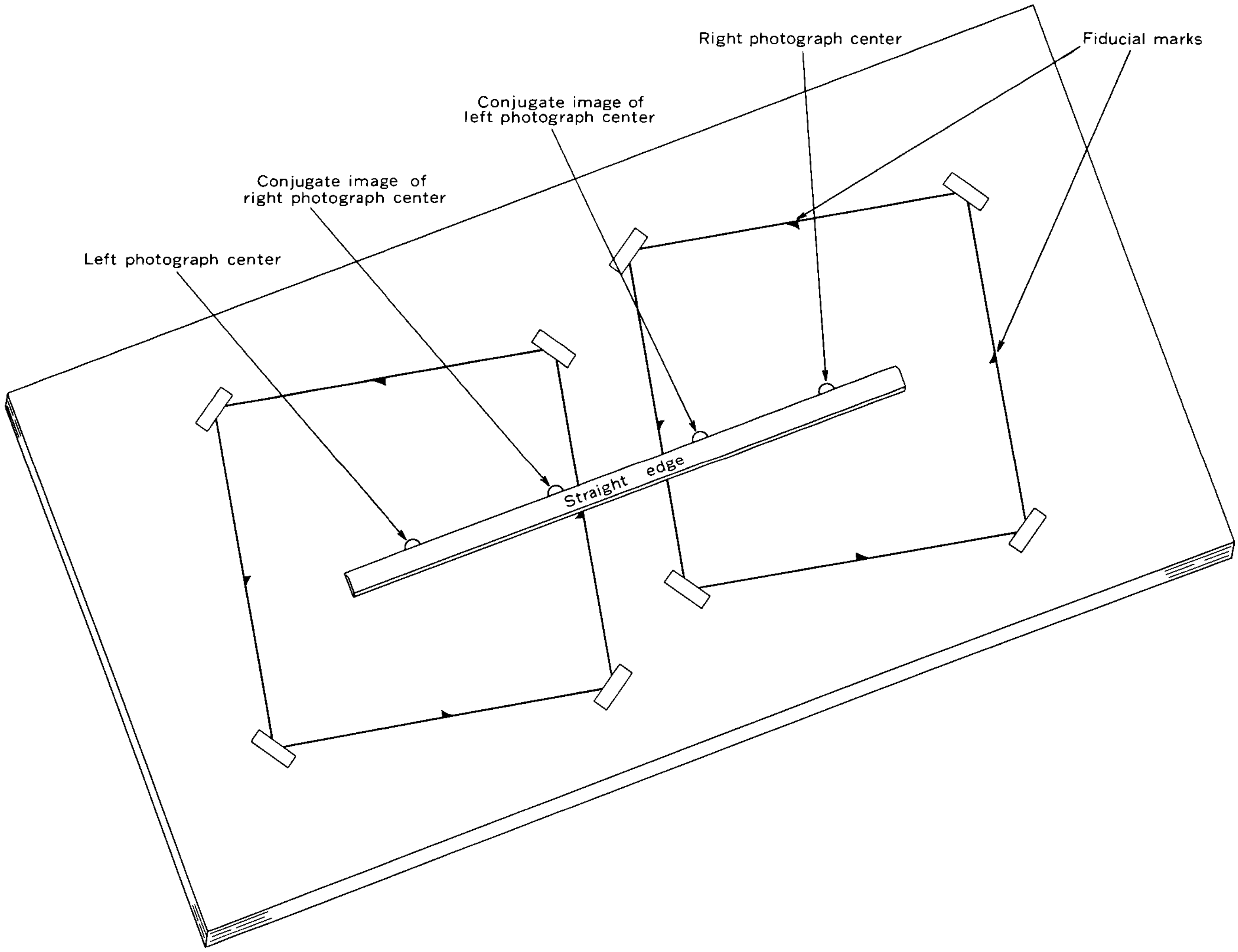

FIGURE 25.—Sketch showing correct orientation of photographs for stereoscopic viewing.

To obtain the height of an object or difference in altitude between two points the difference in parallax must be related to the geometry of the stereoscopic model. For measuring heights from paper prints this relation is best expressed by a formula which, in its simplest terms, is

$$h=\frac{H}{b}\cdot\Delta p \qquad (1)$$

where h=height of the object, in feet, or difference in altitude being determined;
H=height of airplane, in feet, above mean terrain (determined from specifications of photographic mission or relation $H=f/S$, see below);
b=photobase (commonly determined by averaging the distances between the center and conjugate center of each photograph of the stereoscopic pair); units of measure may be millimeters or inches but must be the same as Δp;
and Δp=parallax difference, in millimeters or inches, as determined with stereometer-type instrument (distance *A–B* of figure 23).

It will be noted that as H increases, the measure of Δp for any given vertical interval will decrease; however, the absolute value for any one unit of Δp will increase correspondingly. On the other hand, if focal length is increased and flying height remains constant the measure of Δp for a given vertical interval will increase but the absolute value for any one unit of Δp will decrease correspondingly.

The above formula (1) may be used without any appreciable error if relief in an area is low; Δp will be small. If relief in an area is high one of the following two formulas, (2) or (3), should be used:

$$h=\frac{H'}{ab+\Delta p}\cdot\Delta p \qquad (2)$$

where h=height of the object, in feet, or difference in altitude being determined;
H'=height of airplane, in feet, above the lower of the two points whose parallax difference has been measured;
ab=photobase adjusted to the lower of the two points whose parallax difference has been measured (commonly determined by measuring the distance between photograph centers—*0–0′* of fig. 23—and subtracting from it the distance between conjugate image points at the lower altitude—distance *A* of fig. 23); units of measure may be millimeters or inches but must be the same as Δp;
and Δp=parallax difference, in millimeters or inches, measured with stereometer-type instrument (distance *A–B* of figure 23);

or

$$h=\frac{H'}{ab-\Delta p}\cdot\Delta p \qquad (3)$$

where h=height of the object, in feet, or difference in in altitude being determined;
H'=height of airplane, in feet, above the upper of the two points whose parallax difference has been measured;
ab=photobase adjusted to the upper of the two points whose parallax difference has been measured (commonly determined by measuring the distance between photograph centers—*0–0′* of fig. 23—and subtracting from it the distance between conjugate image points at the upper altitude—distance *B* of fig. 23); units of measure may be millimeters or inches but must be the same as Δp;
and Δp=parallax difference, in millimeters or inches, measured with stereometer-type instrument (distance *A–B* of figure 23).

Formula (2) is used when H' and ab are determined by referring to the lower of the two points whose altitude difference is desired, as in measuring upward from the base to the top of a cliff. Formula (3) is used when H' and ab are referred to the upper point, as in measuring downward from the top to the bottom of a cliff. Most commonly the lower of two points is selected as the reference point and measurements are made from that point to some higher point in the stereoscopic model; thus formula (2) is more widely used than formula (3).

Parallax differences generally can be read within small tolerances (see p. 73), and errors in computing differences in altitude result mainly in the determination of flying height and photobase, assuming photographs have little or no tilt. It is therefore generally desirable to determine flying height (H') and adjusted photobase (ab) carefully because a given percentage error in one of them may cause a similar percentage error in the computation of altitude difference. In addition, failure to use formula (2) or (3) when parallax difference (Δp) is large will also cause a considerable error in the final result even though the adjusted photobase (ab) has been carefully determined.

For calculation of absolute heights as is necessary, for example, in determining stratigraphic thickness or displacement on faults, the factor H' may be determined from a base map of known scale or from other control using the relation $H'= f/S$. If the altitude difference between some two points, *A* and *B*, is desired and if neither A nor B falls in a convenient map position for scaling a distance and determinnig H' for one of them, it may be necessary to make parallax measurements with respect to some selected third point, C, for which the flying height (H') can be readily calculated.

Where altitudes are to be used for computing angles of dip it is not necessary to know the absolute height of H'; the tangent relation of angles

$$\text{Tan angle of dip}=\frac{\text{vertical distance}}{\text{horizontal distance}} \quad (4)$$

involves only relative horizontal distances and relative differences of altitudes, and thus any value may be assumed for H' when measuring parallax difference and determining the scale of the photograph to be used in computing dips. In photogrammetric terms this relation may be expressed as

$$\text{Tan angle of dip}=\frac{\text{flying height (feet)} \times \text{parallax difference}}{\text{horizontal distance on ground (feet)} \times \text{adjusted photobase}} \quad (5)$$

$$\text{or Tan angle of dip}=\frac{H'\cdot\Delta p}{d\cdot(ab\pm\Delta p)}. \quad (6)$$

Since

$$\frac{\text{flying height (feet)}}{\text{horizontal distance on ground (feet)}}$$

is also equal to

$$\frac{\text{focal length (inches)}}{\text{horozontal distance on photograph (inches)}}$$

the following formula may also be used to calculate angles of dip when flying height, H', is not known or cannot be determined:

$$\text{Tan angle of dip}=\frac{\text{focal length} \times \text{parallax difference}}{\text{horizontal distance on photograph} \times \text{adjusted photobase}}. \quad (7)$$

The tangent of dip, in photogrammetric terms, has been described in more detail by Desjardins (1943b, p. 1536–1538) and Elliott (1952, p. 8). When angles of dip are determined from enlarged photographs and formula (7) is used, the effect of photographic enlargement on focal length must be considered; effective focal length is increased in direct proportion to the amount of photographic enlragement (see p. 4).

Hemphill (1958a, p. 43) has devised a chart that shows the number of feet represented by each millimeter of parallax change as H' and $(ab + \Delta p)$ of formula (2) vary. The factor determined from the chart is then multiplied by Δp to arrive at h, in feet, provided formula (2) is used. A simple circular photogrammetric computer has also been designed that permits easy computation of the number of feet represented by each millimeter or hundredth millimeter of parallax as flying height and photobase vary. In addition, the computer allows multiplication of this factor by the parallax change to give altitude differences in feet. The number of feet represented by each hundredth millimeter of parallax measured on paper prints may also be determined from the ratio

$$\frac{\text{Flying height (feet)}}{\text{Photobase (millimeters)} \times 100}.$$

This relation is further discussed on page 73.

Need for correct orientation of photographs.—Misorientation of a stereopair of photographs can be considered from the standpoint of rotation around the center of one or both of the photographs. This rotation results in misalinement of the stereopair and flight line. Parallax differences are not then measured in the true x direction, or flight-line direction, but at a slight angle to it; an error in the adjusted photobase also results. The measurement of parallax difference is not normally significantly affected but the adjusted photobase on a stereopair misoriented by a few degrees, even though the human eyes can tolerate a certain amount of error and yet see a well-defined stereoscopic image, may be in error by as much as 5 to 10 percent. This will cause a similar error in differences in altitudes determined by the parallax method when paper prints are used.

USE OF DOUBLE-PROJECTION INSTRUMENTS

When double-projection instruments are used to determine altitude difference between two points, only one distance need be measured. This is a vertical distance within the stereoscopic model that results from the translation of linear parallax recorded on the glass-plate diapositives to angular parallax in the viewing arrangement (fig. 24). The vertical position of intersecting light rays to the lower point to be measured is determined by placing the floating dot on the apparent ground in the stereoscopic model and recording the instrument reading. The vertical position of the upper point is recorded in a similar manner. The difference in readings is a measure of the parallactic displacement and is related to the difference in altitude of the two points. With double-projection instruments measurements are normally made in increments of tenths of millimeters, although some instruments are so designed that selection of proper gear trains permits readings to be converted directly to heights in meters or feet.

In stereoscopic models formed in double-projection instruments the vertical scale remains constant with respect to the horizontal scale and a simple multiplication factor—called the K factor—for relating increments of vertical measurement to absolute feet can be determined by converting the standard fractional scale (representative fraction) of the model to feet per unit of vertical measurement, that is, per 0.1 millimeter. This is most rapidly accomplished using the formula

$$K=\frac{\text{model scale denominator}}{3{,}048 \text{ (number of tenths of millimeters in 1 foot)}}.$$

Thus a stereoscopic model with a scale of 1:4,000 would have a K factor of 4,000/3,048 or 1.31 feet per 0.1 millimeter of vertical measurement. Increments of vertical measurement are merely multiplied by the appropriate K factor to obtain differences in altitude in feet. A constant factor for converting increments of vertical measurement to feet is appropriate because the horizontal and vertical scales are equal and constant throughout the stereoscopic model, but when paper prints are used, the horizontal scale is not constant throughout the model and hence different multiplication factors must be determined for different levels in the model.

Because the horizontal and vertical scales in stereoscopic models from double-projection instruments are equal and constant throughout the model, inclined distances, such as stratigraphic thicknesses of dipping beds, may also be measured. A special device for measuring distances in inclined directions was developed by R. H. Morris and C. L. Pillmore of the Geological Survey; it consists of a multiplex tracing table modified so that the platen, platen socket, and light source can be tilted as a unit (fig. 22). An additional worm-screw drive, separate from the conventional worm-screw drive, allows the platen to move in an inclined direction perpendicular to the surface of the platen. The resulting measured distance within the model is converted to feet in the usual manner, and a measure of the inclined distance is obtained.

TILT

Tilt in present-day vertical photography is generally small—under good flying and photographic conditions 50 percent of the photographs taken for domestic mapping are reported to be tilted less than 1° and 90 percent tilted less than 2° (see Tewinkel, 1952, p. 319). But tilt may be significant in the photogrammetric calculation of many geologic measurements, and care must therefore be exercised in determining altitudes from parallax measurements. The significance of tilt on vertical measurements used in geologic interpretation depends in large part on the geologic problem. Where vertical measurements must be referred to a horizontal datum, as in structure contouring, tilt may cause significant errors, but where relative vertical measurements between pairs of points are desired, as in constructing isopach lines, tilt may have relatively little effect especially where points of any one pair are separated by only a small horizontal distance (see p. 73). If only simple streometers are available for parallax determinations it may be necessary to entirely discard some photograph prints unless (a) vertical control is available and the geologist carries out the tedious task of constructing a correction graph (Desjardins, 1950, p. 2304–2305; McNeil, 1952, p. 610–615; and Visser, 1954, p. 849–853), or (b) points of measurement are selected so that the effect of tilt will be minimized (Hemphill, 1958a, p. 46–47, 49). It is also possible to partially correct for tilt locally on planar orientations, such as the strike and dip of beds, by stereographic projection and appropriate rotations in stereographic constructions.

If photogrammetric instruments are available that allow photographs to be tilted, it is generally possible to eliminate any large amount of tilt (greater than 1°) by careful inspection of physiographic features of the stereoscopic model, thereby permitting reliable parallax measurements to be made even though vertical control is not available for leveling the model. For example, lakes or other standing bodies of water may appear tilted, or certain streams or stream meanders may appear to flow uphill (fig. 109). Tilt is also often detected by observing that headwater tributaries in subdued divide areas where gradients are very low appear to flow uphill. Adjustment of the instrument so that the lakes appear flat and streams have a normal gradient will minimize tilt, and parallax measurements can then be made.

For certain sensitive measurements, such as measurement of low stream gradients or measurements used to determine the strike of low-dipping beds, it is essential that vertical control for leveling models be available and that a precision plotting instrument, such as the Kelsh plotter, be used. Because a small amount of tilt may seriously affect the measure of stream gradient the economic advantage of photogrammetric techniques may be lost where the measure of gradients is the primary photogrammetric objective, inasmuch as a considerable amount of vertical control must be obtained by ground survey to level the stereoscopic models. However, for many geologic measurements, particularly where relative intervals are to be measured, ground control, although desirable, is not essential for making satisfactory parallax determinations, either from paper prints or glass-plate diapositives.

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DETERMINATION OF ALTITUDE DIFFERENCES FROM A SINGLE PHOTOGRAPH

Under certain conditions altitude differences between two points may be determined by making appropriate measurements of radial displacement on a single photograph and substituting them in the formula

$$h=\frac{mH}{r}$$

where h=difference in altitude desired;
m=relief displacement of upper image point with respect to the lower image point;
H=height of airplane above lower image point;
and r=radial distance from principal point of photograph to lower image point.

The distance m and r must be measured in the same units. The height, h, will then be in terms of the units chosen for H.

This procedure is only applicable to vertical objects where the upper point is known to be directly above the lower point. Under these restricted conditions, the length of the image of an object, such as a tree, or a cliff face at right angles to a radial line from the principal point, is a measure of the relief displacement. The radial distance to the lower point can be easily measured, and the flying height can be obtained from the formula $H=f/S$ (see p. 53–54) when base maps are available, or from the specifications of the photographic mission. Thus, for example, if the radial displacement of a cliff is 0.03 inch, the flying height of the airplane 10,000 feet, and the lower point is 3 inches from the photograph center, the height of the cliff will be

$$h=\frac{0.03\times 10{,}000}{3.0}$$

$$h=100 \text{ feet.}$$

Because relief displacement is generally small, a small error in measuring such a distance on a single photograph will result in a relatively large error in the height of the object, which further limits the usefulness of the formula for determining vertical intervals.

GEOLOGIC USES OF PARALLAX MEASUREMENTS

Parallax measurements always result in the determination of spot altitudes or vertical intervals when papers prints are used; and generally result in spot altitudes or vertical intervals when glass-plate diapositives are used in double-projection instruments, except when a special tracing table is used that permits measurement of inclined distances (fig. 22). These spot altitudes and differences in altitudes combined with horizontal distances determined from the stereoscopic model, or under some circumstances from a single photograph, may be used to compile structure-contour maps and to determine dips of beds, thicknesses of beds, offsets on faults, gradients of streams, and related data.

Because of relief displacement, however, it may be necessary to correctly locate the relative horizontal positions of points, whose altitudes have been measured, before computing strikes and dips, determining stratigraphic thicknesses, or any other geologic measurements where dips are involved. Because tilt is usually negligible in present-day photography, horizontal positions of points generally may be plotted satisfactorily with any instrument that removes relief displacement, such as the radial planimetric plotter, paper-print plotters, and double-projection plotters even though the stereoscopic model cannot be leveled. Horizontal distances may then be scaled off. However, in the absence of plotters for locating the relative map positions of radially displaced points when measurements are made with parallax bar and paper prints, an overlay or similar procedure may be used to determine corrected horizontal distances, unless orthophotographs (see page 69) are available from which correct horizontal distances may be scaled.

The overlay procedure requires first laying out on transparent material a line equal in length to the adjusted photobase. The overlay is then placed over the right photograph of the stereoscopic pair so that the line drawn is coincident with the flight direction and its right end terminates at the photograph center. Radial lines are then drawn on the overlay from the photograph center through all points whose relative horizontal positions are to be determined. The procedure is repeated with the overlay positioned over the left photograph, again with the original line coincident with the flight direction and its left end terminating at the photograph center. The intersection of a pair of lines through the same image points is the corrected horizontal position for that point.

DETERMINING STRIKES AND DIPS

Where bedding surfaces coincide with topographic surfaces it is generally sufficient to measure the altitude difference between only two points, one directly downdip from the other in calculating the amount of dip. The horizontal distance between these two points, together with the difference in altitude, gives the required information for determining the angle of dip from the trigonometric relation

$$\frac{\text{Vertical distance}}{\text{Horizontal distance}}=\text{tangent of angle dip.}$$

If relief in an area is low the horizontal distance may be scaled directly from a single photograph without significant error in computing the dip, but where relief is moderate or high a correction for the relief displacement of the upper point with respect to the lower point generally should be made. In the unique circumstance where the strike is radial from a photograph center or where the surface on which the dip to be measured is at or near a photograph center, there is little or no relief displacement in the dip direction, and no correction in scaling the horizontal distance need be made. Hemphill (1958a, p. 53) suggested that the corrected horizontal distance between the upper and lower points should be at least 0.2 inch for computing dip angles. Where dips are greater than 50°, a longer horizontal distance is needed to determine the dip angle reliably, as the tangent increment per degree of dip is significantly greater for steep angles of dip than for low angles of dip.

The strike line generally can be determined readily by inspection of the stereoscopic model and noting two points of equal altitude on a bed. Where dips are low, however, tilt in the photographs will affect the direction of strike; the lower the dip, the greater the effect, generally, on the amount of shift in the azimuth of the strike line. Graphs may be constructed to show the effect of tilt on low-dipping beds. (See Hemphill, 1958a, p. 48.)

Where a bed crops out in a valley wall it will generally be necessary to determine the altitudes of three points on the bed. In areas of moderate or high relief corrections for relief displacement must be made before distances between these points can be determined; otherwise distances may be scaled directly from the single photograph. Determination of the strike direction and amount of dip are then made graphically or graphically and trigonometrically.

DETERMINING STRATIGRAPHIC THICKNESS

In areas where beds are horizontal or nearly horizontal the stratigraphic thickness may be determined directly by converting to feet the parallax difference between the top and the bottom of the bed. No correction is necessary for relief displacement. However, if beds are inclined, the angle of dip must first be determined; then corrections must be made for relief displacement and for the effect of dip on the stratigraphic thickness. The thickness may be calculated by simple trigonometry or by graphic solution (fig. 26).

Desjardins (1950, p. 2308–2309; 1951, p. 829–830) suggested that floating lines be employed with paper prints for determining stratigraphic thicknesses where beds do not dip more than 15°. In the "floating line" procedure, lines are drawn on transparent strips of

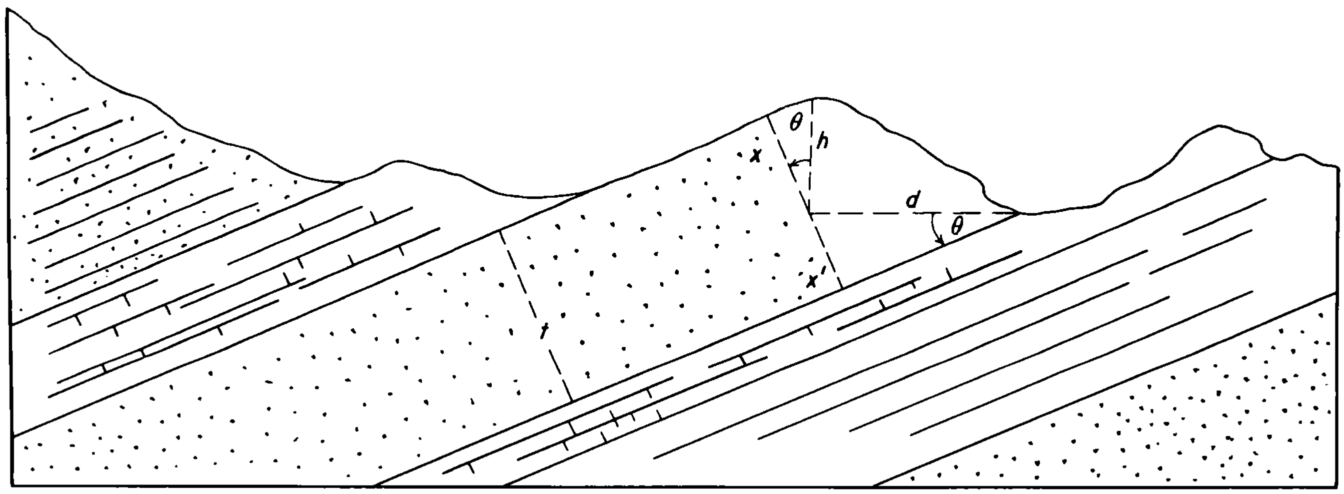


FIGURE 26.—Diagram of gently dipping beds showing relation of stratigraphic thickness to differential parallex determined at any two points along dip direction and at the formation contacts.

Stratigraphic thickness is determined from the formula

$$t = x + x' = h \cos\theta + d \sin\theta$$

where t=stratigraphic thickness;

h=difference in altitude between some point on the lower contact of the bed and some point, along a line at right angles to the strike line, at the upper contact of the bed; altitude h is determined from the parallax formula;

d=corrected horizontal distance between points at lower and upper contacts of the bed;

and θ=angle of dip.

material that are superposed over each of the photographs. When one line over one photograph is positioned parallel to a line over the second photograph, a single floating line will appear when viewed stereoscopically unless the lines are parallel to the flight direction. The line will float above or within the model and appear to be horizontal; its vertical position in the model will depend on the separation of the two individual lines in the flight direction. A series of lines will form a grid or reference plane (Smith, H. T. U., 1943a, p. 171; Desjardins, 1943a, p. 219; Hackman, 1957, p. 593). When any one pair of lines is divergent rather than parallel the floating line in the stereoscopic model will appear to plunge. By changing the horizontal separation of any two lines in the flight direction the floating line can be made to rise or fall in the model, just as with the floating dot of the parallax bar. When the floating-line procedure is used in measuring stratigraphic thicknesses, a line is first floated preferably in the bedding plane at the upper formational contact, and parallax measurements are then made at the lower formational contact and on the floating line at a position in space vertically above this point (see fig. 27). If beds are horizontal or nearly horizontal the parallax difference will be approximately a measure of the stratigraphic thickness. If the beds dip, the stratigraphic thickness will bear a cosine relation to the dip angle and parallax measurement (see fig. 27).

Where dips are steep it may be desirable to measure a horizontal distance along a line at right angles to the strike direction between two formation contacts and relate this distance and dip angle to stratigraphic thickness. Points must be chosen at approximately the same altitude in the stereoscopic model (fig. 28).

ISOPACH MAPPING

The use of aerial photographs in studies of certain areas in the Colorado Plateau of Western United States has included the photogrammetric compilation of isopach maps that show local thickenings of certain formations in which uranium minerals are likely to occur. These thickenings of formations are channel-fill deposits in stream channels that were cut in the underlying formation. Uranium minerals are locally concentrated in these deposits. In the Monument Valley area of southern Utah it has been demonstrated that isopach lines, indicating the trends and thicknesses of different channel-fill deposits, could be drawn

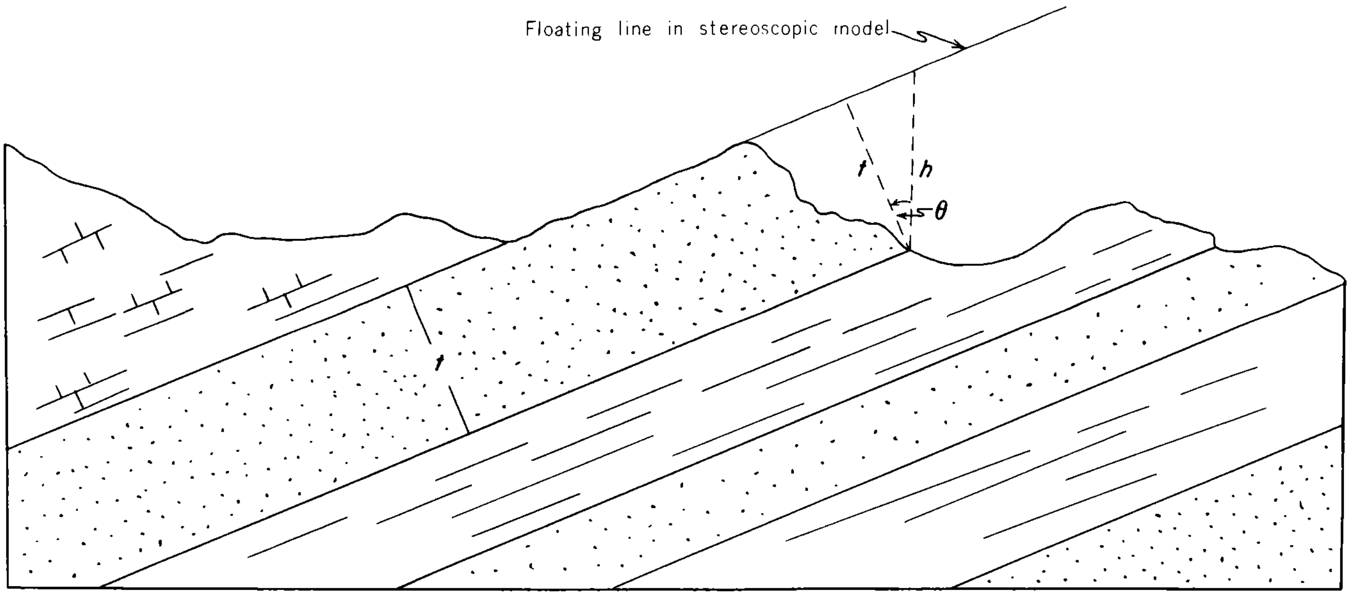


FIGURE 27.—Diagram of gently dipping beds showing relation of stratigraphic thickness to differential parallax determined by floating-line method.

Stratigraphic thickness is found from the formula

$$t = h \cos \theta$$

where t = stratigraphic thickness;
h = difference in altitude between bottom of bed and point on floating line vertically above, as determined from the parallax formula;
and θ = angle equivalent to angle of dip.

on the basis of measurements made on vertical aerial photographs. In this area uranium minerals are present in channel-fill deposits at the base of the Shinarump member of the Chinle formation of Triassic age. However, because the top of the Shinarump member is eroded away in many areas, or because it is gradational with the overlying member of the Chinle formation, a stratigraphic unit below the Shinarump member was chosen as the unit for which isopach lines were drawn. A thinning of this underlying unit then was interpreted to indicate a thickening of, or channel deposits of, the overlying Shinarump member. The unit selected for isopach measurements, the Moenkopi formation, is expressed on aerial photographs as a dark-toned slope-forming unit that contrasts markedly with the light-toned cliff-forming units of both the underlying De Chelly sandstone member of the Cutler formation and the overlying Shinarump member of the Chinle formation (fig. 44).

A series of altitude measurements was then made along the contact of the Moenkopi and Shinarump formations from aerial photographs by means of the Kelsh plotter, and the locations of these measurements were plotted on a base sheet. Similarly, a series of altitude measurements was made along the contact of the De Chelly and Moenkopi formations and the locations were plotted on the base sheet. Measurements along the respective geologic contacts were generally spaced at horizontal distances of about 500 feet. Because the stratigraphic units dip locally it was necessary to compute the strike and dip of the beds and to correct for the dip angle in determining the stratigraphic thicknesses of the Moenkopi interval. Thickness computations were plotted at the points of altitude measurements along the contact of the Moenkopi and the Shinarump, and isopach lines were drawn at 10-foot intervals on the basis of the distribution of thickness figures. The relatively large number of readings, both for strike and dip of beds as well as for altitude measurements, permitted elimination of certain computations that were inconsistent with regard to the overall mass of statistical data. The locations and depths of channels of Shinarump member as shown by isopach lines based on photogrammetric measurements and plotting were generally in close agreement with those determined by field methods. Details of the photogeologic study are described by Witkind, Hemphill, Pillmore, and Morris (1960).

FACIES CHANGE

Measurements from aerial photographs in conjunction with stratigraphic studies of Cretaceous rocks in northern Alaska have demonstrated the rate and direction of "shaling," or facies change, of certain formations. In the Utukok-Corwin area resistant rocks of the Kukpowruk formation, which is predominantly silty shale, siltstone, and sandstone, overlie less resistant

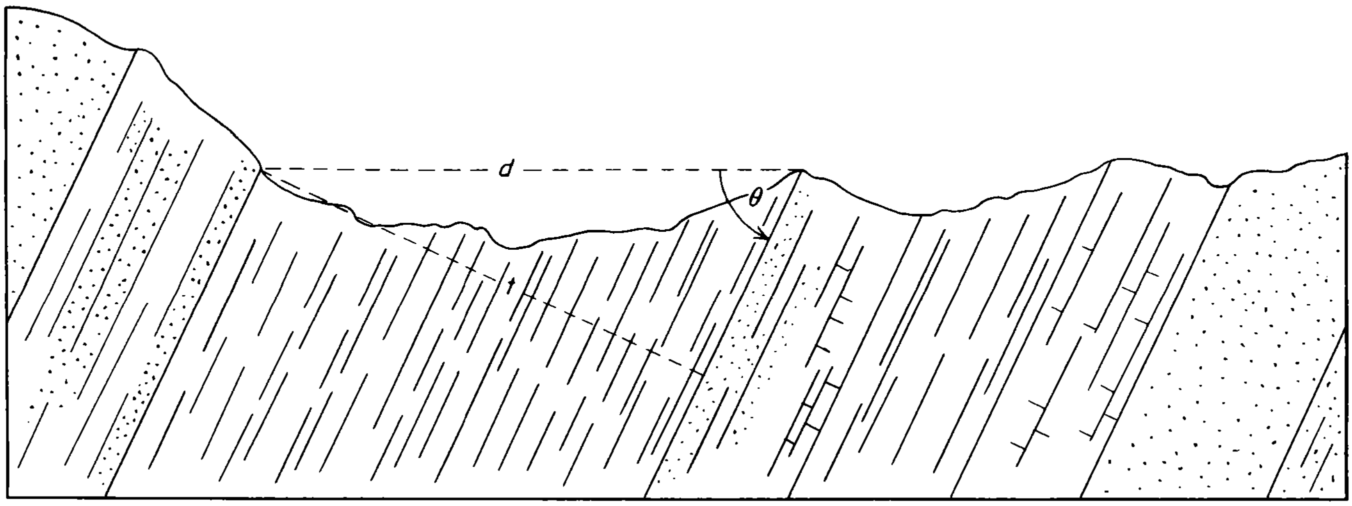


FIGURE 28.—Diagram of steeply dipping beds showing relation of stratigraphic thickness to dip angle and horizontal distance between top and botton of bed.

Stratigraphic thickness is determined from the formula

$$t = d \sin \theta$$

where t=stratigraphic thickness;
d=horizontal distance at right angles to strike line between points at same altitude on top and bottom of bed;
and θ=angle of dip.

rocks of the Torok formation, which is largely clay shale, claystone, and silty shale. The Torok formation commonly forms the lowlands, which are characterized by rather uniform and low-dipping topographic slopes. The Kukpowruk formation forms high, resistant ridges that can be traced many miles. The contact of the two formations is marked by a break in topography that has been mapped in the field in conjunction with the study of aerial photographs. Slopes below the contact are generally smooth and unbroken; slopes above the contact are marked by conspicuous topographic breaks caused by hard, resistant sandstone beds in the basal part of the Kukpowruk formation. Vertical exaggeration of the stereoscopic model accentuates these topographic breaks in slope. Photogeologic and field studies show that these resistant beds pinch out usually in an easterly or northerly direction (see fig. 97). It is significant that their topographic expression is lost. Ground observations along stream cuts indicate that the resistant beds grade laterally into shaly sections.

Quantitative studies from aerial photographs of the amount of section affected by facies change in the Utukok-Corwin area show that several thousand feet of sandy section of the Kukpowruk formation grade laterally to the east and north into shale of the Torok formation. Chapman and Sable (1960) stated that the methods used in these studies included tracing on vertical aerial photographs a resistant unit within the Kukpowruk formation around the flanks of a large open structure and then measuring the stratigraphic intervals between the resistant bed and the contact of the Kukpowruk and Torok formations to determine the new relative stratigraphic positions of the contact in different parts of the area. Photogrammetric measurements were made whenever possible in localities of good field control; a few stratigraphic thicknesses were determined solely by photogrammetric methods without field control. Locations for measurements were chosen along east-west and north-south lines. Relative stratigraphic positions of the contact of the Kukpowruk and Torok formations were then plotted graphically against lateral distances between points of measurement; this resulted in a line whose gradient showed the average rate of rise of the contact between points of measurement. An average eastward-rising gradient of 58 feet per mile and an average northward-rising gradient of 97 feet per mile were calculated.

It was concluded on the basis of plotting these average gradients as vector quantities that a resultant maximum gradient of 115 feet per mile exists and that more than 10,000 feet of sandy beds grade into shaly sections over the area studied. The maximum gradient direction was further interpreted to lie at right angles to the direction of minimum facies change, which is believed to indicate the general trend of the old shoreline during the period of deposition of the Kukpowruk and Torok sediments. Thus the photogeologic measurement of stratigraphic intervals not only permitted determination of the directions and amounts of facies change, but further allowed inferences concerning the geologic history and environment, which may be significant in the search for petroleum in that area.

STRUCTURE CONTOURING

Structure contours are usually constructed on the basis of a series of spot altitudes, some of which may be photogrammetrically determined at the top of the horizon to be contoured, but many of which will be measured at formation contacts above or below that horizon. Photogeologic procedure is similar to field procedure and requires adjusting the altitudes of all points not on the horizon to be contoured by making appropriate considerations of strike and dip and stratigraphic thickness. Structure-contour lines are then adjusted to the resultant series of altitudes projected to the same formation contact.

NOTOM-15 QUADRANGLE

In photogeologic interpretation and mapping of the Notom-15 quadrangle, Utah, (Hackman and Tolbert, 1955) altitudes for structure contouring were measured using a Kelsh plotter. No previous geologic or topographic mapping had been done in the area; geologic data and altitude measurements were plotted to a control net established by photogrammetric methods. The Notom-15 quadrangle is well-exposed canyon country typical of the Colorado Plateau of Utah. Gently folded sedimentary rocks of Triassic and Jurassic age underlie the area. Canyons transecting the general structure trend made the application of photogeologic procedures ideal. A series of altitude measurements were made along the contact of the Wingate sandstone of Triassic age and the overlying Kayenta formation of Triassic(?) age. The wide exposure of this contact throughout the area permitted sufficient measurements to control structure contouring. Structure contours were then drawn on the top of the Wingate sandstone. Subsequent fieldwork corroborated the general structure as contoured by Kelsh plotter from aerial photographs and also corroborated the distributions of rock formation as interpreted and mapped from photographs. Positioning of other planimetric data, such as streams, was shown to be in excellent agreement with the subsequently compiled standard topographic map of the quadrangle. The positioning of data and altitude determinations by Kelsh plotter thus resulted in a highly reliable geologic map of the area.

DISCOVERY ANTICLINE

Procedures used in contouring the Discovery anticline in northern Alaska included stereometer measurement of altitudes combined with simple trigonometric computations and graphic constructions to compile a generalized structure-contour map (Marshall and Rosendale, 1953). These procedures contrast markedly with the Kelsh-plotter compilation of the Notom-15 quadrangle, but demonstrate that simple methods may be useful in obtaining structural information of a reconnaissance nature from aerial photographs.

Discovery anticline, a gently folded structural feature approximately 25 miles long and 7 miles wide, is underlain primarily by Cretaceous rocks. The area is generally covered with tundra grasses, but resistant beds within the stratigraphic section are expressed topographically as ridges, or breaks in slope, that can be traced for many miles; some beds are expressed by photographic tone due to differences in vegetation (see fig. 40). Dip slopes rarely coincide with topographic surfaces.

Procedures for obtaining and positioning data for structure contouring involved the arbitrary selection of cross-section lines normal to the general structural trend. Strikes and dips of beds were then determined by simple stereometer methods at numerous localities and projected to the nearest cross-section line. Where the strike line did not intersect the line of section at right angles the apparent dip was determined and plotted on the section line. This procedure was followed for all strikes and dips, and resulted in cross-section lines along which the different dips were plotted. A marker bed was then selected and its profile along the line of section graphically reconstructed on the basis of the positions and amounts of dip previously plotted (fig. 29). It was assumed that bedding throughout the stratigraphic section was parallel. Structure contours were then positioned along each line of section by further graphic constructions (fig. 30). However, the datum for each line of section commonly was different, depending on which part of the stratigraphic section was expressed in any one local area, and it was necessary to obtain stereometer measurements of altitudes between cross-section lines so that structure contours, as positioned along each line of section, could be tied together (fig. 31). The resulting reconnaissance map, plotted on an uncontrolled photomosaic, indicated the general magnitude and closure of the anticline and the attitude and steepness of bedding. Figures 29–31 show graphic constructions in reconnaissance structure contouring from measurements made with stereometer-type instruments.

DETERMINING DISPLACEMENTS ON FAULTS

The vertical component of displacement on some faults may be readily determined from parallax measurements made on marker beds on opposite sides of the fault by simple conversion of parallax difference to feet or other appropriate unit of measurement. If the fault plane dips, relative altitudes on marker beds may be related to the down-dip component of displacement by trigonometric or graphic solution.

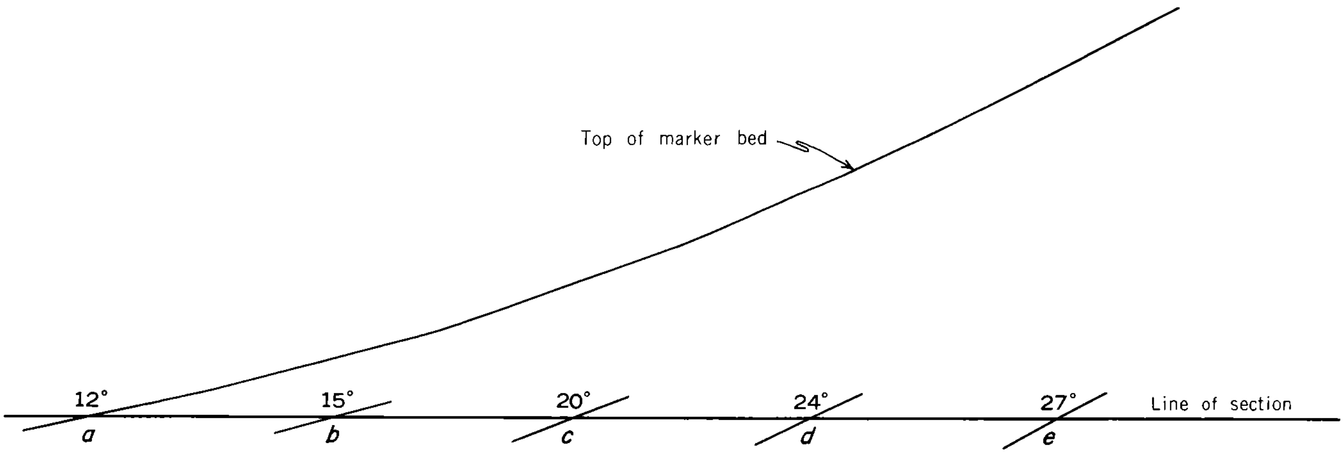


FIGURE 29.—Diagram showing graphic reconstruction of marker bed along line of section.

Dips determined from aerial photographs are first plotted along line of section. The marker bed is then reconstructed by extending bed upward from point *a* at 12° dip for half the distance between *a* and *b*. From this point the bed is extended at 15° dip to a point half the distance between *b* and *c*. From this point the bed is again extended at 20° dip to a point half the distance between *c* and *d*, and so on. A smooth curve is then drawn to represent the marker bed.

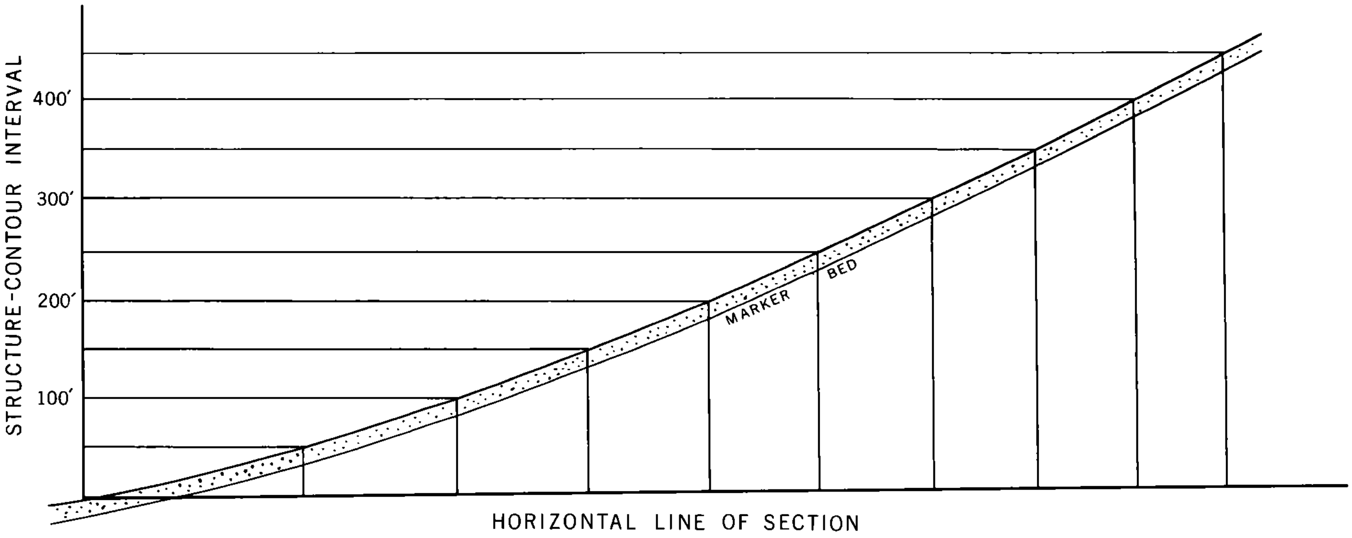


FIGURE 30.—Diagram showing graphic construction in positioning structure-contour lines on top of marker bed and the projecting of these lines to their relative horizontal positions along the line of section.

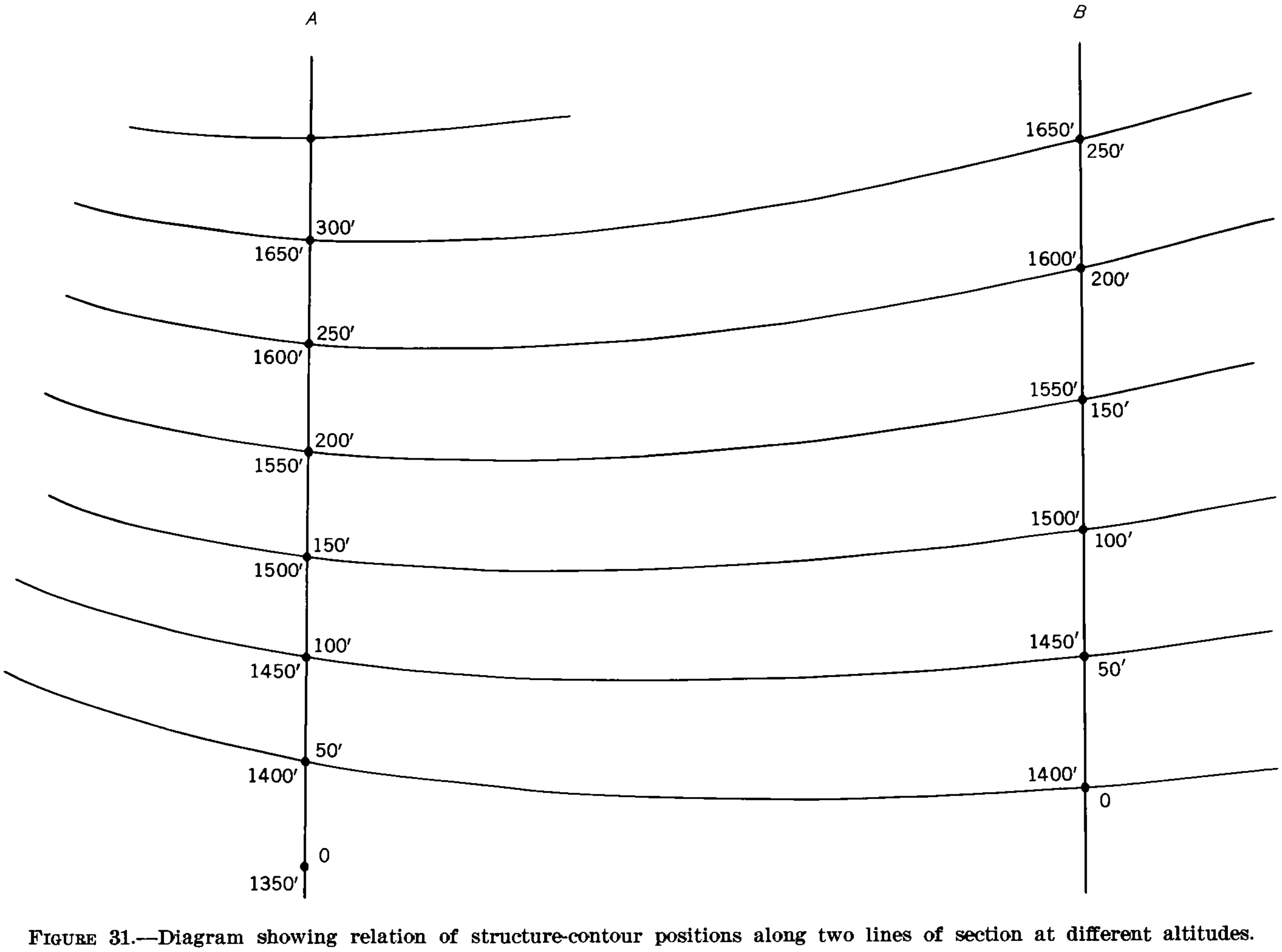


FIGURE 31.—Diagram showing relation of structure-contour positions along two lines of section at different altitudes. Relative positions of 50-foot structure contours along each line of section are shown to the right of each line. Absolute altitudes of structure-contour positions are shown to the left of each line of section. Because the zero points on the reconstructed marker bed along lines *A* and *B* lie at 1,350 and 1,400 feet, respectively, it is necessary to connect the 50-foot contour position on line *A* with the zero contour position on line *B*, in compiling the structure-contour map.

DETERMINING STREAM GRADIENTS

Stream gradients may be calculated from parallax measurements under certain circumstances. Because many stream gradients are very low—a few feet or tens of feet per mile—an instrument should be used that will permit correction for tilt in the photographs. It will also be desirable to have vertical control for the removal of tilt, as a small amount of tilt not removed from the stereoscopic model could seriously affect the computation of stream gradient. If a stream has a meandering course, then the horizontal distance along the stream between points of measured parallax must be determined by a chartometer or similar instrument for measuring distances along a curved path.

DIRECT DETERMINATION OF SLOPE

DIPPING PLATEN

In addition to the indirect determination of slope by the use of parallax measurements in conjunction with trigonometry or graphic solution, direct measurements of some slopes may be made, both from glass-plate dispositives in double-projection instruments and from paper prints. The simplest procedure is with double-projection instruments and involves the use of a modified platen that can be tilted to coincide with the dip of a topographic surface or bedding plane (fig. 32). Because all features of the terrain are optically re-created in the stereoscopic model of double-projection instruments in essentially true relation, the dip of the platen when made to coincide with the ground surface, or to intersect three or more points on a bedding plane, will be a true measure of the dip of that surface. The dip can be measured with a clinometer attached to the platen or by an accessory device such as a "devil level" or Brunton compass. Dips below 40° can be readily obtained by this method, provided topographic expression or rock outcrops permit positioning of the platen. Dips greater than 40° are difficult to determine owing to the difficulty of positioning the dipping platen in the plane of a steeply dipping surface; steep dips should be computed using the parallax methods described above.

STEREO SLOPE COMPARATOR

A unique method for determining angles of slope from paper prints is employed with the stereo slope comparator (fig. 33), which was developed by the U.S. Geological Survey (Hackman, 1956b, p. 893–898). The instrument consists of two gear housings each containing a horizontal shaft on which small targets are mounted that can be fused stereoscopically into a single target. Swing of the horizontal shafts permits positioning the targets in any direction of strike. The gear housings are mounted on sliding tubes that permit the targets to be separated horizontally so that the fused target appears to rise or fall in space, just as the dot in stereometer-type instruments. However, the dip is determined by physical tilting of the target in space. The instrument is unique in that it measures the exaggerated dip of the imaginary slope created by stereoscopic viewing. With vertical photographs of normal 60 percent overlap, most individuals see the terrain exaggerated in height from 2.5 to 3.5 times. The exaggerated dip, recorded on a protractor attachment on the stereo slope comparator, must be reduced to a true dip. This is accomplished by reference to

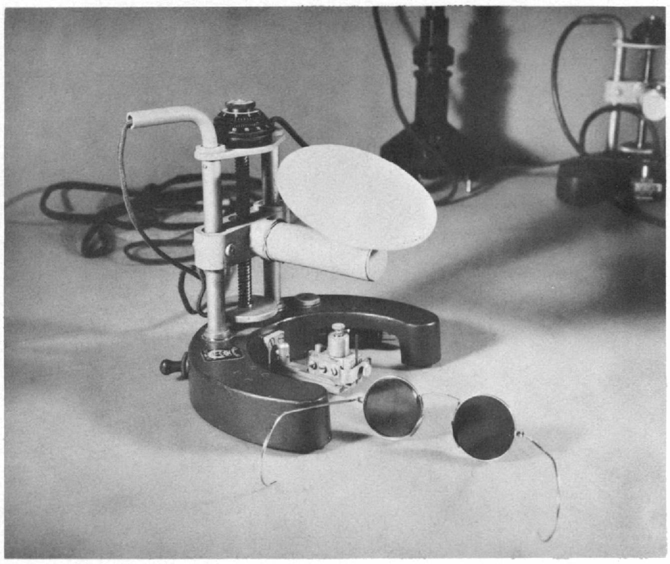


FIGURE 32.—Dipping platen.

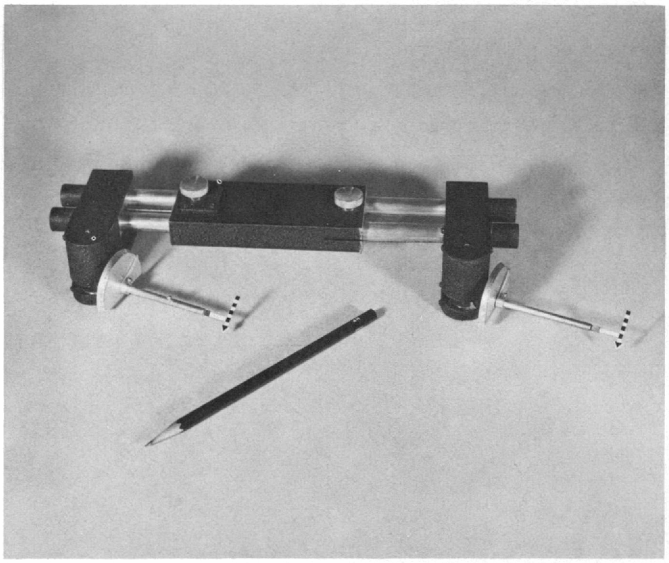


FIGURE 33.—Stereo slope comparator.

INSTRUMENTS FOR DIRECT DETERMINATION OF SLOPE a slope-conversion graph made up of intersecting lines that represent true angle of slope, exaggerated angle of slope, and exaggeration factor (fig. 34). Construction of the graph is based on the relation

$$\text{Tangent true angle of dip} = \frac{\text{tangent exaggerated angle of dip}}{\text{exaggeration factor}}.$$

In determining dips from a pair of paper prints it is necessary to know the exaggeration factor of the interpreter for that stereoscopic model. This factor varies slightly with different individuals and is determined by reference to a supplementary slope chart on which a dipping surface of specific dip has been constructed by methods described by Hackman (1956a, p. 387–391). By measuring the exaggerated dip of this constructed surface, known to represent a given true angle of dip, an exaggeration factor is obtained; it is then possible to make measurements on a specific pair of photographs and to convert any exaggerated dip to a true dip. Because of the difficulty of placing the tilted target in a steeply dipping plane, the instrument is most reliably used where true dips are 20° or less.

DIP ESTIMATION

From paper prints an experienced interpreter can estimate dips, particularly in the range of 1° to 5°, with considerable reliability, as a result of vertical exaggeration in the stereoscopic model. Because of vertical exaggeration, angles of slope in terms of their tangent functions are exaggerated in the stereoscopic models as much as 2.5 to 3.5 times, with the result that low-dipping surfaces, which are in places difficult to observe in the field, are readily interpreted (figs. 45, 88, 90, 91, and 97). For example, a true dip of 1° may appear to be a dip of 3° or 4° in the stereoscopic model, and a dip of 5° may appear to be 15° to 20°. For true dips below 20° an error of a few degrees in estimating the exaggerated dip has only a small effect on the true dip (see fig. 35), and an interpreter is able to make reliable visual determinations of these dips from most stereoscopic models. But steeply dipping surfaces are also exaggerated and made more difficult to evaluate. Any small error in determining the angle of exaggerated dip of steep slopes results in a relatively larger error in the true dip calculation for that slope. Brundall and Harder (1953, p. 150) stated that "the accuracy of individual estimation is generally inversely proportional to the steepness of dip." In estimating dips a correction obviously must be made for the oversteepened slopes as they appear in the stereoscopic model (see figs. 34 and 35).

Factors affecting vertical exaggeration in stereoscopic models have been discussed by several writers (Treece, 1955; Goodale, 1953; Thurrell, 1953; Miller, 1953; Aschenbrenner, 1952; and Stone, 1951), but complete agreement has not been reached concerning the effects of specific factors such as viewing distance and image separation. However, once an interpreter has correlated amounts of dip, determined photogrammetrically or by field procedure, with a given set of conditions such as type of stereoscope, focal length of photography, photobase, and image separation, reliable estimates of true dip can be made over wide areas without reference to known dips.

OTHER METHODS OF DETERMINING ANGLES OF SLOPES

Another method of determining slopes in stereoscopic models is based on the floating-line principle. Brundall and Harder (1953, p. 150–151) briefly mentioned a device consisting of two lines scribed on plastic plates. The lines, seen stereoscopically as a single line floating within the model, can be made to converge so that the floating line appears to plunge in space. The plunging floating line is placed in the component of dip direction at right angles to the flight line. The angular rotation of the scribed lines required to obtain a given amount of steepness of plunge of the floating line is then related to true dip by means of a graph. As this method would result in true dip only for beds striking parallel to the flight line, the correction graph must also consider the azimuth of the dip component observed with respect to the strike of the beds.

Wallace (1950) has used angular relations in the plane of the aerial photograph as the basis for a method of determining strikes and dips from aerial photographs. The method is best applied where erosion has exposed bedding trace lines as contrasted to broad topographic surfaces that coincide with bedding. No parallax measurements are required. It is necessary to measure the angular relation of two bedding trace lines with respect to a known or assumed azimuth line on each photograph of a stereoscopic pair and to determine the plunge of the line of sight from the camera position to the outcrop, or bedding-trace line. These data are then plotted on a stereographic net to determine the strike and dip of the bed (Wallace, 1950, p. 275).

OTHER METHODS OF DETERMINING QUANTITATIVE DATA

Measurement of geologic data, other than altitudes and direct determinations of slope angles, are only infrequently made from aerial photographs. However, the possible applications of light-transmission measurements, from both black-and-white and color pho-

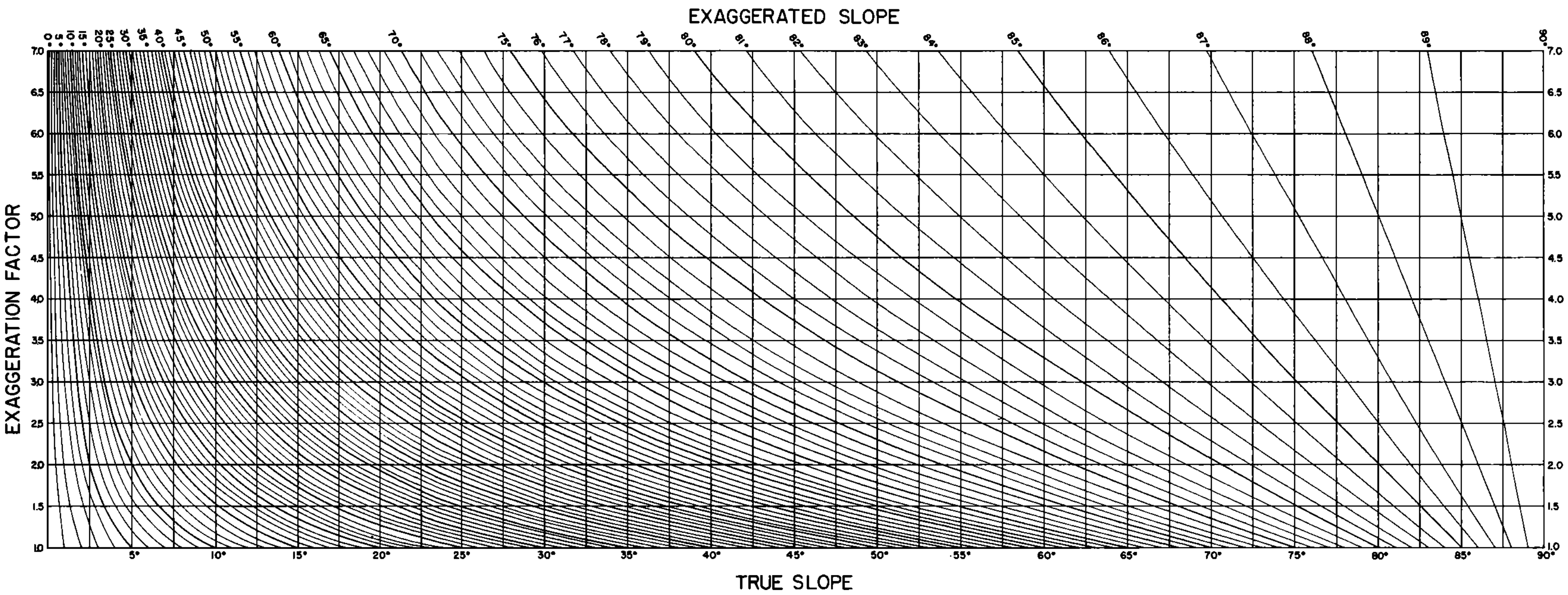


Figure 34.—Slope-conversion chart showing relation of exaggeration factor, exaggerated slope, and true slope.

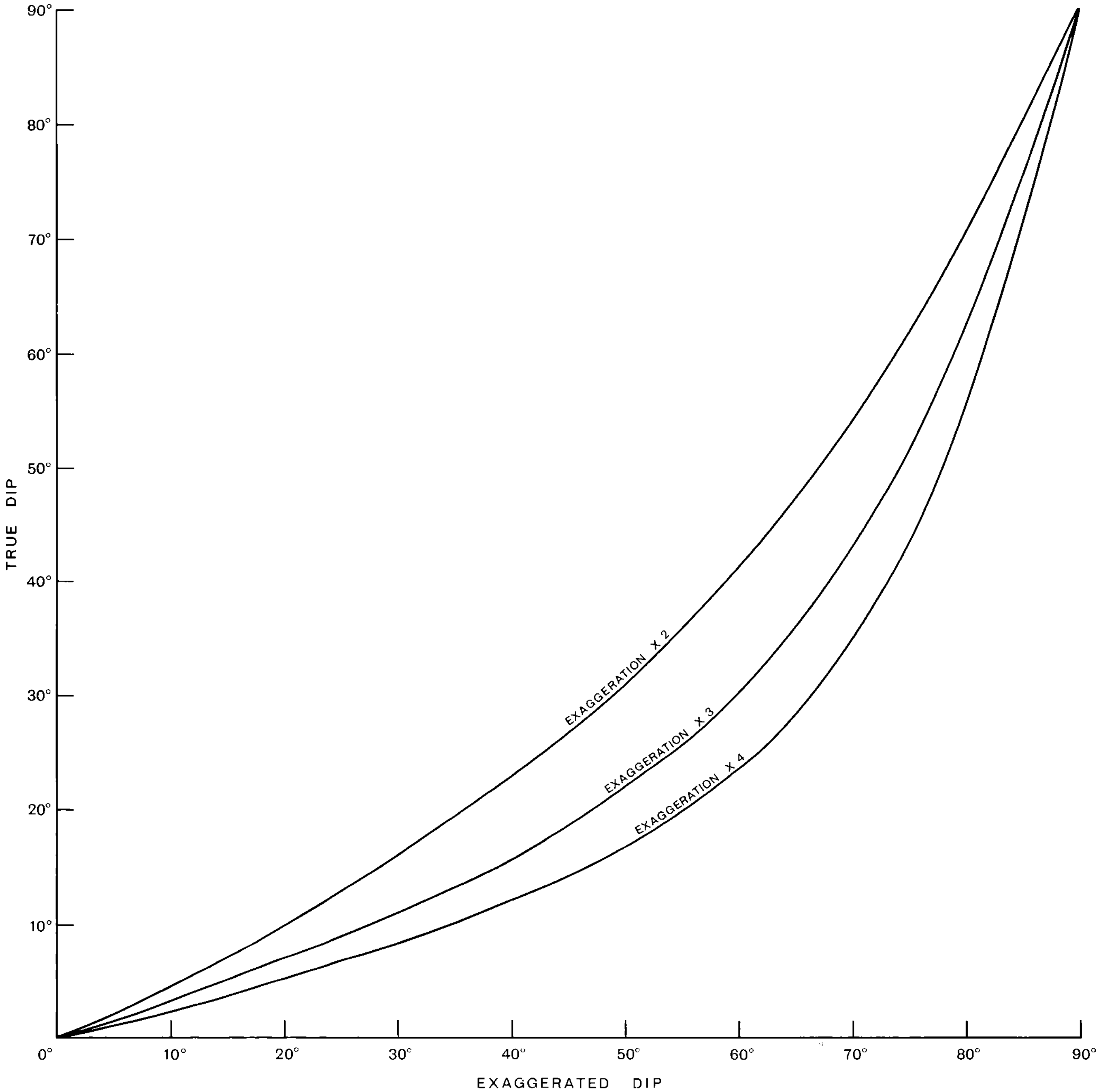


FIGURE 35.—Diagram, based on tangent functions, showing relation of true dips to exaggerated dips seen in stereoscopic models.

tography, light-reflectance measurements, measurements related to heat-retention characteristics of terrain photographed, infrared absorption, size, frequency, and orientation measurements of physiographic features, and perhaps others, offer challenging opportunities for future study (see Ray and Fischer, 1960).

PLOTTING

Map compilation—planimetric positioning of data—is basic to most geologic studies and generally requires methods of plotting data orthographically. Thus, data plotted or interpreted on vertical aerial photographs, most of which are perspective in view, must be replotted on an orthographic base. The orthographic base may be planimetric or topographic. Where no base map exists perspective aerial photographs provide a medium for constructing a control layout on which geologic and other data may be plotted orthographically.

CONSTRUCTION OF CONTROL LAYOUT

A control layout is an orthographic plot of a series of points selected on aerial photographs that cover a given area. These points are used to control the positioning of data plotted from the perspective photograph. Plotting, or transfer, of data from the photograph may be done with simple overhead projectors or sketchmasters under some circumstances, or with stereoplotting instruments described above. The accuracy of the final plot will depend primarily upon the control net and the instrument used in plotting (see p. 74–75).

Basically a control layout or control net is established by triangulation from the aerial photographs in much the same manner as field triangulation is carried out. This aerial triangulation requires mechanical construction of templets which are assembled together into the triangulation network. There are two general methods of constructing templets. One method involves radial triangulation using the principal point of the single photograph as a principal triangulation station to construct radial templets; the other method involves radial triangulation using some orthographically positioned pass point from the stereoscopic model as a principal triangulation station to construct stereotemplets.

Where single photographs are used for triangulation it is generally assumed that the photographs are truly vertical and have no tilt; relief displacement is radial from the photograph centers. However, a tilt of 1° or 2° does not significantly affect horizontal positioning over small areas. Templets from single photographs may be constructed by the hand-templet method, the radial-arm ("spider"-templet) method or the slotted-templet method. Photographs are first prepared by marking the centers, conjugate centers, and selected pass points, usually six in number, along the margins of a photograph; pass points are selected which are common to adjoining flight strips and common to succeeding and preceding photographs within the flight strip. From each photograph, azimuth lines are then constructed from the photograph center through all other selected points to form a templet for that photograph. Azimuth lines may be drawn in pencil on an overlay sheet (hand-templet method); they may be constructed of metal arms ("spider"-templet method), or they may be cut as slots in a piece of cardboard (slotted-templet method). After templets have been constructed for all photographs they are assembled into a triangulation network in which the intersections of azimuth lines locate the orthographic positions of the points selected. The result is a base sheet with a series of points located in their correct relative horizontal positions. Where horizontal control points are available, the distance between plotted positions of any two of them determines the scale of the control layout. Details of constructing and assembling these templets are described by Kelsh (1952, p. 419–429).

Construction of stereotemplets requires the use of a stereoplotting device to plot selected points common to adjoining flight strips and within the flight strip. The templet is actually a double templet of the area of the stereoscopic model rather than the single photograph. Azimuth lines are constructed for each part of the templet using one of the pass points as a principal triangulation station for one part of the templet, and using a different, generally diagonally opposite, pass point as the principal triangulation station for the second part of the templet. These two parts are joined together to form the completed templet for each stereoscopic model. Details of constructing and assembling the stereotemplets have been described by Scher (1955). Because of the longer base line of stereotemplets the resulting triangulation network is said to have a stronger scale solution than can be obtained from radial templets constructed from single photographs. Other photogrammetric advantages are mentioned by Scher (1955).

ORTHOGRAPHIC POSITIONING

PLOTTING ON ORTHOGRAPHIC BASE MAPS OR CONTROL LAYOUTS

The main objective in orthographic plotting of geologic data is to show the true planimetric relations of geologic features by removing relief and tilt displacement that may be present in perspective vertical aerial photographs. Relief displacement is commonly large, but tilt displacement is generally small and is usually disregarded when positioning geologic data on a planimetric base sheet. When positioning geologic data to a topographic base both relief and tilt displacement may be significant and require plotting from a leveled stereoscopic model. For horizontal positioning of data to a planimetric base in areas of low relief the relief displacement will be small; overhead projectors may be used to transfer data from the photograph to base map or control net. For example, with common photography of 1:20,000 scale taken with a 6-inch-focal-length lens, radial displacement near the edge of the photograph will only amount to about 0.1 inch where topographic relief does not exceed 300 feet. Basically relief displacement of a given amount of relief is a function of flying height and is independent of focal length and scale (see p. 74–75).

Where relief displacement is excessive it is possible to change the photograph scale by racking the overhead projector up and down and, provided base map control is sufficiently dense, to scale small areas of the photograph to the base, thus compensating for much of the radial displacement of the perspective photograph. The reliability of the final plot will be in part a function of the density of control points on the base. The suitability of the final plot will depend on the geologic objective. On most radial triangulation networks it is common to find eight control points, exclusive of the photograph center, for each photograph; this number of points will not normally be sufficient to give a reliable plot of the geologic detail in areas of moderate or high relief unless a stereoplotting instrument is used. The vertical sketchmaster, in which the image of a single photograph is seen superposed on the base map or control sheet, generally is used in the same way that overhead projectors are used in plotting. The same general limitations of the overhead projector apply to the sketchmaster; that is, radial displacement due to moderate or high relief cannot be effectively removed.

Orthographic plotting may also be accomplished with the radial planimetric plotter (fig. 14), or with the more complex paper-print plotters, such as the KEK or Mahan plotters. (See p. 42, 45). The radial planimetric plotter is the simplest to operate. It is easily scaled to control points on the base map or triangulation network and effectively corrects for the radial displacement of vertical aerial photographs. Fine detail, such as the configuration of reentrants in contact lines, may be lost in plotting, however. Tilt inherent in photographs cannot be eliminated, but horizontal positioning due to small amounts of tilt found in present-day photography do not significantly affect horizontal positioning of photographic detail for most geologic interpretations. The KEK and Mahan plotters may also be used to plot geologic data from paper prints. These instruments permit compensation for any inherent tilt that may be present in the photographs but are more difficult to operate than the planimetric plotter.

Whenever paper prints are used in plotting or transferring geologic data to base maps or control sheets it may be desirable to annotate, or mark, the geologic features to be transferred. This is particularly desirable when overhead projectors are used and is usually a necessity for all instruments if someone other than the interpreter is to do the plotting.

Double-projection instruments afford a high degree of reliability in plotting geologic data from aerial photographs. The ability to correct for tilt and relief displacement combined with an enlarged view of the stereoscopic model when the Kelsh, multiplex, or ER–55 plotters are used permits a highly reliable compilation of geologic data. Even when vertical control is lacking, it is possible to remove most of any tilt inherent in the stereoscopic model by careful reference to physiographic manifestations of tilt such as oversteepened or reverse stream gradients, tilted meanders of a stream, or tilted bodies of standing water (see p. 55).

True orthographic positioning is not always attained, however, in geologic compilations from aerial photographs. Not only is there a question at times of the reliability of interpretation because of the subjective nature of much photogeologic study, but the various instruments themselves have differing degrees of accuracy inherent in their construction. Positioning of clearly identified geologic features by overhead projector, which does not permit adjustments for tilt or effective removal of relief displacement, would be far less reliable under most circumstances than positioning by double-projection instruments. However, the geologic product sought should determine in part the procedure to be used in plotting. Normally there is no reason to use an instrument that will plot detail more accurately than is needed to satisfy the geologic requirement. For example, in small-scale reconnaissance mapping, it is hardly necessary to use a precision plotting instrument for horizontal positioning. The problem of instrument requirement in relation to the geologic problem is further considered under a discussion of interpretation and plotting systems (see p. 69–75).

Only where a significant saving in time and money can be shown is it justifiable to use an instrument whose capability exceeds the minimum requirements of the geologic problem. Such a condition may exist for example where small-scale photographs of an area are available. Much of the United States is now covered by photographs at a scale of approximately 1:60,000. The use of such small-scale photographs in an instrument such as the Kelsh plotter may reduce by as much as 90 percent the number of stereoscopic models that would normally be oriented for interpretation, measuring, and plotting if 1:20,000-scale photographs were used. Even when 1:20,000-scale photographs are used with simple instruments the common practice is to separate the operations; that is, the stereoscope is used to interpret geologic detail and another instrument, such as the stereometer, is used to determine vertical measurement. Thus, by using a precision plotter, which combines interpretation, measuring, and plotting, a significant saving in time and money may be expected.

PLOTTING ON ORTHOPHOTOGRAPHS

An orthophotograph is a photograph that has the position and scale qualities of a map. In addition it has the abundant imagery of the conventional perspective photograph and hence a wealth of photographic detail (fig. 47). Theoretically the orthophotograph, with tilt and radial displacement eliminated in preparation (Bean and Thompson, 1957), has the desirable detail of a photograph and the geometric characteristics of an accurate planimetric map. The method of constructing the orthophotograph from double-projection stereoscopic models results in a small loss of photographic resolution, but horizontal positioning accuracy is comparable to that of the standard topographic map of the same scale.

The orthophotograph, when viewed with an alternate perspective aerial photograph, forms a stereoscopic model, although with only a small amount of stereoscopic relief as contrasted to viewing two perspective photographs. In viewing an orthophotograph with a perspective photograph it is generally best to use the same perspective photography as was used in the preparation of the orthophotograph. Combining the orthophotograph with a perspective photograph permits plotting of geologic detail from the perspective photograph to the orthophotograph and gives a reliable photomap. Geologic data on the orthophotograph then can be transferred by direct projection to a topographic or other base, if desired, or merely traced off to give a reliable planimetric map of areas where no base maps exist. As an aid to field geologic mapping, in which a daily plot of observed data is desirable, the orthophotograph may be especially helpful.

The range of potential applications of orthophotography has been summarized by Bean and Thompson (1957, p. 178) who stated that "* * * whenever there is an advantage in being able to determine accurately on an aerial photograph the positions of points, the lengths or directions of lines, the courses of curved lines, or the shapes or areas of given tracts, the orthophotograph offers a potential means of accomplishing the desired end." In addition, as the basis for constructing mosaics the orthophotograph has a significant application, especially in areas of moderate or high relief.

PLOTTING ON GRIDDED BASE MAPS

Gridded base maps may be especially valuable for field plotting of geologic data without the assistance of photogrammetric instruments. In constructing a gridded base map a grid made up of small squares, usually 1 centimeter on a side, is first superposed photographically onto the perspective aerial photograph. The same grid is then orthographically transferred to the base map by a photogrammetric technician using stereoplotting instruments (Landen, David, oral communication, 1958). The grid lines are straight as superposed on the perspective photograph but are curved on the base map (figs. 115 and 116). By dividing the photograph into many small grid squares the effects of tilt and relief displacement become so small as to be negligible within any one square. Information sketched within grid squares on the perspective photograph is transferred visually to the base map by matching grid squares on the photograph with those on the map. The method may be especially useful in the field where it is desirable to keep a compilation of each day's work.

VERTICAL POSITIONING IN CROSS SECTIONS

In addition to the orthographic positioning of photogeologic data on base maps it is commonly desirable to plot geologic cross sections. The third dimension of the stereoscopic model is then added in part to the normal two-dimensional planimetric presentation of geologic information. Vertical positioning of geologic data, as shown in cross section, may be helpful to the geologist interpreting the aerial photographs of an area, as well as to the map reader who may be less familiar with the geology of the area.

Cross sections are easily and rapidly constructed with a profile plotter from streoscopic models in double-projection plotters. Modification of the tracing table permits profiles to be drawn in any direction within the stereoscopic model (figs. 19 and 20). Sections may be drawn at a horizontal-vertical ratio of 1:1 or they may be exaggerated as much as 5 times. When a 1:1 ratio is used, dips of beds or components of dip, stream gradients, thickness of beds, and similar data may be obtained directly from the section. Exaggerated profiles may be desirable where relief of terrain is low, or, for example, when interpreting the significance of vertical position of thin stratigraphic units in correlation studies. Vertical positioning in sections may also show information suggesting the presence of faults.

INTERPRETATION, MEASURING, AND PLOTTING SYSTEMS

An interpretation, measuring, and plotting system (see fig. 36) may be defined as a combination of photographs and instruments that will permit attaining specific qualitative and quantitative geologic information from stereoscopic models. The optimum system is generally achieved by combining the minimum

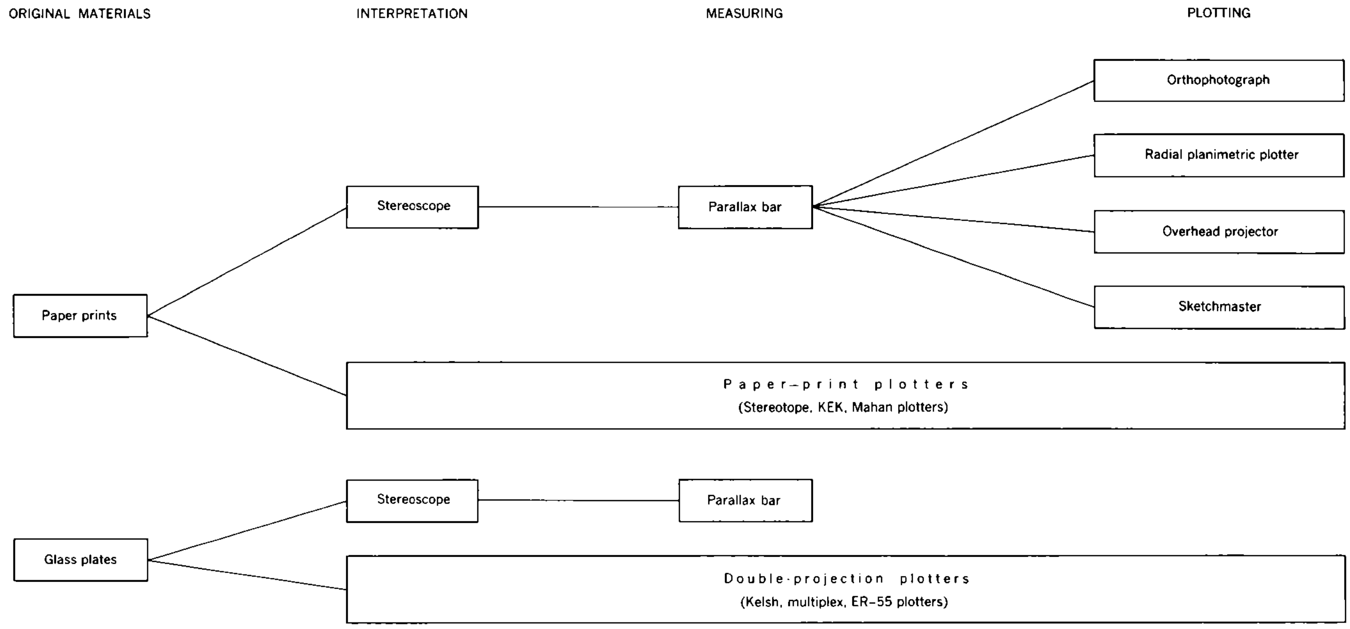


FIGURE 36.—Photogrammetric systems for geologists.

scale photographs and minimum instrument capability that will provide the desired geologic measurements within given accuracy requirements. That is, the scale of photographs should be the smallest that will permit differentiation of photographic detail needed for qualitative interpretation, as well as the smallest that will permit photogrammetric measurements within specified limits. Fundamentally, the geologic objective of a particular study is the controlling factor in the choice of the optimum system of interpretation, measuring, and plotting. The geologic objective may permit the use of existing instruments and photograph scales or it may necessitate new photography or instruments to attain given accuracy requirements.

The type of geologic map and its intended use—the geologic objective—can be considered on the basis of accuracy requirements or limits of error, both in obtaining vertical measurements and in plan positioning of geologic features, provided photographic detail is adequate for qualitative interpretation. For example, a detailed structure-contour map may require an accuracy of vertical measurement within ± 5 feet of altitude and a horizontal position of geologic features within 1/25 inch of true map position. In contrast a small-scale structure-reconnaissance map for planning purposes may permit a vertical tolerance of ±50 feet and have only general horizontal positioning requirements. Thus the choice of an interpretation, measuring, and plotting system may be reduced to certain mathematical requirements that can be satisfied by combining instrument capability with appropriate photography; or the geologic objective or tolerances of measurement may be modified to permit the use of existing photography and instruments.

However, geologic maps, unlike topographic maps, have no standard accuracy limits except those imposed by the individual geologist, with the one exception in the Geological Survey that solid lines, representing faults, contacts, or similar geologic features, should generally be within 1/25 inch of their correct map positions for general geologic maps at a scale of 1:63,360 or larger. Horizontal positioning of data within 1/25 inch of true map position may be accomplished with almost any plotting instrument or plotting system, especially if relief of the area is low and excessive tilt is not present in the photographs. Hence, the vertical-accuracy requirement specified by the geologist for a given geologic problem is ideally the determining factor in choosing an interpretation, measuring, and plotting system. This accuracy requirement, as well as the maximum range of measurements expectable for any system, may be equated against instrument capability and photograph scale as follows:

Geologic requirement of vertical-measurement accuracy or Expected maximum range of vertical-measurement error ⇄ Instrument capability in terms of *K* and *V* factors (see fig. 37).

Figure 37 is an elaboration of this equation and shows the general relations between the geologic requirements of vertical accuracy or expected maximum error in measuring spot altitudes or vertical intervals

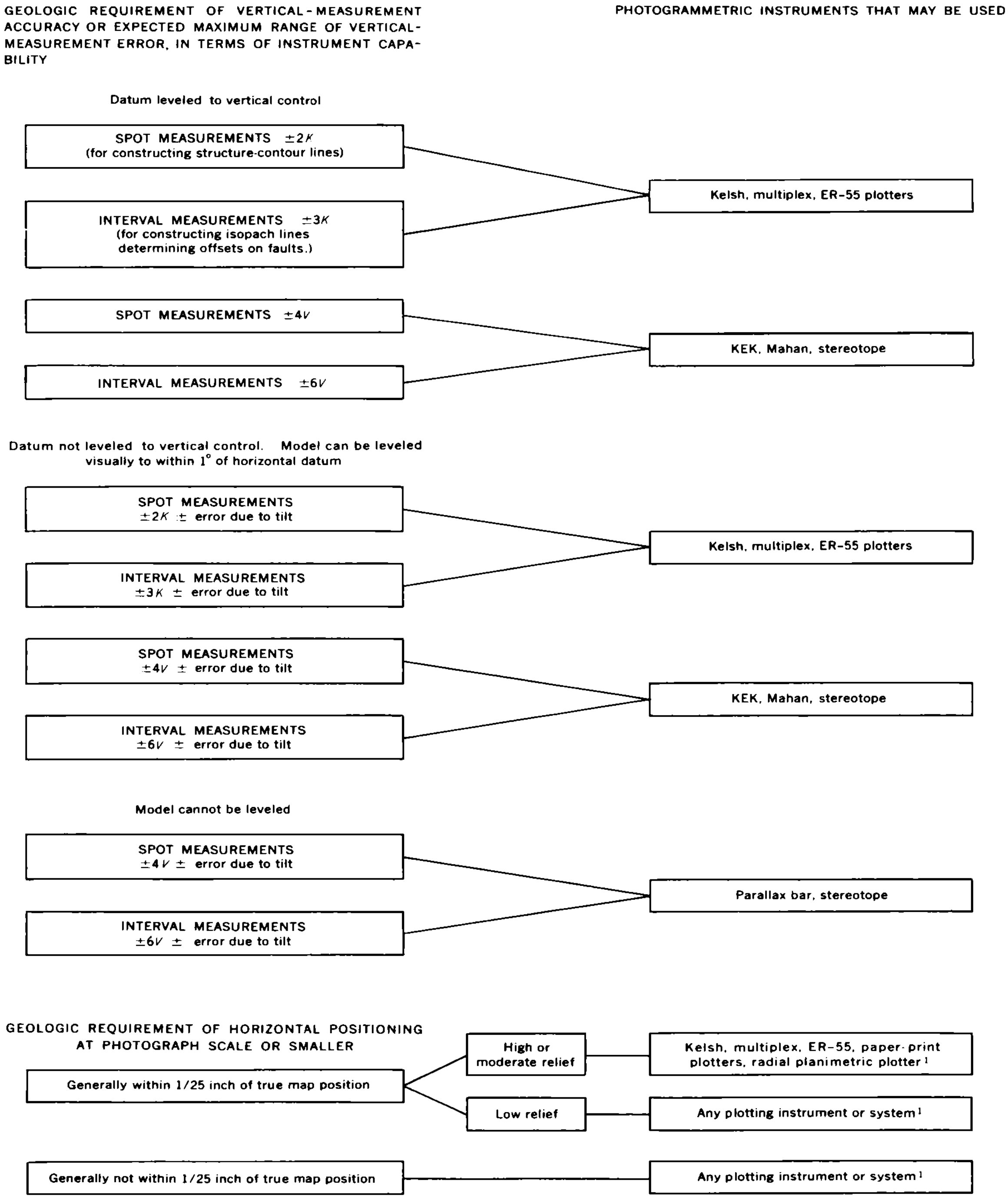


FIGURE 37.—Photogrammetric measuring and plotting systems for geologists showing relation of different instruments to vertical-measurement and horizontal-positioning errors.

where K factor = difference in altitude, in feet, on the ground per unit of vertical measurement in an anaglyphic-type model, that is, per 0.1 millimeter

$$= \frac{\text{model-scale denominator}^{[2]}}{3{,}048}.$$

where V factor = difference in altitude, in feet, on the ground per unit of measurement from a parallax bar or a paper-print plotter, that is, per 0.01 millimeter

$$= \frac{\text{flying height (feet)}}{\text{photobase (millimeters)} \times 100}.$$

[1] No excessive tilt assumed to be present for paper-print models that cannot be leveled.

[2] Model scale for Kelsh plotter is usually about 5 times original photography scale; for ER-55 usually about 3.5 or 5 times, depending on the projector model; and for multiplex usually about 2.5 times.

in terms of instrument capability on one hand and photogrammetric instruments that may be used for measuring and plotting on the other hand. The determination of spot altitudes or relative vertical intervals satisfies most geologic requirements of altitude measurements from stereoscopic models and permits construction of structure-contour lines, and isopach lines, and the determination of dips of slopes, displacements on faults, and similar data. Figure 37 can be used in choosing the best selection from existing photograph scales and instruments for measuring vertical distances, or it can be used to determine what combination of photograph scale and instruments would be optimum in making vertical measurements within certain specified tolerances. For economic reasons the geologist more often than not will be concerned with the best selection of existing photographs and instruments but this selection may not be the optimum interpretation, measuring, and plotting system. This may require modification of his geologic objective, at least in reporting the limits of measurement.

INSTRUMENT CAPABILITY

Instrument capability, selected as the principal basis for the systems shown in figure 37, is an empirically derived factor generally considered with respect to topographic mapping systems as the minimum contour interval—stated in terms of a fraction of the flying height—that can be plotted to fulfill certain accuracy requirements. For geologic measurements it is desirable to consider instrument capability as the minimum increment of vertical measurement that generally can be determined by the geologist from the stereoscopic model. This permits a simple evaluation of expected maximum errors in geologic measurements when double-projection stereoscopic models are used, or when stereoscopic models from paper prints are used. It also allows the geologist to determine what photograph scale and instrument combinations will give him a desired accuracy of measurement. Because the minimum increment of vertical measurement is empirically derived, the limits of error for vertical measurements described below may be subject to modification.

To determine the expected maximum error for a given combination of photograph scale and instrument three possible individual errors must be considered. These are (a) instrument capability in terms of the geologist's ability to measure horizontal linear parallaxes and increments of vertical measurement, (b) curvature of the datum within a stereoscopic model when double-projection instruments are used, or paper and lens distortions when paper prints are used, and (c) tilt. Consideration of the cumulative effect of all three possible errors is necessary in determining the expected maximum error for a particular measuring and plotting system, except for leveled models where tilt has been eliminated. In measuring spot altitudes or relative intervals these errors may be compensating rather than cumulative and therefore many measurements will be well within the expected maximum error determined for a particular combination of photograph scale and instrument.

Experience has shown that for double-projection plotters, it is generally possible for the geologist to determine any one reading to one unit of vertical measurement. One unit of vertical measurement is equal to 0.1 millimeter. With care the increment of measurement may be read closer than one unit of vertical measurement. The amount of altitude difference, in feet, on the ground represented by one unit of vertical measurement in the model—called the K factor—depends solely on the scale of the projected stereoscopic model, and is determined by the ratio

$$\frac{\text{Model-scale denominator}}{3{,}048}.$$

This factor is constant throughout the stereoscopic model. Hence spot altitude readings generally may be read within an amount equal to $\pm K$, that is, the geologist may read a point one unit (0.1 millimeter) too high or one unit (0.1 millimeter) too low. In addition, an error of $\pm K$ is added for curvature of the model datum. Thus the maximum error for spot altitudes can be expected to be on the order of $\pm 2K$ for models leveled to vertical control. Where errors due to reading and to curvature of the datum are compensating a minimum error approaching zero can be obtained. For interval measurements the altitudes of two image points in the stereoscopic model of course must be measured. Each point may be read within an amount equal to $\pm K$, or a total reading error $\pm 2K$. Curvature of the model datum may affect the reading of each point a similar amount and can be disregarded when relative intervals are measured on points close together in plan view; for points close together the expected maximum error generally will be similar to that for spot altitudes. But if points of measurement are not selected close together an added error of $\pm K$ due to datum curvature may be introduced. Thus the maximum error for relative interval measurements is on the order of $\pm 3K$ (figs. 37 and 38).

When vertical control is absent many double-projection stereoscopic models and some models from paper prints may be leveled visually to within 1° of a horizontal datum by observing certain physiographic

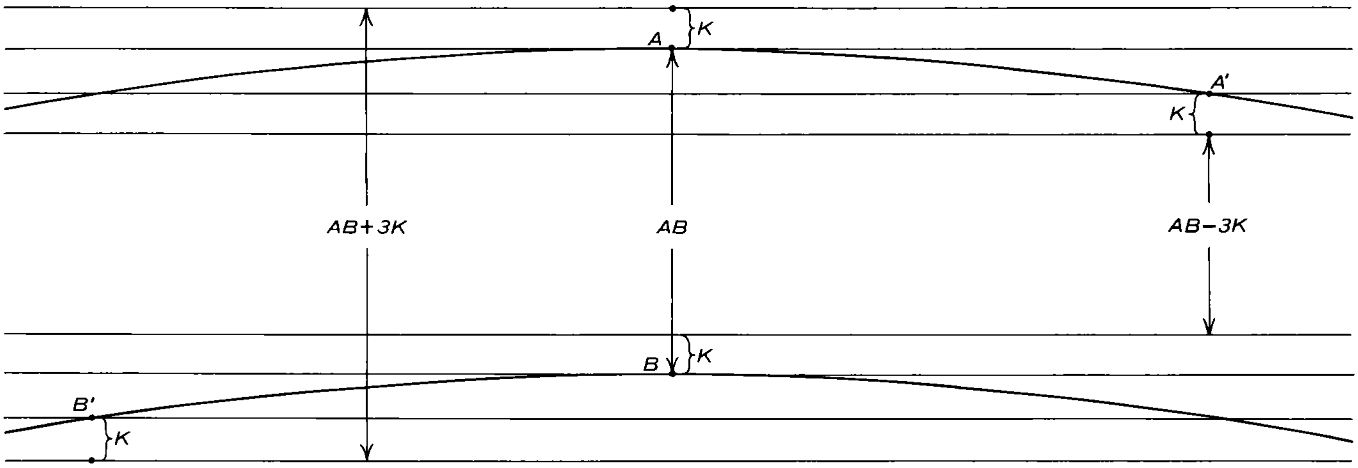


FIGURE 38.—Diagram showing datum-curvature relation to maximum expected error in measuring vertical intervals from leveled double-projection stereoscopic model.

Let AB equal the interval desired. If the upper point is measured at A' an error equal to $-K$, or one unit of measurement, may result from datum curvature; when point B' is measured an error of $+K$ may result. If points A and B' are chosen for measuring the interval and point A is measured one unit too high (equivalent to $+K$) and point B' is measured one unit too low (also equivalent to $+K$) a maximum expected error, including datum-curvature error, of $+3K$ may result. Likewise if points A' and B are chosen for measuring the interval a maximum expected error, including datum-curvature error, of $-3K$ may result.

features in the model (see p. 55) and making appropriate instrument adjustments. For double-projection stereoscopic models that are leveled visually some error due to tilt thus may be present in addition to possible errors in reading and curvature of the model datum; the order of maximum error for spot altitudes becomes $\pm 2K$ $\pm$ error due to tilt, and for relative interval measurements becomes $\pm 3K$ $\pm$ error due to tilt. When relative stratigraphic thicknesses, displacements on faults, or similar geologic measurements are being made, errors due to tilt or from curvature of the model datum may be minimized by measuring points close together in the stereoscopic model. For points spaced far apart the error due to tilt can exceed the error in reading intervals.

Limits can also be placed on reading units of measurement with paper-print plotters or parallax bars, except that a V factor rather than a K factor is employed. A differentiation of factors is necessary as the V factor, unlike the K factor, is not constant throughout the model, but varies slightly due to differences in scale at different altitudes in models formed from paper prints. For practical purposes, V is the ratio:

$$\frac{\text{Flying height (feet)}}{\text{Photobase (millimeters)} \times 100}.$$

The V factor represents the difference in altitude in feet on the ground per unit of measurement from a parallax bar or paper-print plotter, that is per 0.01 millimeter. Experience has shown that parallax measurements from paper prints may be read within about ± 0.02 millimeter or $\pm 2V$. Considering possible errors due to paper or lens distortion and due to tilt, total expected errors for spot altitudes and relative intervals may be determined as shown on figure 37. (See also p. 74.) Errors resulting from paper and lens distortions are considered to be equivalent to about two units of measurement or about $2V$.

Thus two different factors are considered in relating geologic accuracy requirements or expected maximum vertical measurement errors to photograph scale and instrument capability. These factors are the K factor for use with stereoscopic models from glass plates in double-projection plotters, and the V factor for use with stereoscopic models formed from paper prints. For any given system of measurement it is likely that many measurements will fall well within the expected maximum errors as determined from figure 37, especially if high-resolution photographs are available that may permit reading units of vertical measurement less than K or V, and if points of measurement are carefully chosen. Also, errors of reading and datum curvature or tilt may be compensating rather than cumulative, as stated above. In a recent test of determining altitudes of gravity stations with multiplex leveled to vertical control, Kinoshita and Kent (1960) found that 96 per cent of the points measured fell approximately within the limits of $\pm K$ and that 71 percent of the points measured fell approximately within the limits of $\pm K/2$. Results of this special test do not represent the general order of vertical accuracy that geologists may expect to obtain by photogrammetric methods, but they do suggest that many measurements made will be well within the limits shown in figure 37.

RELATION BETWEEN INSTRUMENT CAPABILITY, SCALE, AND VERTICAL MEASUREMENTS

Let it be desired to determine the accuracy of spot altitudes for compiling a structure-contour map of an area covered by recent, high-quality 1:20,000-scale photography flown at 10,000 feet. Adequate vertical control is available for leveling stereoscopic models and a Kelsh plotter is available for measurement and compilation. The expected maximum error shown in figure 37 for spot altitudes for leveled models is $\pm 2K$. Because the scale of the Kelsh model is approximately 5 times that of the original 1:20,000-scale photography (fig. 37), a projected stereoscopic model at a scale of 1:4,000 would result. Thus the K factor for this model would be 4,000/3,048 or 1.31 feet (fig. 37). Spot altitude measurements could be expected to be correct within $\pm 2K$ or ± 2.62 feet for most points in the model.

Many geologists will have only paper prints and simple measuring devices to use so as a second example let it be desired to determine the expected maximum error in measuring a stratigraphic interval with a parallax bar and paper prints already available. Photographs at a scale of 1:20,000 and taken at 10,000 feet are available. Inspection of physiographic characteristics of the terrain indicates that very little tilt, estimated not to exceed 1°, is present. Rock units are clearly expressed, the formations are essentially flat lying, and points of measurement are within ¼ inch on photographs or a distance of about 400 feet on the ground. The photobase distance is 90 millimeters. Figure 37 shows that with parallax bar the expected range of error for relative intervals is $\pm 6V$ ± error due to tilt,

$$\text{where } V = \frac{10,000}{90 \times 100} = 1.1 \text{ (fig. 37)}.$$

The maximum error due to tilt, however, could amount to 14 feet in this example and thus a total expected error of 20.6 feet could result. But the reading error plus paper and lens distortion error may well be less than $\pm 6V$ and the points of measurement may well lie in a direction other than the maximum tilt direction; thus, a measurement error of much less than 20.6 feet will probably result. Figure 37 is constructed to show only the order of maximum error. The percentage of error will depend on the total thickness of the stratigraphic interval; the percentage of error becomes smaller as the thickness of the interval increases.

The geologist will be concerned generally with the expected maximum error of measurement that photographs and instruments already at his disposal will give, and figure 37 is readily used to determine expected maximum errors of measurement for a given photograph scale and instrument combination. However, to determine what photograph scale and instrument combination would be needed to attain specified accuracy requirements is not so easy, as the photograph scale and instrument may be varied and yet give the same required tolerances of vertical measurements. For practical purposes it may be best to equate the vertical-accuracy requirement against instrument capabilities, and to determine from this the scale of photographs that would be needed. Thus, if a requirement for measuring vertical intervals of ± 5 feet is specified it can be seen, for leveled double-projection stereoscopic models, for example, that $\pm 3K$, the maximum expected error for relative intervals, must equal 5 feet or K must equal 1.66 approximately. It follows (see fig. 37) that the projected model-scale denominator must equal 1.66×3,048 or about 1:5,000.

The scale of photographs required to provide a projected stereoscopic model of 1:5,000 depends on the double-projection plotter used. For the Kelsh plotter, the original photography scale would be approximately 1:25,000; for the ER–55 plotter, approximately 1:17,000 or 1:25,000 depending on the projector model; and for the multiplex, approximately 1:12,000 (fig. 37). Similar computations can be made for other instrument capabilities and requirements of vertical measurements. Where two different combinations of instruments and photograph scales will provide the desired accuracy of vertical measurement, the optimum interpretation, measuring, and plotting system will be determined by the smallest scale of photography that will allow recognition and qualitative interpretation of geologic features pertinent to the given geologic objective.

HORIZONTAL POSITIONING

Horizontal positioning within 1/25 inch of true map position generally can be accomplished at photograph scale or smaller with any of the plotting instruments that removes relief and tilt displacement. Such instruments include the double-projection plotters and some of the paper-print plotters. The small amount of tilt inherent in present-day vertical photography is generally of little significance in horizontal positioning of geologic features, however, and the radial planimetric plotter may also be used to plot geologic features within 1/25 inch of true map position. Orthophotographs may also be used for reliable horizontal positioning of data (see p. 69). In addition, geologic features in areas of low relief may be plotted within 1/25 inch of true map position by sketchmaster or overhead reflecting projector if tilt is negligible. Where relief is low, radial displacement (also called relief displacement) of image points is commonly less than 1/25 inch. For example, on vertical photographs taken from a flying height of 10,000 feet, displacement where the relief is 100 feet amounts to 1/25 inch at a point 4 inches from the center of the photograph. Nearer the center of the photograph the displacement is less. Thus, geologic data on such photographs can be plotted generally within 1/25 inch at photograph scale or smaller with simple overhead reflecting projectors, or can even be traced directly from the photographs and still be within the 1/25-inch tolerance for general geologic maps. The amount of radial displacement, m in inches, is determined from the formula

$$m=\frac{rh}{H}$$

where r=radial distance on the photograph, in inches, from principal point to base of image displaced;
h=height of object displaced, in feet above datum (height of terrain);
and H=flying height, in feet, above datum;

(h and H must be referred to the same datum and be measured in the same units. The amount of displacement, m, is then in the same units of measure as chosen for r). Thus, the limit of relief that can be adequately plotted within the 1/25-inch tolerance for general geologic maps is basically a function of flying height and not of focal length. Displacement due to relief varies inversely with flying height.

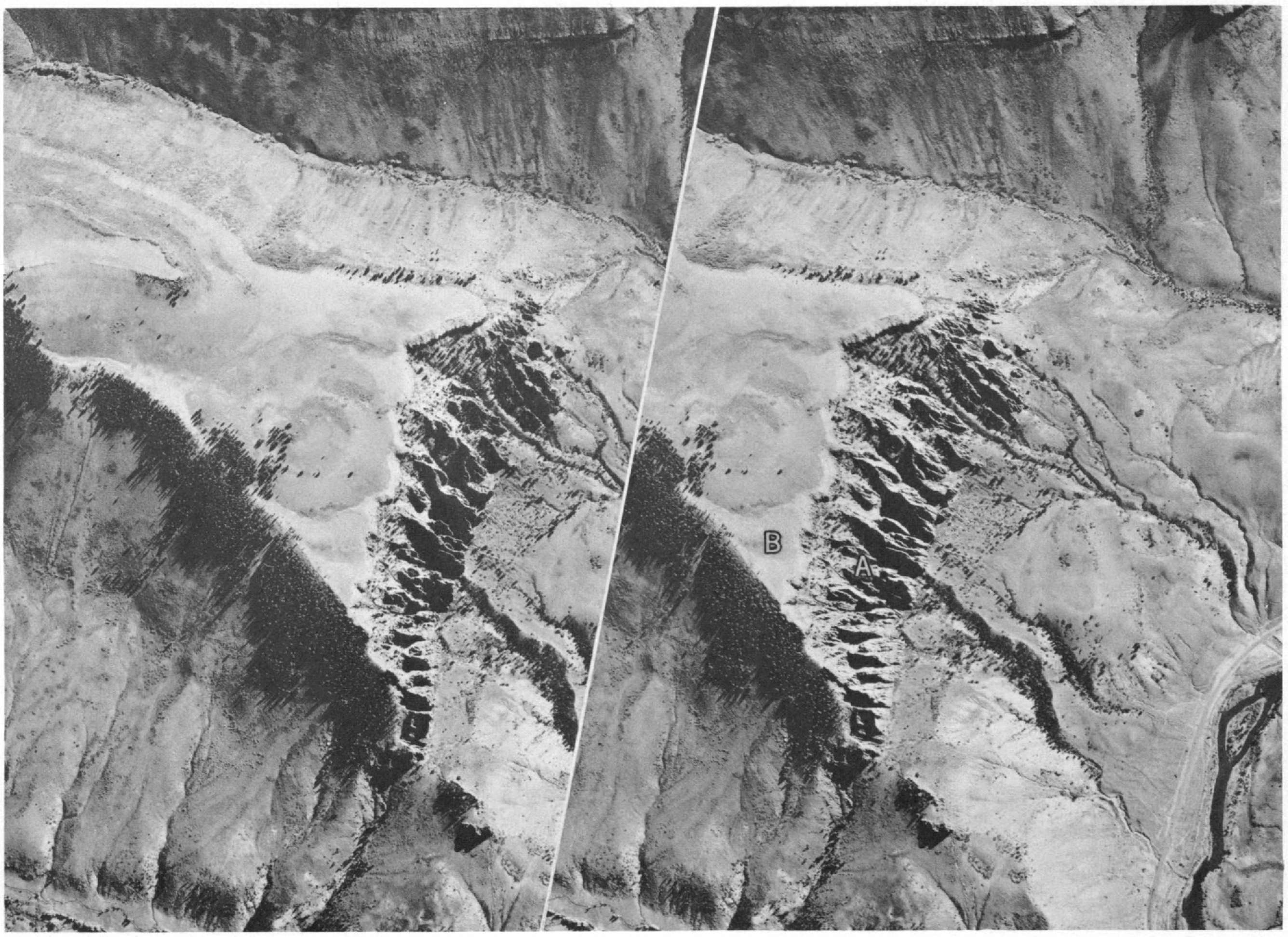
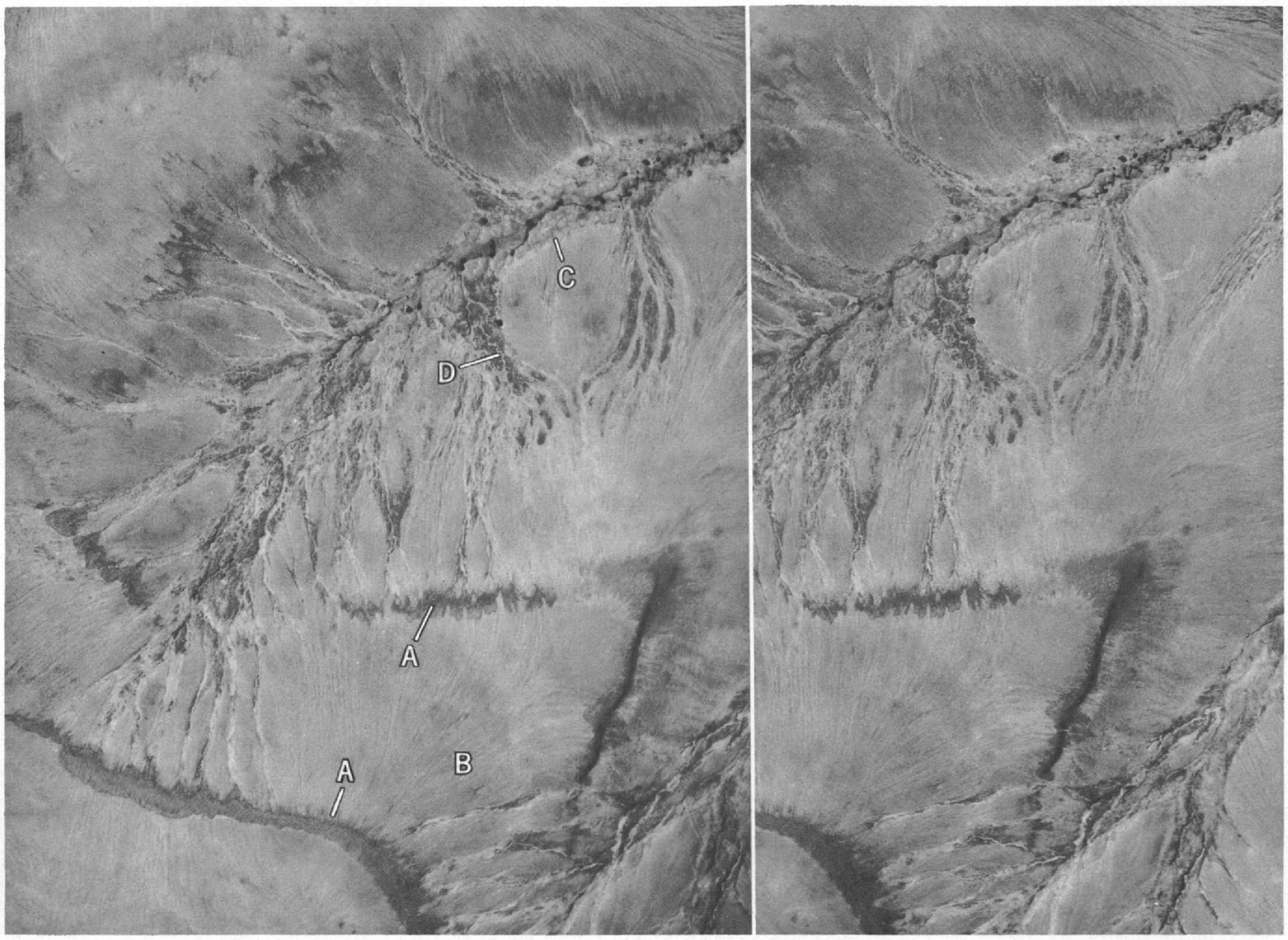


FIGURE 39.—POORLY RESISTANT PYROCLASTIC ROCKS OVERLAIN BY RESISTANT CAPPING FORMATION (COLORADO).

[Approximate scale 1 : 20,000. Photographs by Soil Conservation Service]

Coarse pyroclastic rocks, *A*, are highly dissected in contrast to the more resistant and protecting welded tuff caprock, *B*, in this area of flat-lying formations. Deep dissection of pyroclastic rocks, occurring here preferentially on one slope, permits delineation of contacts that can be traced into nearby areas where strong dissection has not taken place. The use of the floating-dot reference mark of many photogrammetric instruments may be especially helpful in tracing a geologic contact from an area where the contact is well expressed to an area where the contact is obscured. Sandstone and shale below the pyroclastic rocks are in large part poorly exposed because of the slope wash that covers the deposits.



Stereoscopic pair

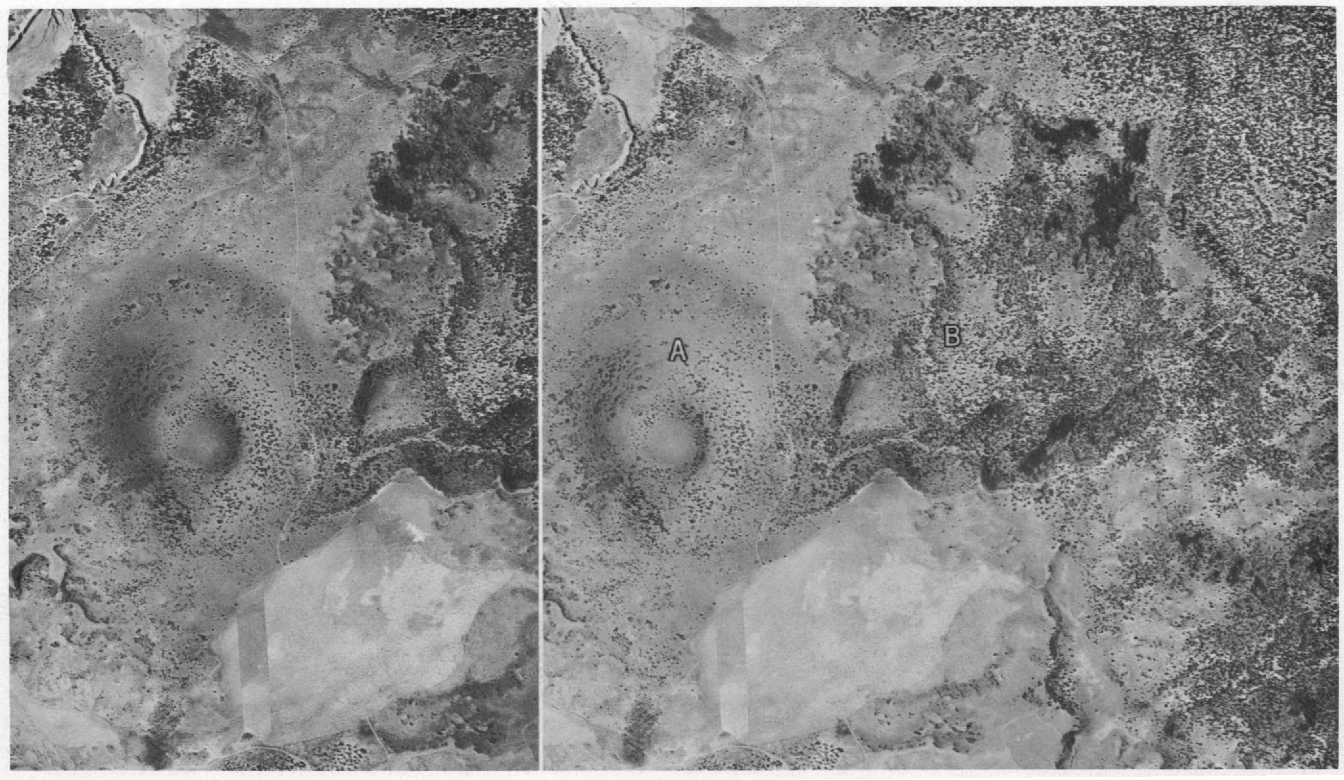
Approximately 1 mile

FIGURE 40.—AREA UNDERLAIN PREDOMINANTLY BY GENTLY FOLDED SANDSTONE, SHALE, CONGLOMERATE, AND GRAYWACKE (NORTHERN ALASKA).

[Approximate scale 1 : 20,000. Photographs by U.S. Navy]

In some areas where outcrops are sparse or lacking bedding may be traced on the basis of topography and vegetation. Resistant beds of sandstone and conglomerate cause small topographic rises, in some areas as little as 2 feet, which are easily discerned in the stereoscopic model because of vertical exaggeration present in viewing most stereoscopic pairs. The steepened slope caused by the resistant bed is commonly populated with a different mossy and grassy vegetation from that of surrounding areas, and bedding is revealed as wide, strongly curved bands of vegetation that are recognized on photographs by their lighter or darker photographic tone than surrounding areas. Such bands of vegetation, as at *A*, are commonly seen clearly on aerial photographs or from a distance on the ground, but are not always readily distinguished when standing directly on them on the ground.

Permafrost is shown by the presence of beaded drainage, indicated by isolated pools of water connected by short, incised watercourses along main stream. Striped slopes, *B*, are typical but not unique to permafrost areas (contrast fig. 53). Note high-center polygons, *C*, that exhibit raised centers surrounded by depressed dark-toned edges. Angular drainage channels, *D*, are related to melting out of ice wedges and are common in permafrost areas.



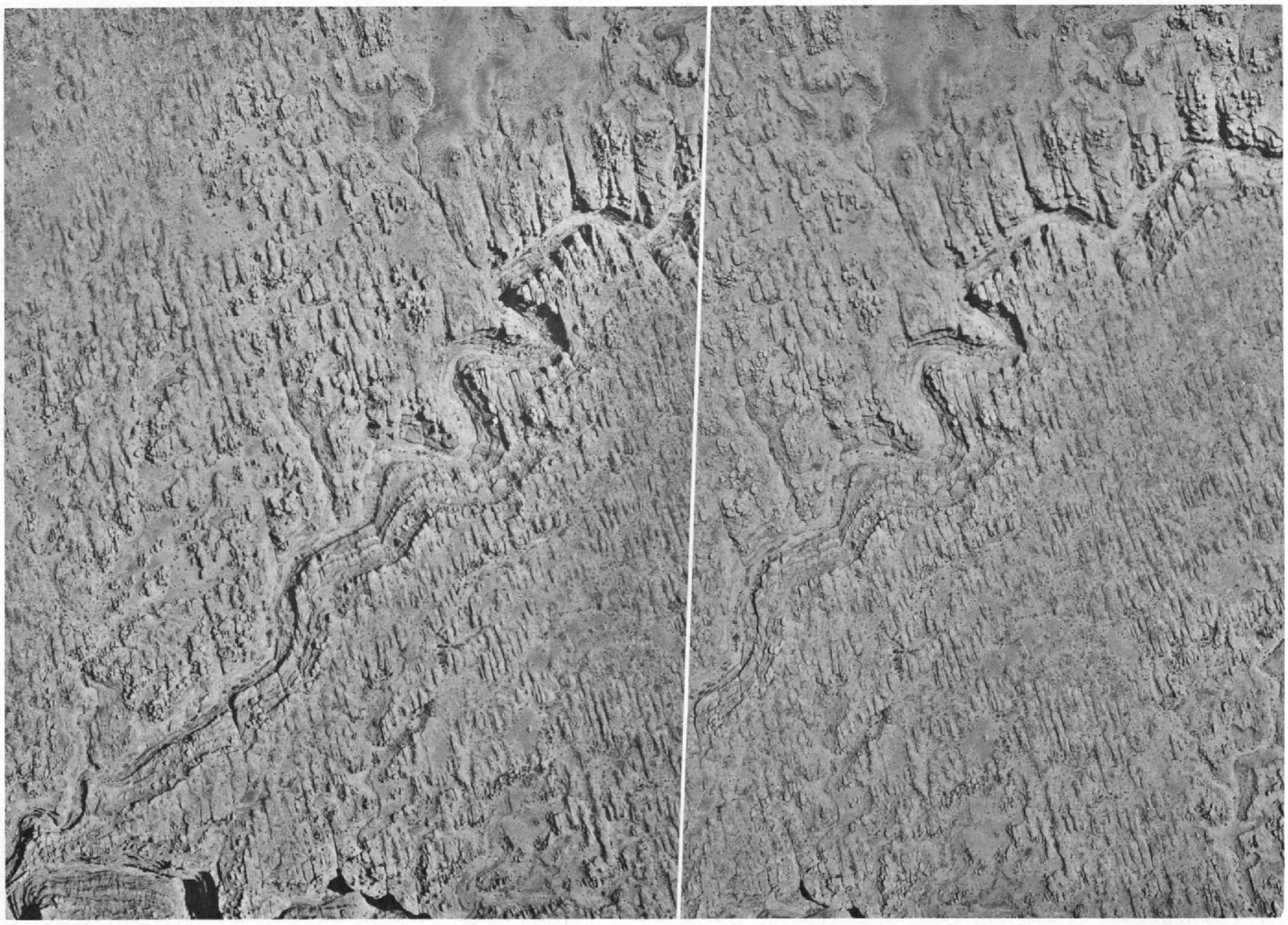
Stereoscopic pair

Approximately 1 mile

FIGURE 41.—EXTRUSIVE VOLCANIC ROCKS AND ASSOCIATED CINDER CONE (UTAH).

[Approximate scale 1 : 20,000. Photographs by Commodity Stabilization Service]

Cinder cone, *A*, is readily identified on the basis of shape of the constructional landform. Associated flows, *B*, are dark toned, irregular in ground plan, and marked by very uneven topographic surfaces. Many lava flows lack surface drainage rills, which suggests permeable material. Note especially the lack of surface drainage channels on flanks of cinder cone.



Stereoscopic pair

Approximately 1 mile

FIGURE 42.—FLAT-LYING SANDSTONE (SOUTHERN UTAH).

[Approximate scale 1 : 20,000. Photographs by U.S. Geological Survey]

Prominent wide-spaced joints are shown by many short lineations. Where beds are essentially flat lying, joints commonly form in a right-angle pattern and give the terrain a blocky appearance locally, although one direction of jointing may dominate and give a conspicuous linearity to the topographic grain. The light photographic tone and coarse-textured drainage is typical of coarse sedimentary rocks. Major drainage is dendritic; this pattern is commonly characteristic of flat-lying rocks. Minor drainage is controlled by joints.

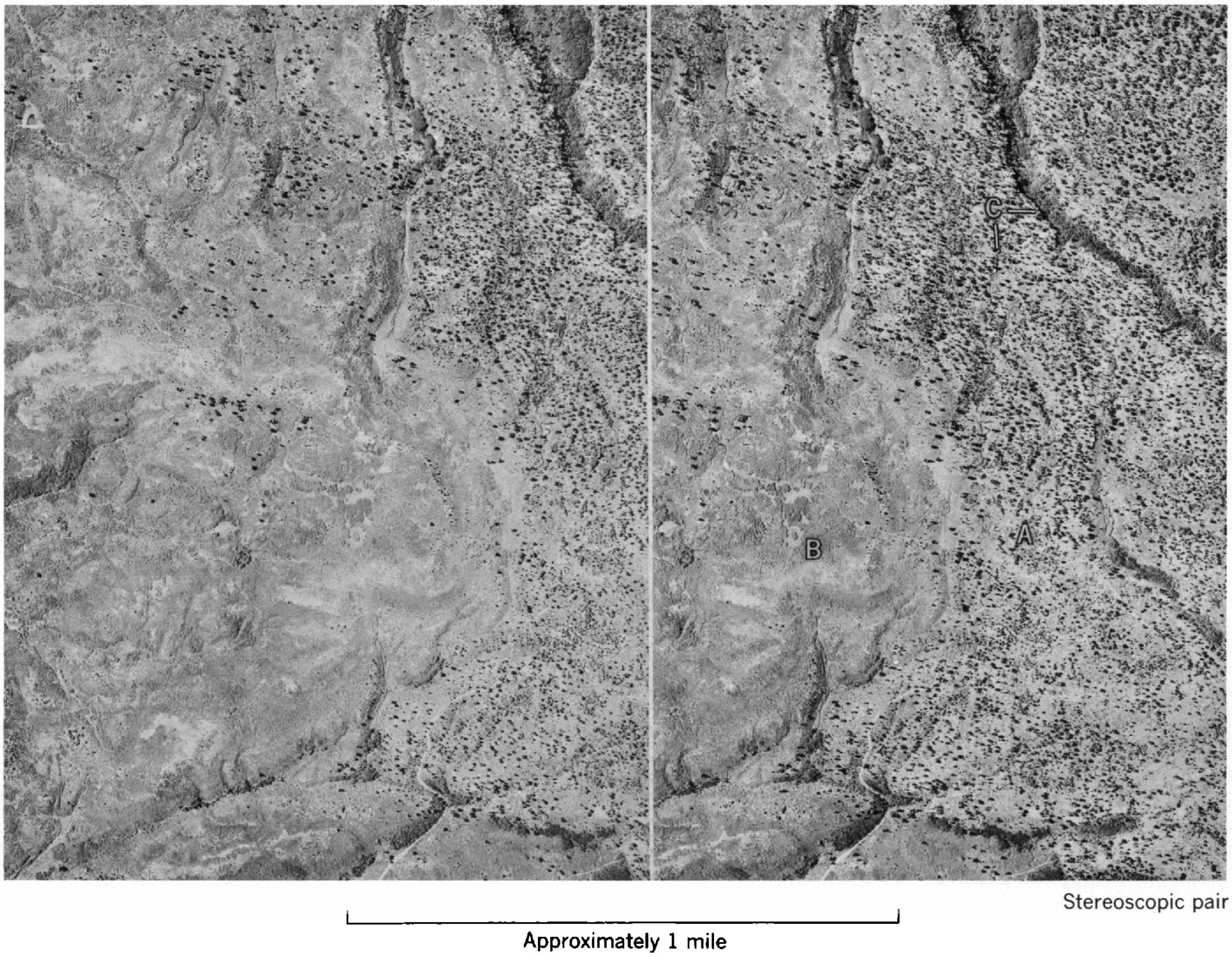


FIGURE 43.—SANDSTONE AND CONGLOMERATE BEDS INTRUDED BY DIORITE PORPHYRY LACCOLITH (UTAH).

[Approximate scale 1 : 20,000. Photographs by Commodity Stabilization Service]

Conspicuous contrast in vegetation results from different lithologic types. Sandstone and conglomerate beds, *A*, are covered largely with scattered tall jack, yellow, and ponderosa pine trees. Diorite porphyry, *B*, is covered with scrub oak as much as 10 feet high. This dense growth of scrub oak forms a photographic texture that contrasts with areas covered with pines. Note serrated edges of bluffs, *C*, which are expressions of joints in sandstone and conglomerate beds.

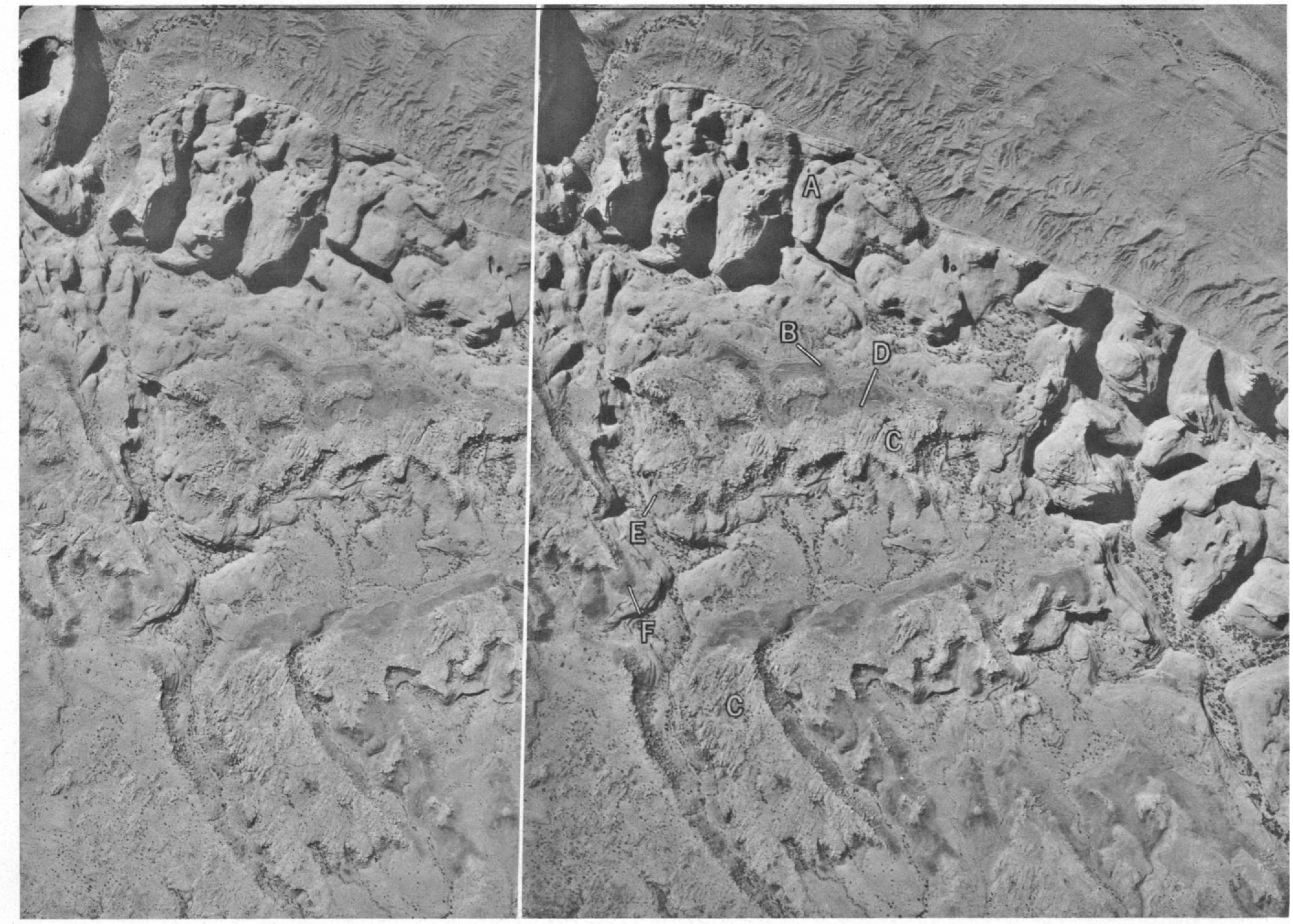


FIGURE 44.—GENTLY DIPPING BEDS OF SANDSTONE, SILTSTONE, AND CONGLOMERATE THAT LOCALLY CONTAIN CHANNEL-FILL DEPOSITS (ARIZONA).

[Approximate scale 1 : 20,000. Photographs by U.S. Geological Survey]

Light photographic tone of rocks, *A*, is typical of massive crossbedded sandstone in this area. Dark-toned rocks, *B*, are reddish thin-bedded shaly siltstone, shale, and fine-grained sandstone. Light-toned conspicuously jointed rocks, *C*, are uranium-bearing sandstone, conglomerate, and mudstone. Locally the dark-toned rocks have been eroded by channel scour, and the channels have been filled with sandstone and conglomerate that now lie unconformably on the older rocks. Erosion of dark-toned rocks along line *D*, which represents the line of unconformity and orientation of a channel in this area, is conspicuous by the photographic tone change. At *E* the dark-toned rocks have been completely eroded away and light-toned jointed sandstone and conglomerate rest on the light-toned massive crossbedded sandstone. At *F* the dark-toned rocks again become conspicuous where overlying rocks thin. Differences in stratigraphic thicknesses of the dark-toned rocks, which reflect a thickening of overlying rocks that were deposited in old river channels, can be measured photogrammetrically. Isopach lines may be drawn to indicate the orientation of the channel and the general depth of the channel.

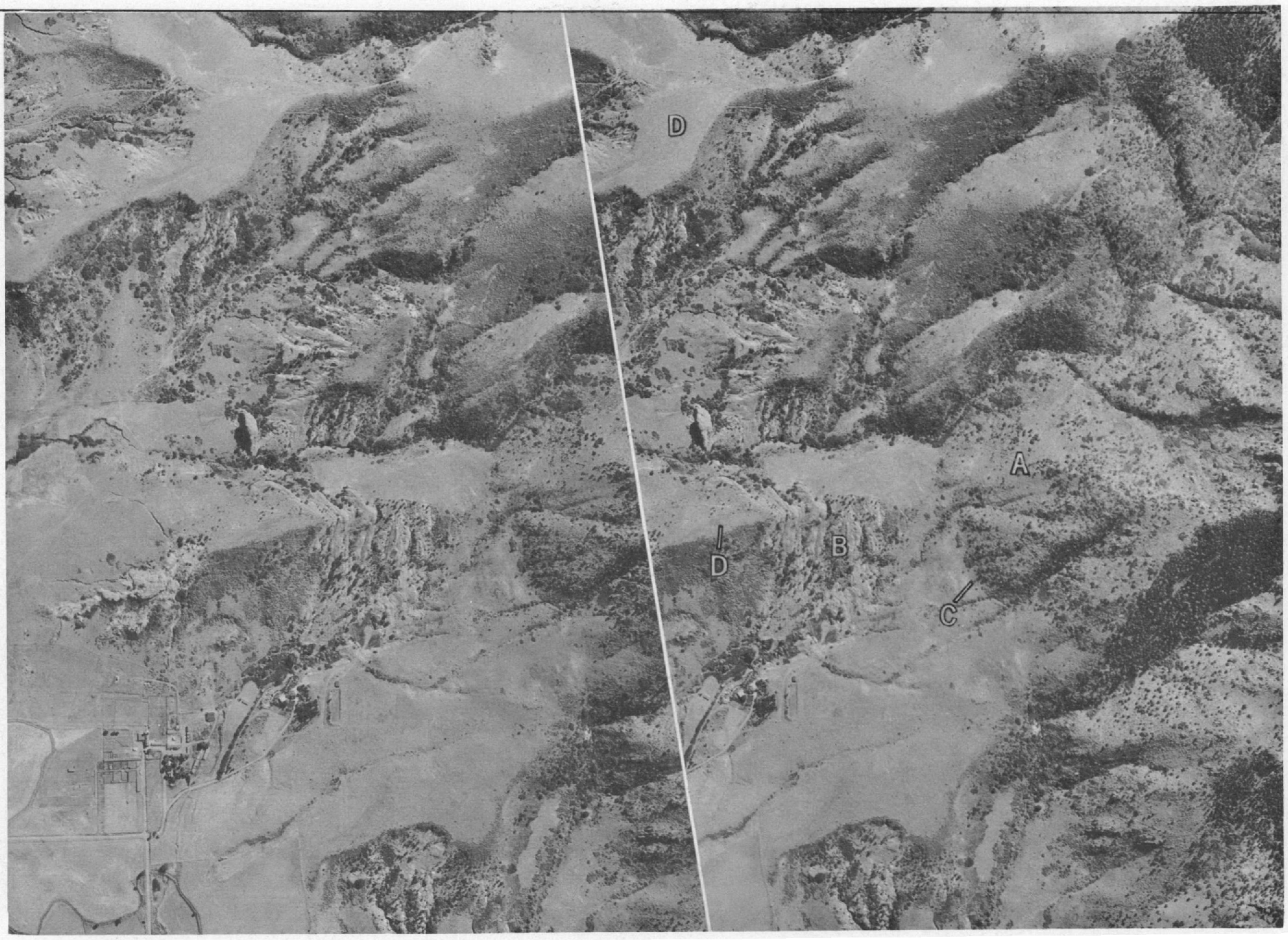


FIGURE 45.—GNEISS, SCHIST, AND GRANITE FLANKED BY DIPPING SEDIMENTARY ROCKS TRUNCATED BY PEDIMENT GRAVEL (COLORADO).

[Approximate scale 1 : 21,000. Photographs by U.S. Air Force]

Topographically high, vegetated area, *A*, is underlain by gneiss, schist, and granite. Light-toned sedimentary rocks, *B*, lying unconformably on the igneous and metamorphic rocks, are primarily arkose and sandstone. Trace of unconformity between sedimentary rocks and igneous and metamorphic rocks is indicated by break in slope, *C*, which is locally accentuated by contrast of trees on steep slope uphill from the trace of the unconformity with grassy vegetation on the gentler slope below. Note effect on dip of vertical exaggeration in the stereoscopic model. The arkose and sandstone unit dips about 25°. The grass-covered pediment gravel, *D*, which truncates the underlying sedimentary rocks, dips 2° to 3°.

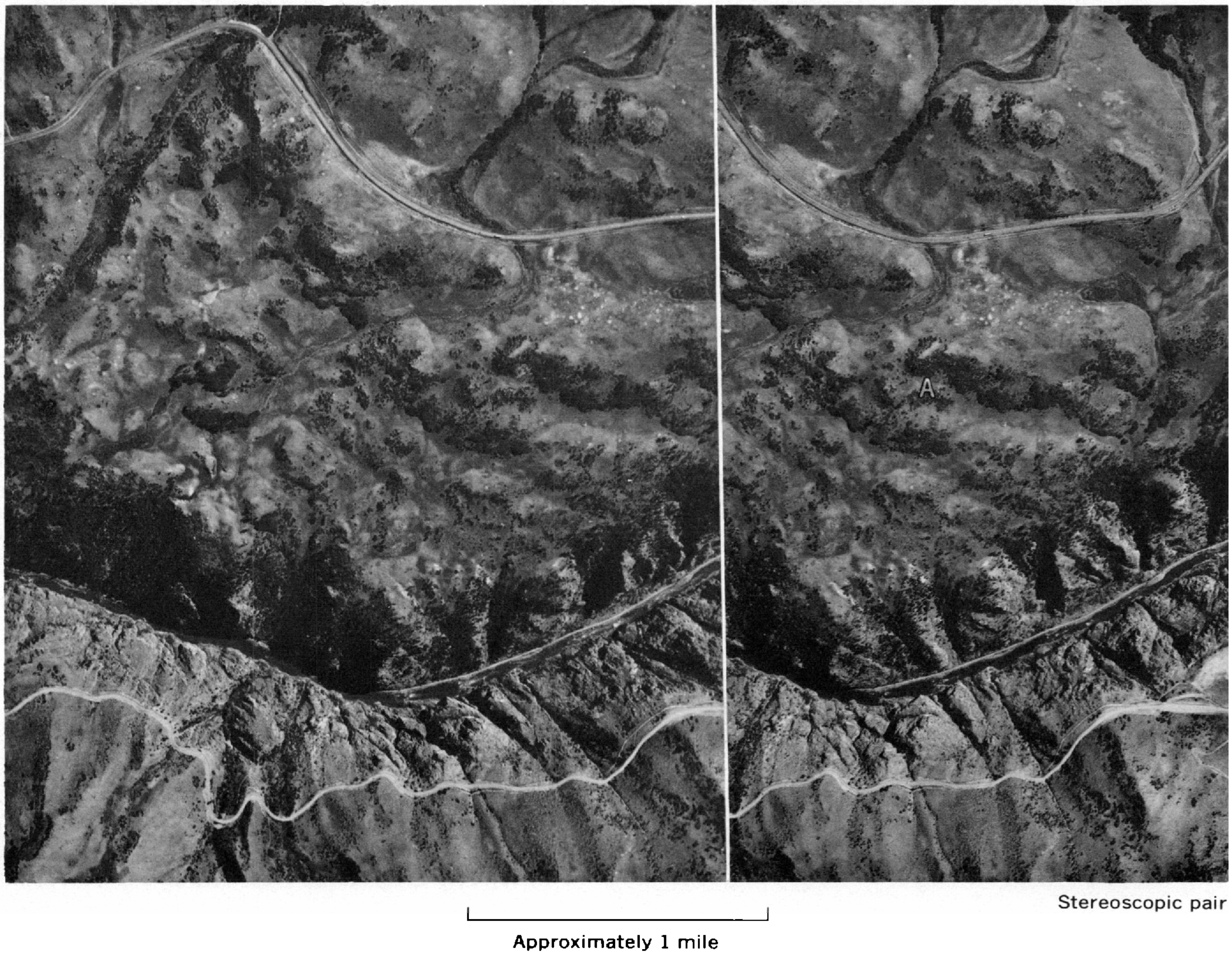


FIGURE 46.—LANDSLIDE AREA (COLORADO).

[Approximate scale 1 : 37,000. Photographs by U.S. Geological Survey]

Landslides are indicated primarily by landform. Note the characteristic hummocky topography of slide material prominent at *A*. Minor ridges of the slide area are commonly parallel to the contour of the slope; clumps of vegetation locally are oriented parallel to the contour of the slope also. Poorly resistant sedimentary rocks underlie the landslide debris; resistant volcanic flows (not shown) cap the sedimentary rocks. In many areas where poorly resistant rocks underlie a resistant caprock, conditions for landsliding are favorable. Highly fractured rocks in canyon are schist and gneiss.

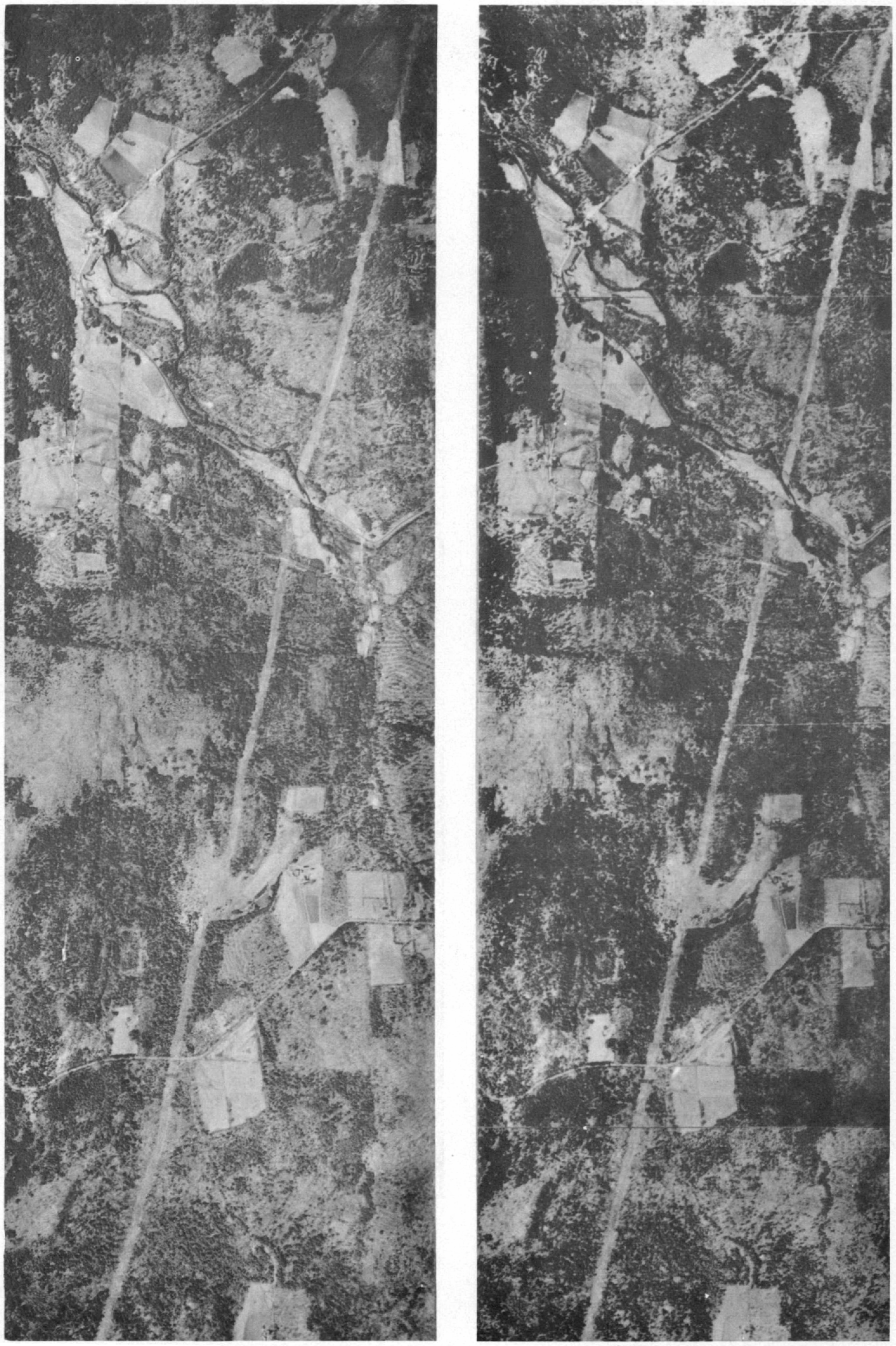
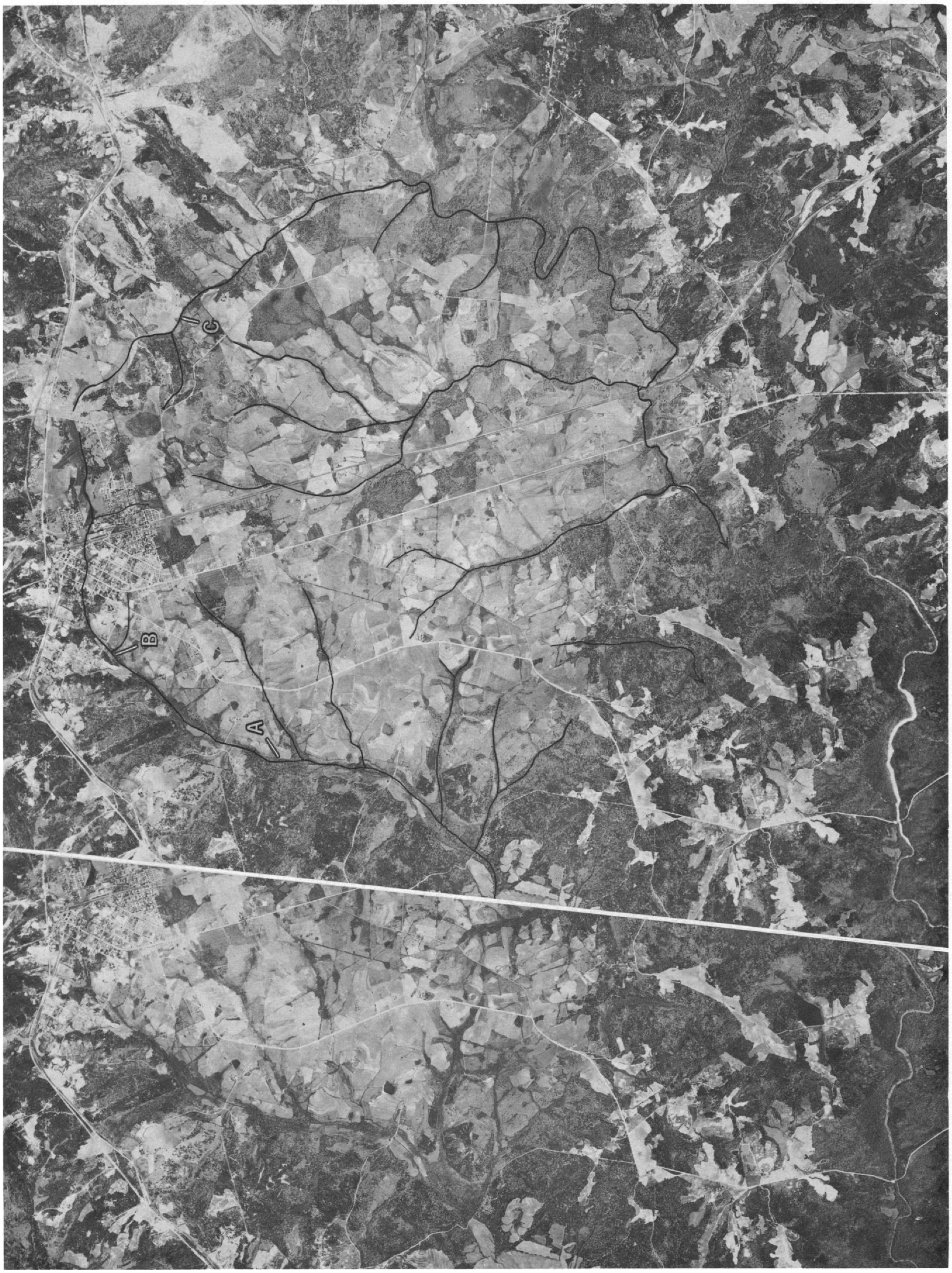


FIGURE 47.—ORTHOPHOTOGRAPH AND PERSPECTIVE PHOTOGRAPH OF SAME AREA.

(Left) Part of perspective aerial photograph showing distortions in powerline caused by relief displacement of image points. (Right) Orthophotograph of the same area showing that relief displacement has been eliminated in preparing orthophotograph. Note that the powerline is straight.



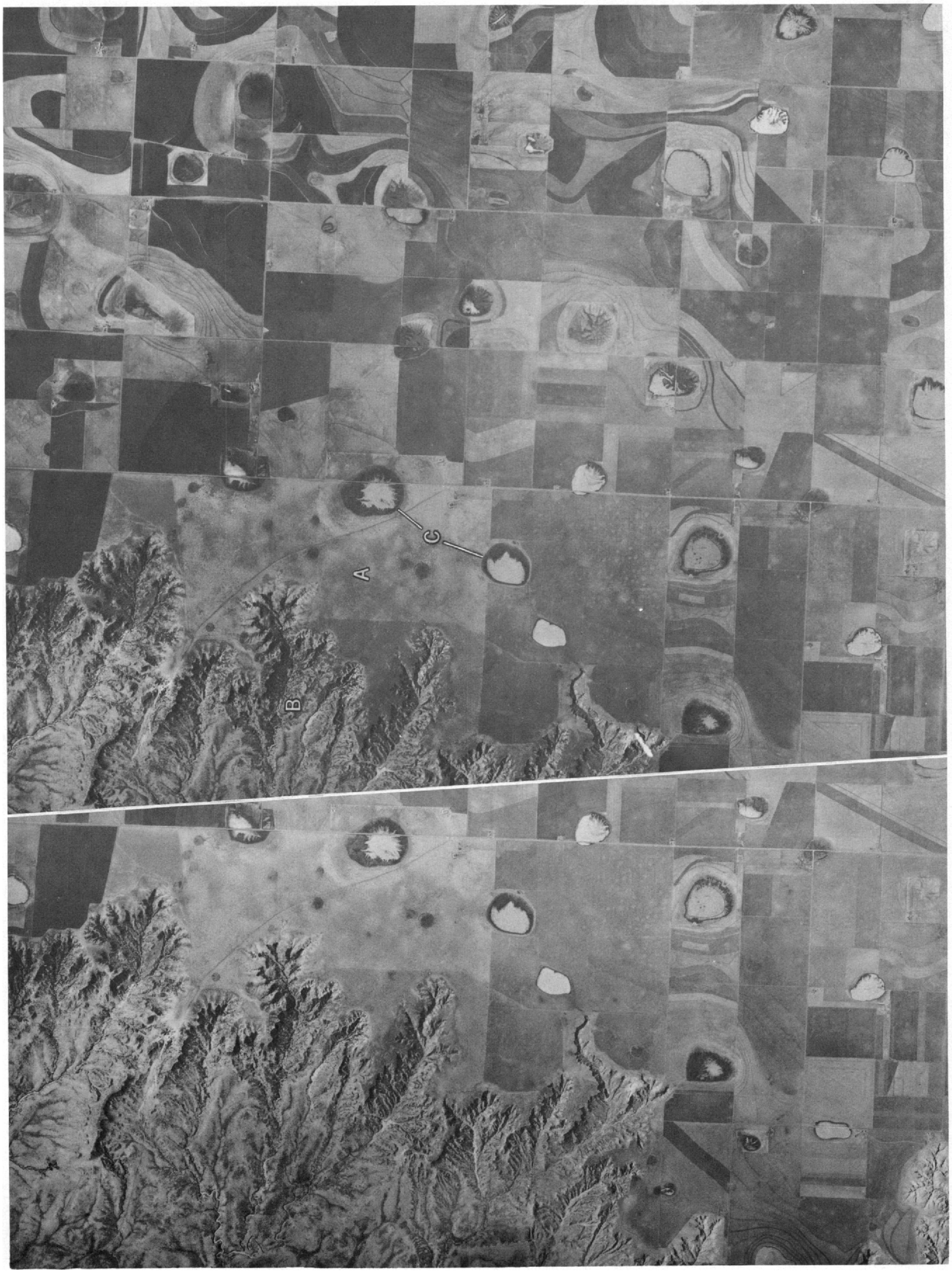
Stereoscopic pair

Approximately 1 mile

FIGURE 48.—AREA SHOWING RELATION OF PHOTOGRAPHIC TONE, LAND-USE PATTERN, AND DRAINAGE TO RESIDUAL SOIL, ROCK TYPE, AND GEOLOGIC STRUCTURE (SOUTH CAROLINA).

[Approximate scale 1 : 60,000. Photographs by Army Map Service]

Aerial photographs commonly show an association of features that is meaningful to the interpreter. Here photographic tones, land-use pattern, and drainage pattern are associated with specific soils, rock types, and geologic structure. Note that the small scale of the photographs is a significant factor in showing the striking land-use pattern and drainage pattern (see also fig. 4). The circular land-use pattern of the farmed area generally bounded by vegetated areas, as at *A*, represents soils developed on underlying mafic rocks. Rocks in the immediately surrounding vegetated areas are largely silicic intrusive types. The drainage characteristics of the area also suggest a pluglike or domal geologic structure. Streams at *B* and *C* form a conspicuous annular pattern around the area of mafic rocks and probably mark the contact of the mafic rock body.



Stereoscopic pair

Approximately 1 mile

FIGURE 49.—SHALE AND THIN SANDSTONE INTERBEDS CAPPED BY POORLY CONSOLIDATED GRAVEL AND SAND, LOCALLY CEMENTED WITH CALCAREOUS MATERIAL (TEXAS).

[Approximate scale 1 : 63,360. Photographs by Army Map Service]

Lack of surface drainage at *A* indicates high degree of permeability in capping material. Note in contrast the striking fine-textured drainage on the relatively impermeable shale area, *B*. Broad depressions, *C*, in capping gravel and sand are very shallow and show little relief even with vertical exaggeration found in the stereoscopic model. These depressions resulted in large part from wind action; some solution of local calcareous cementing material also may have taken place. Dark areas within depressions represent a darker vegetation growth; light-toned areas represent in part washed-in fine materials that were dry and hence light colored at the time the photographs were taken. Locally some light-toned evaporite deposits may be present.


Stereoscopic pair
Approximately 1 mile
A
A
B
B
C
D
E
F

782-139 O - 65 - 9

Figure 50.—RECENTLY FAULTED STRAND LINES OF FORMER LAKE (NEVADA).

[Approximate scale 1 : 20,000. Photographs by Soil Conservation Service]

Strand lines of beach sand, *A*, are shown strikingly by dark photographic tone and slightly higher altitudes than surrounding surficial material. Note that strand lines are truncated by a recent fault, *B*, shown by narrow band of dark vegetation and by low scarp. Drainage density is relatively high on the thin alluvial cover, *C*, but decreases noticeably on opposite side, *D*, of fault where better drained, thicker deposits of alluvial material are present. Strand line is faulted up about 25 feet at *E* by recent fault movement. An irregular fault trace is also seen at *F*.

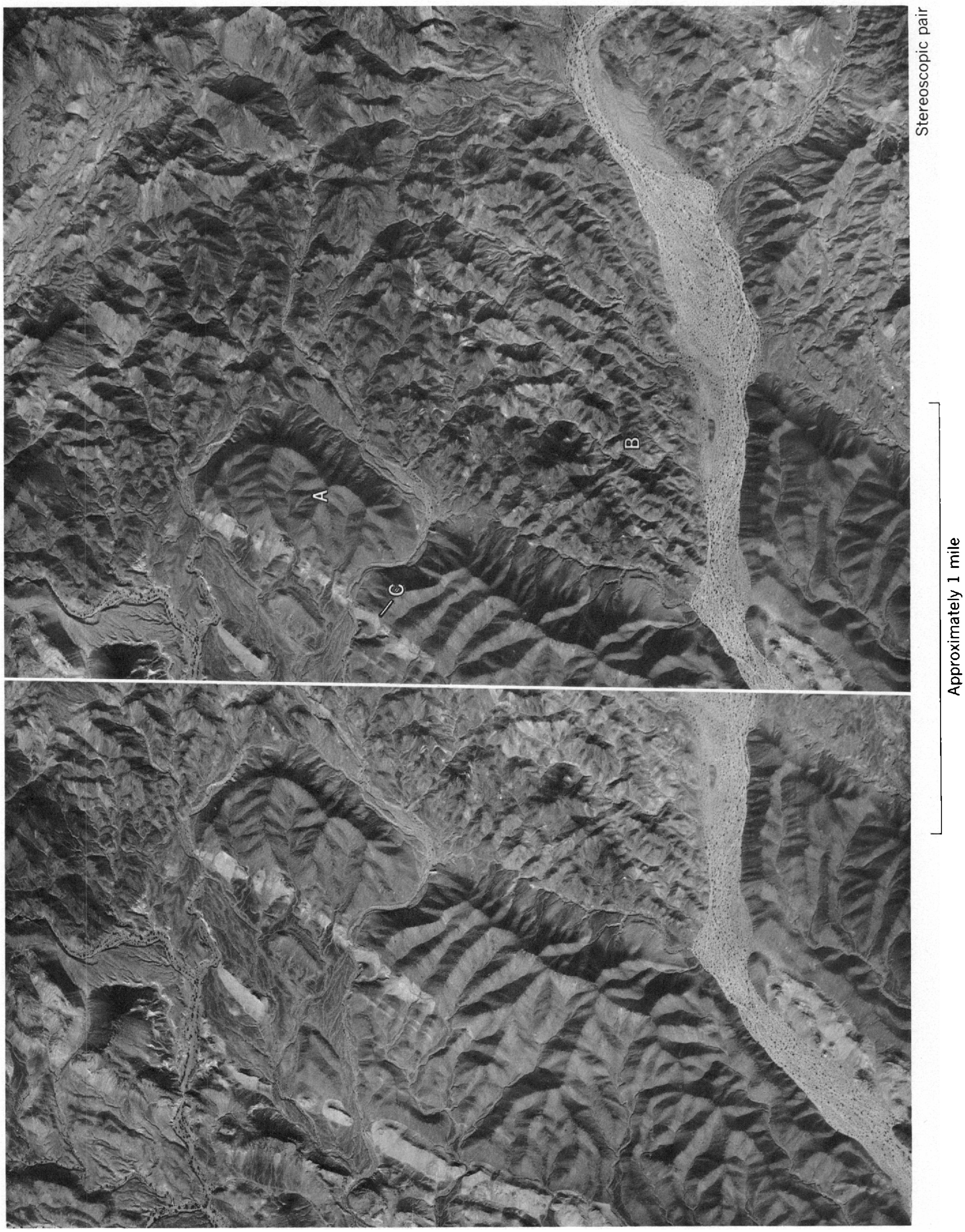
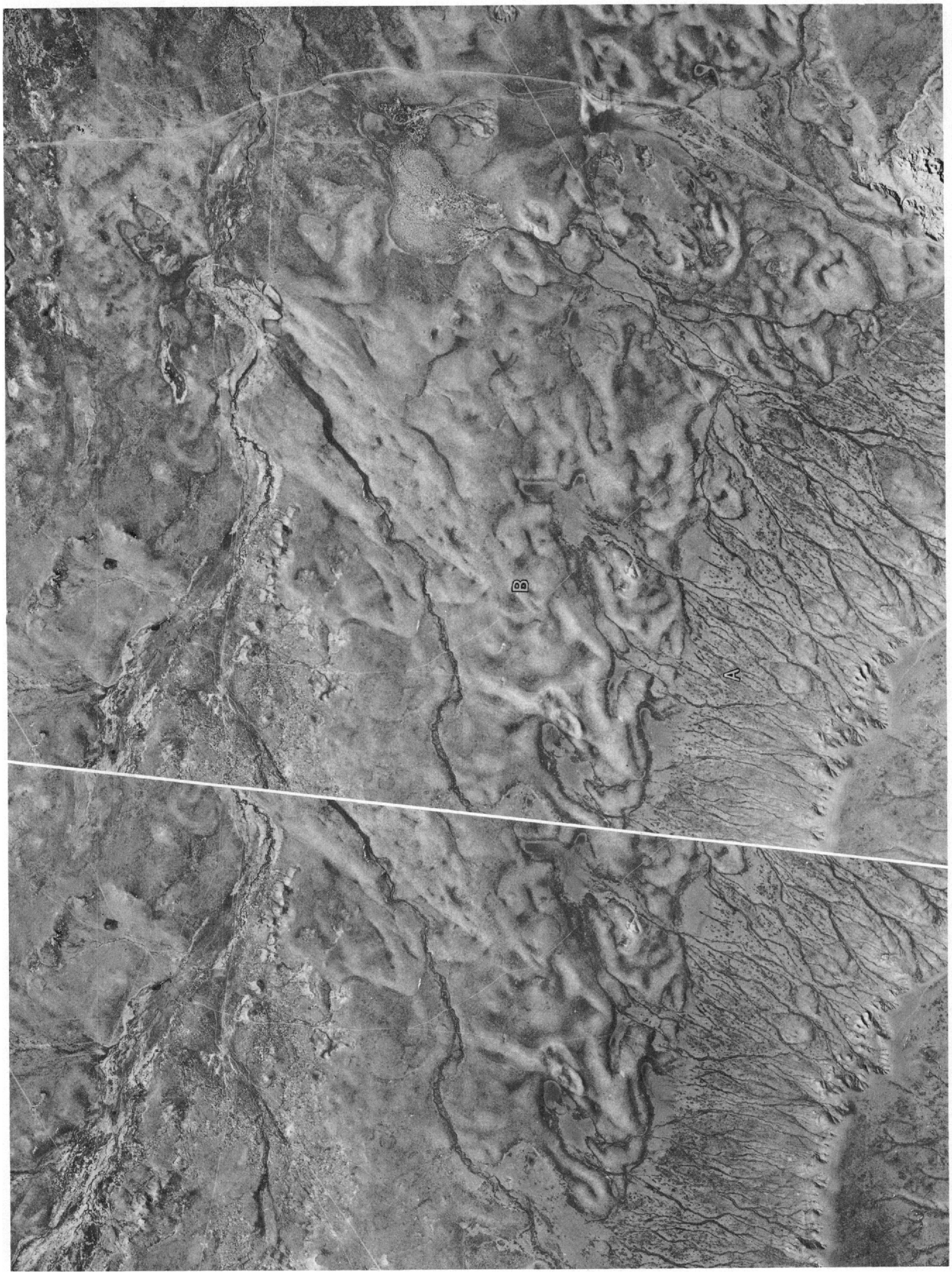

Stereoscopic pair
A
B
C
Approximately 1 mile

FIGURE 51.—STEEPLY DIPPING SEDIMENTARY ROCKS INTRUDED BY QUARTZ DIORITE (CALIFORNIA).

[Approximate scale 1 : 20,000. Photographs by U.S. Geological Survey]

Generally massive dark-toned conglomerate sequence, *A*, exhibits coarse-textured drainage and erosional characteristics, whereas fine-grained weakly foliated quartz diorite, *B*, has a fine-textured drainage and erosional topography. Widely spaced joints, conspicuous in many intrusive masses, are not present in the quartz diorite. Dendritic drainage in the conglomerate sequence is not typical of most dipping sedimentary rocks; the dendritic drainage pattern suggests a massive character and uniformity of the conglomerate sequence and general lack of bedding which might control the drainage. Local light-toned interbeds, *C*, indicate strike and dip of the sedimentary rock sequence.



Stereoscopic pair

Approximately 1 mile

FIGURE 52.—AREA SHOWING DRAINAGE CHARACTERISTICS IN SURFICIAL MATERIALS (WYOMING).

[Approximate scale 1 : 28,000. Photographs by U.S. Geological Survey]

Strong contrast in drainage densities of areas *A* and *B* reflect differences in underlying materials. Fine-grained surficial sedimentary deposits, *A*, that form a thin cover on impermeable shale here exhibit fine-textured drainage. The many drainage rills flowing across the fine-grained surficial material disappear into sand dune area, *B*, which is composed of granular material of high permeability. Although partly stabilized and covered by vegetation the sand dunes locally show barchan shapes, which aid in their identification.

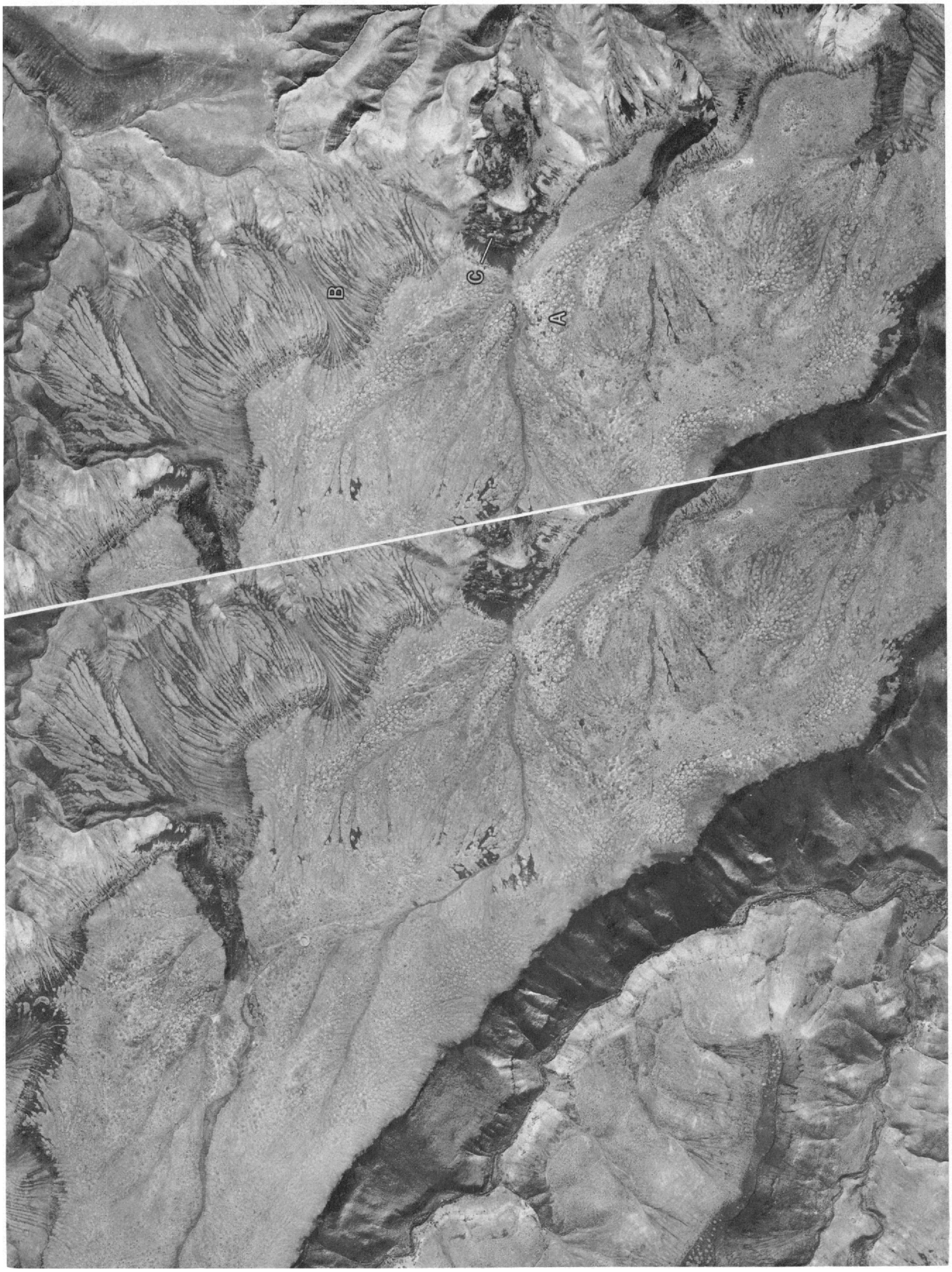
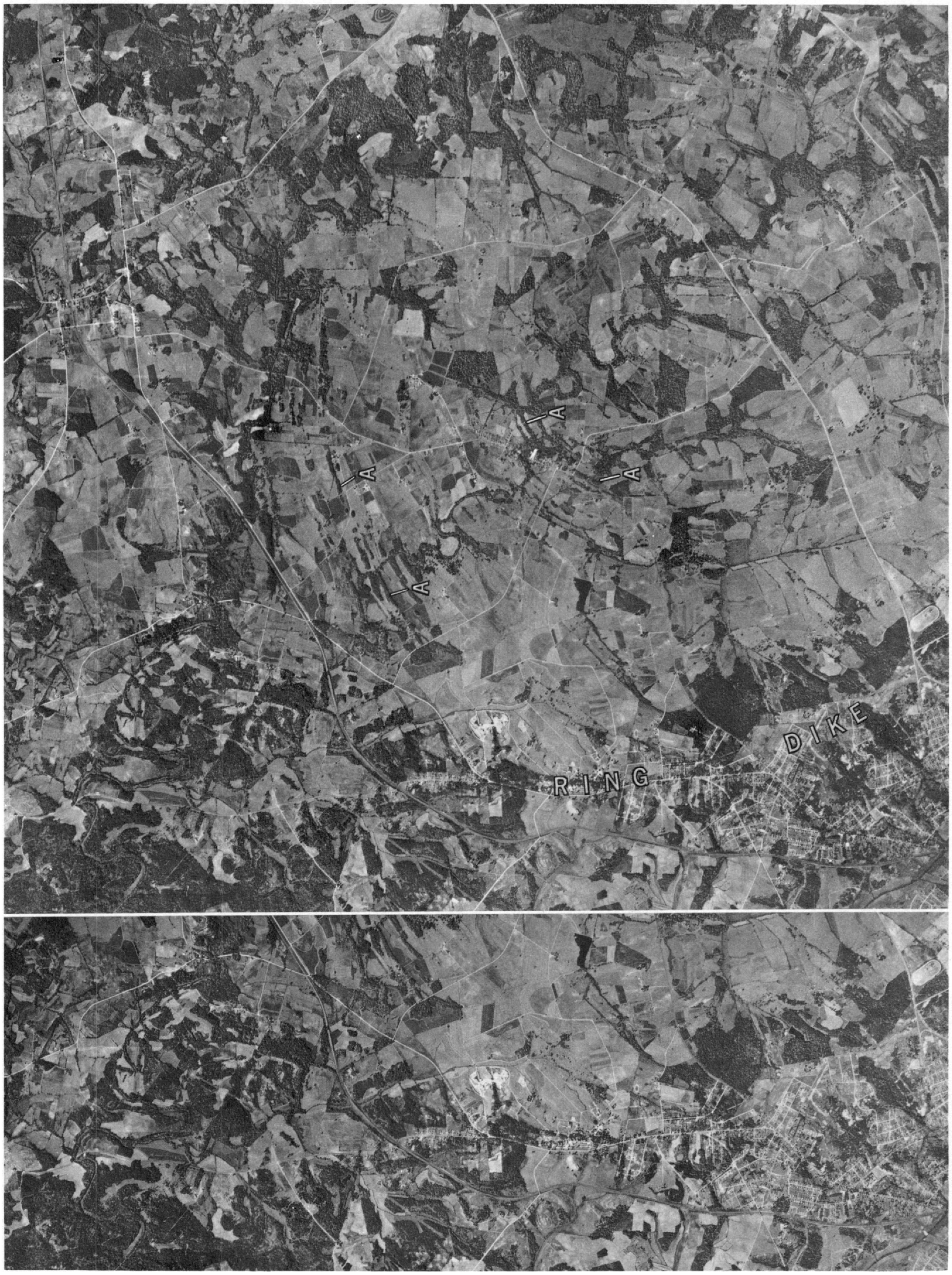

A
B
C
Stereoscopic pair
Approximately 1 mile

Figure 53.—AREA OF BASALT FLOWS (IDAHO).

[Approximate scale 1 : 20,000. Photographs by Commodity Stabilization Service]

Conspicuous "snakeskin" pattern is commonly found on the undissected basalt flows, *A*; it is not observed on other rock types in this area. The pattern consists of white or light-toned spots scattered in a dark field. Note that a rounded "shape" is a distinctive part of the pattern. The light-toned rounded areas are mounds of clay and silt 20 feet or more across and 2 or 3 feet high. Grass grows on these areas and causes the light photographic tone; the basalt is typically barren or covered with sagebrush and has a dark photographic tone. The striped pattern of closely spaced drainage rills, *B*, is also typical of basalt talus slopes in this area; however, similar-appearing stripes are found on a variety of rock types in other areas (see fig. 40). Where basalt cappings are underlain by poorly resistant rocks, conditions are favorable for landslides, as at *C*.



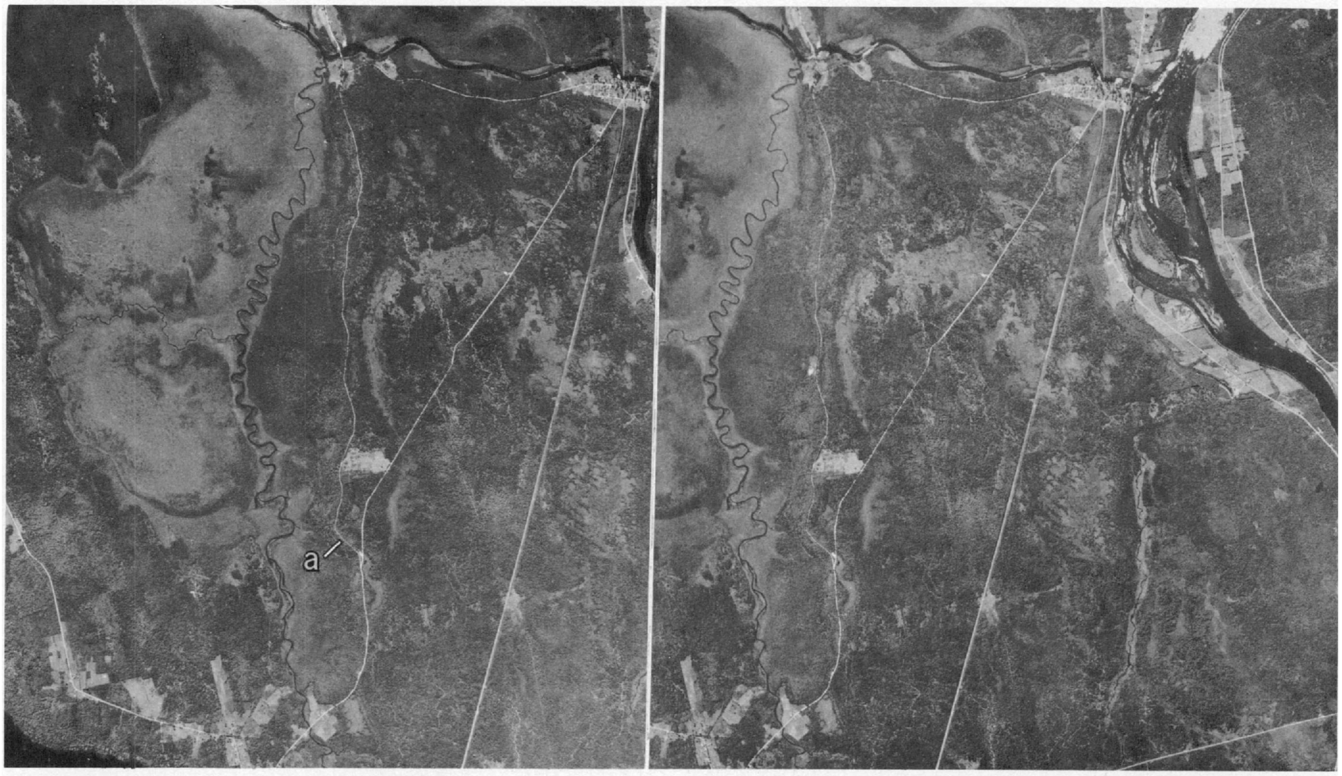
Stereoscopic pair

Approximately 1 mile

Figure 54.—RING-DIKE AREA (NORTH CAROLINA).

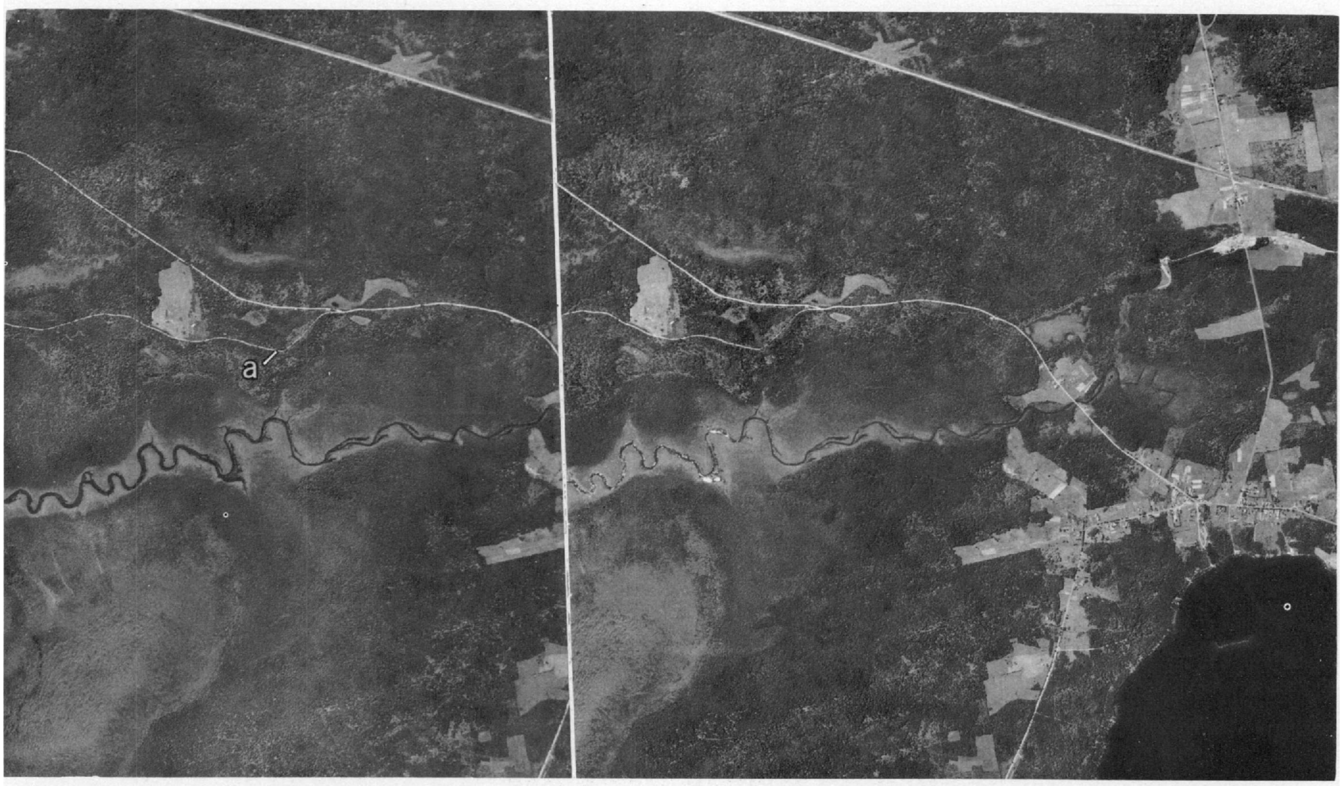
[Approximate scale 1 : 58,000. Photographs by Army Map Service]

Ring dike about 1 mile wide and an area of gabbro-diorite within the ring dike can be differentiated from surrounding areas primarily on the basis of the lesser tree coverage and greater land use within the ring-dike area. A ring structure is also suggested by the concentric pattern of trees, *A*, which may reflect structure within the igneous rocks. The contact of syenite of the ring dike and gabbro-diorite of surrounding areas cannot be identified in the stereoscopic model, and aerial photographs of this terrain serve primarily to differentiate anomalous features which then must be examined in the field. Note excavation in syenite of the ring dike.



A Stereoscopic pair

Approximately 1 mile



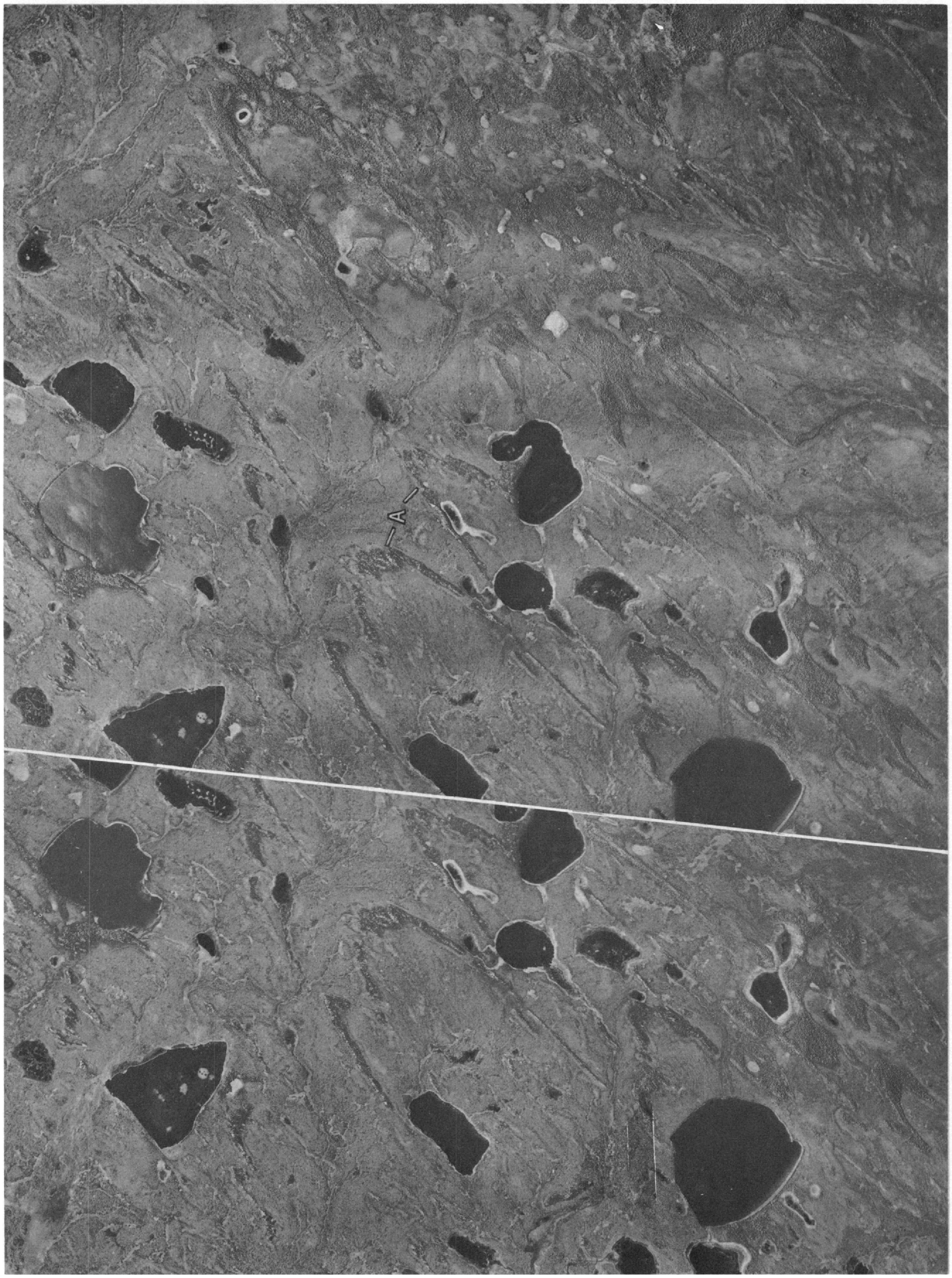
B Stereoscopic pair

Approximately 1 mile

FIGURE 55.—AREA IN MAINE SHOWING ESKER LANDFORM ON PHOTOGRAPHS OF TWO DIFFERENT SCALES.

[*A:* Approximate scale 1 : 70,000. Photographs by Army Map Service]
[*B:* Approximate scale 1 : 44,000. Photographs by U.S. Geological Survey]

The serpentine shape in plan view and local topographic relief of the esker are readily distinguished in the stereoscopic view of figure *A*. The esker ridge is discontinuous, but the various segments are clearly part of the same ridge. The association of isolated ridge segments is readily made when small-scale photographs showing a large area are viewed. Landform is the primary recognition feature of esker ridges. In figure *B* the esker landform is not as readily identified as in figure *A*, and on commonly available 1:20,000-scale photographs the serpentine shape would probably not be seen in any one stereoscopic model. Esker sands and gravels are commonly well drained and are a source of borrow material for the construction engineer. Note old secondary road, *a*, built along the top of the esker, probably because of good subgrade and drainage.



Stereoscopic pair

Approximately 1 mile

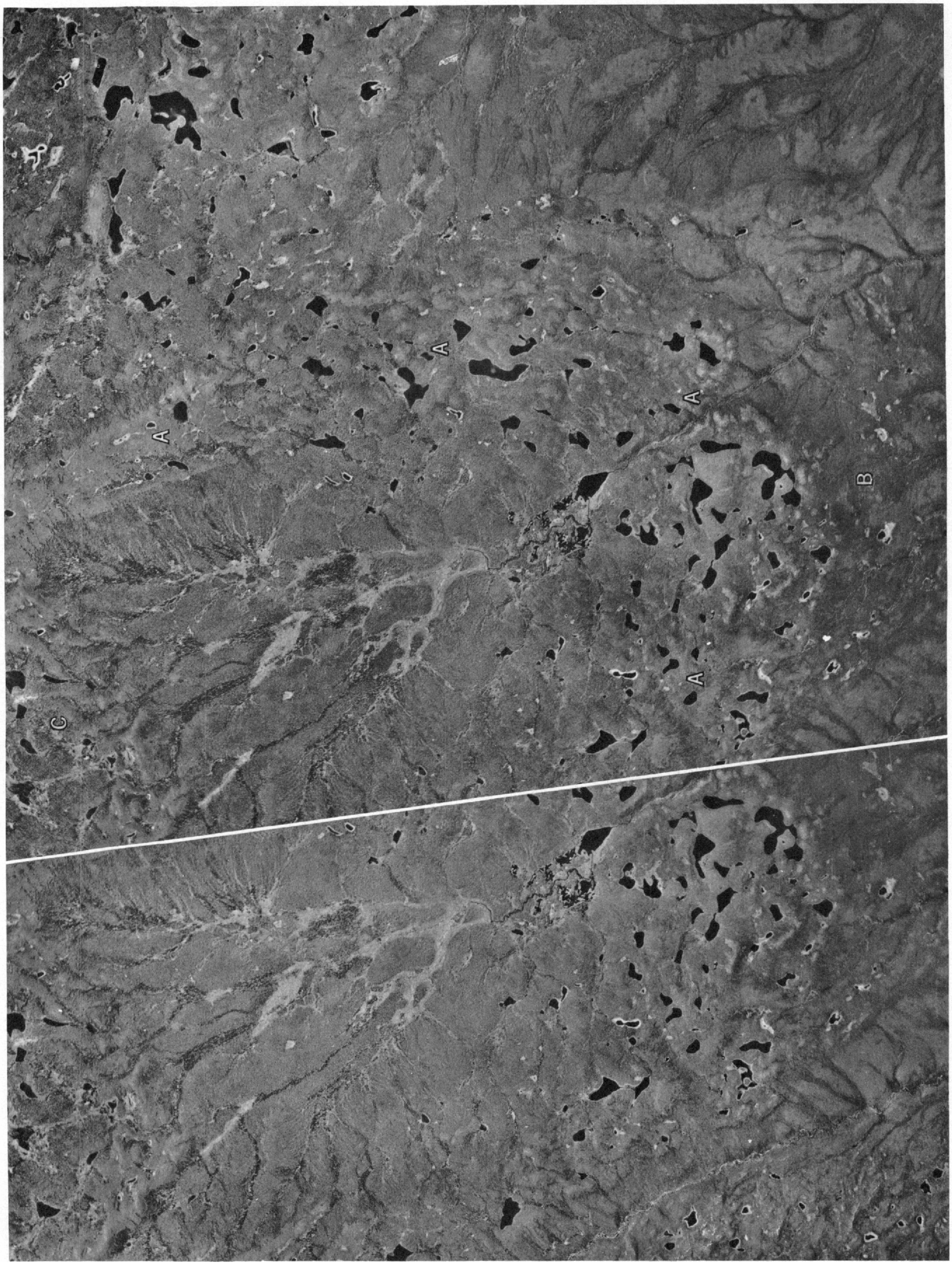
782-139 O - 65 - 10

FIGURE 56.—STABILIZED SAND DUNES (CENTRAL ALASKA).

[Approximate scale 1 : 40,000. Photographs by U.S. Air Force]

Strong contrasts in photographic tone and photographic texture mark sand dunes and interdune areas. Dunes, as at *A*, are now stabilized and covered with trees. Coarse well-drained sands of the dunes support dark-toned black spruce. Light-toned interdune areas of frozen silt support grasses. Lakes were formed on the original glacial outwash plain, which was the source of sand for dune formation. The shape of the dune landform is an important aid to recognition, and the association of trees is significant in the interpretation of the soils and ground conditions. Relief of the dunes is vertically exaggerated in the stereoscopic model.

Stereoscopic pair



Approximately 1 mile

FIGURE 57.—MORAINAL DEPOSITS OF TWO GLACIATIONS (CENTRAL ALASKA).

[Approximate scale 1 : 40,000. Photographs by U.S. Air Force]

Arcuate plan-view shape of terminal moraine, *A*, is marked by a lighter photographic tone than that of the surrounding area. This moraine is characterized by an abundance of small undrained lakes and ponds and by poorly integrated drainage. In older terminal moraine, *B*, lakes and ponds are largely drained, but arcuate plan of this moraine is still preserved. Terminal moraine, *C*, represents an advance only slightly younger than *A*. Note similarity of topographic expression and development of ponds and lakes in moraines *A* and *C*.

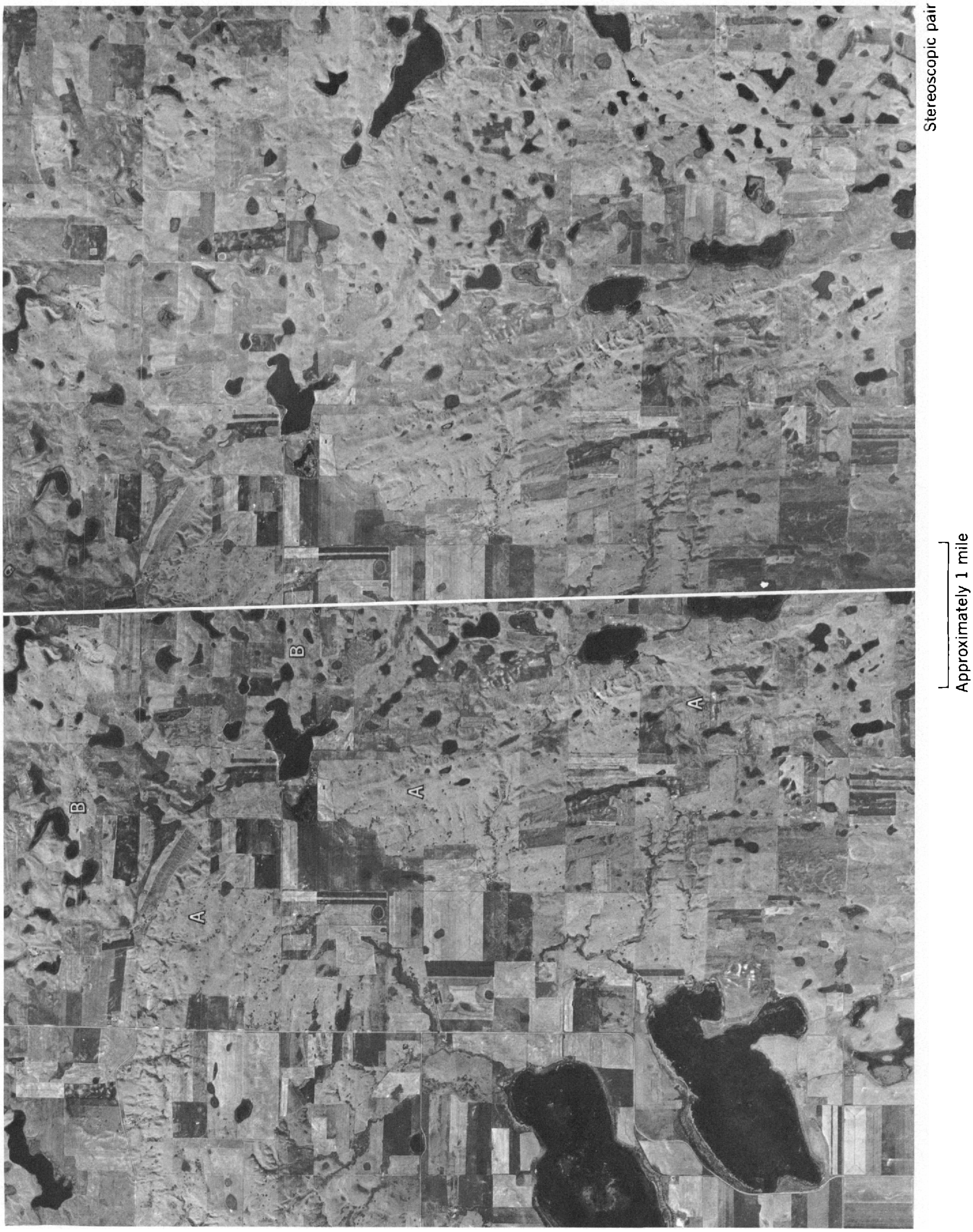
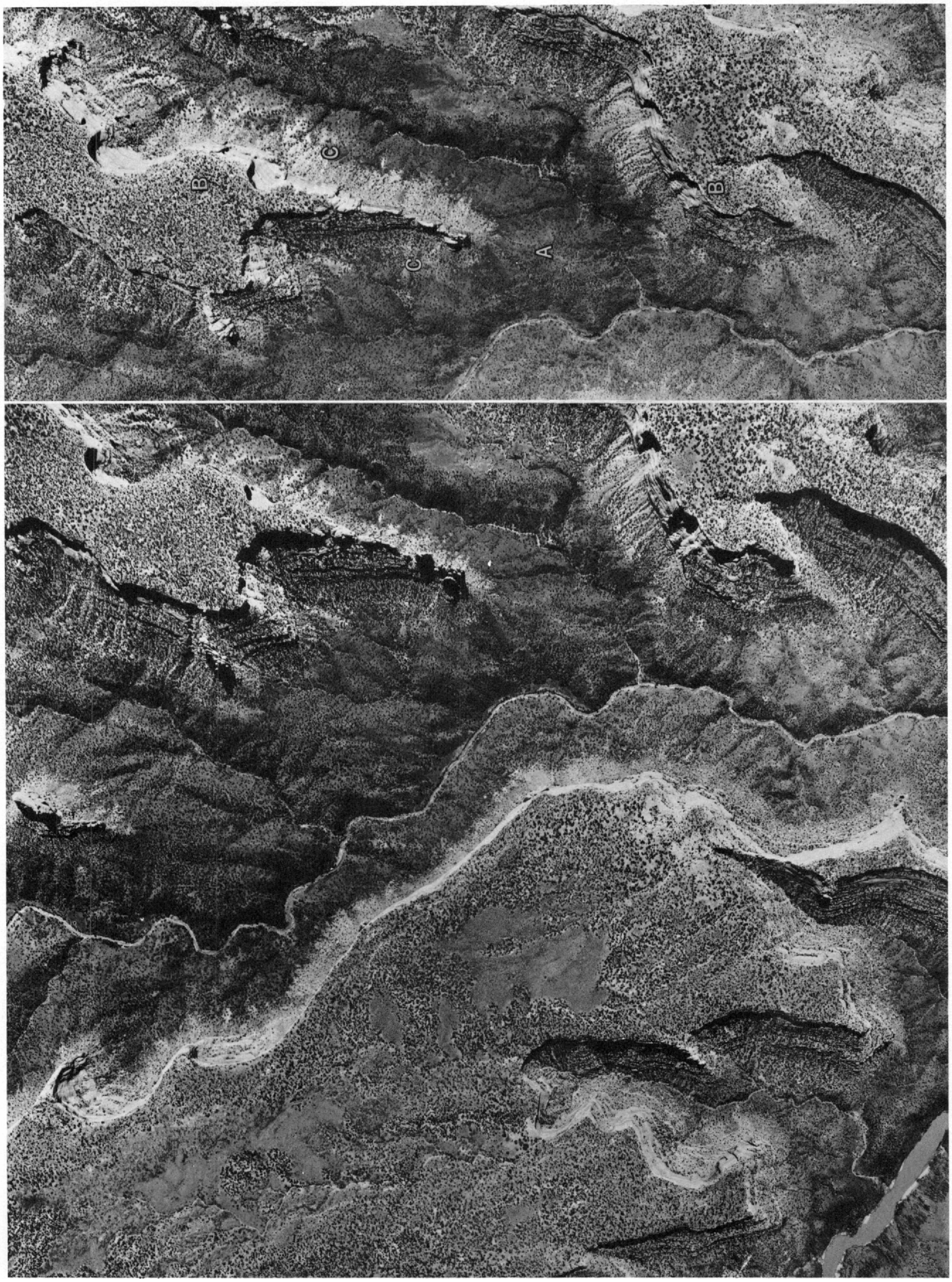

Stereoscopic pair
Approximately 1 mile
A
B
A
B
A

FIGURE 58.—MORAINAL DEPOSITS OF CONTINENTAL GLACIATION (SOUTH DAKOTA).

[Approximate scale 1 : 60,000. Photographs by Army Map Service]

Terminal moraine, *A*, contains generally few lakes and ponds in contrast with older ground moraine, *B*, in which water-filled kettle holes are numerous. Arcuate plan-view shape and higher relief than surrounding ground moraine are typical of the terminal moraine. Note drainage rills developed on parts of topographically high terminal moraine, but general lack of well-developed surface drainage in ground-moraine areas. Ponding also indicates poor drainage in this area. Linear trends parallel to arcuate border of terminal moraine—which represent depositional and erosional characteristics—are similar to some linear trends indicative of faults in other areas.



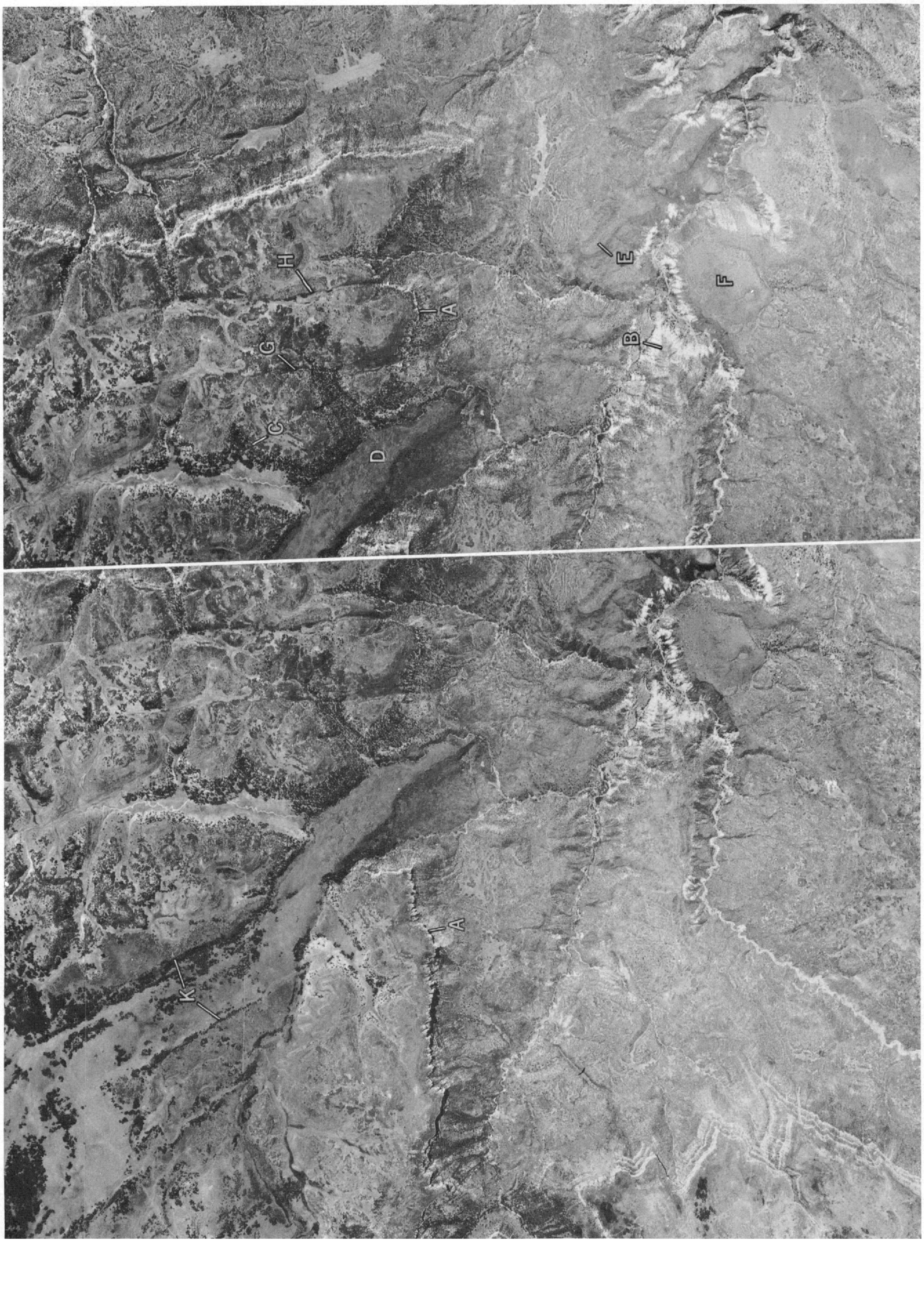
Stereoscopic pair

Approximately 1 mile

FIGURE 59.—GENTLY DIPPING SEDIMENTARY ROCKS LYING UNCONFORMABLY ON GNEISS-GRANITE-SCHIST COMPLEX (UTAH).

[Approximate scale 1 : 20,000. Photographs by U.S. Geological Survey]

Strong photographic tone differences mark the gneiss-granite-schist area, *A*, and the sedimentary rocks, *B*. Relatively even dip-slope surfaces of sedimentary rocks contrast strongly with hummocky erosional topography of underlying crystalline rocks. The fine-textured dendritic drainage on the crystalline rocks stands out, although such fine-textured drainage is not necessarily diagnostic or typical of igneous and metamorphic areas. The gneiss-granite-schist area shows no bedding, but bedding is marked in the overlying sedimentary rocks by topographic breaks in slope. Light photographic tone and vertical cliffs are characteristic of thick sandstone formation in this area. Large talus blocks, at base of slope, *C*, indicate massive and resistant character of overlying rocks. Shale and silty shale unit below sandstone has a lesser angle of slope, but this slope is masked in part by debris from overlying sandstone.



Stereoscopic pair

Approximately 1 mile

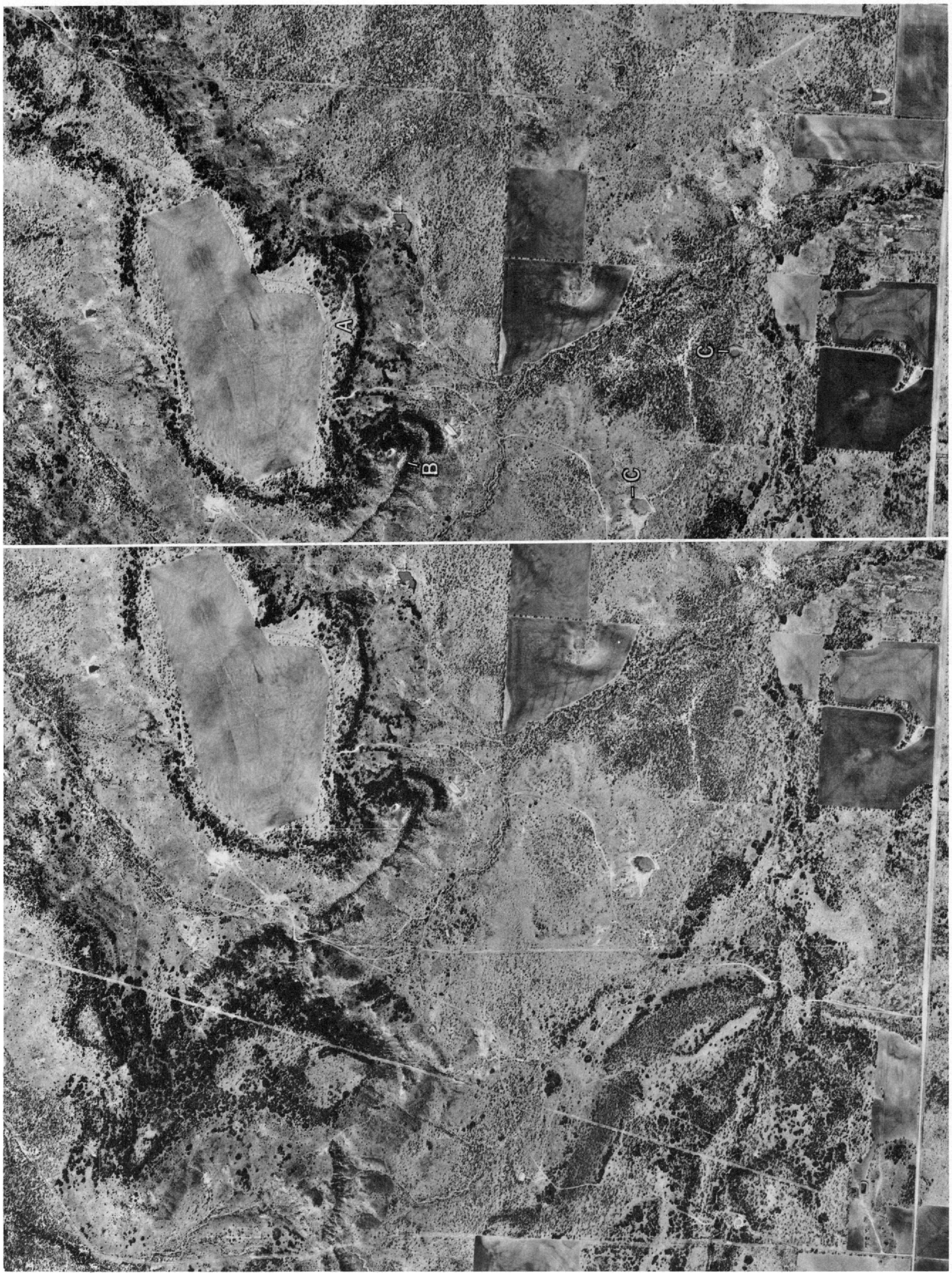
Figure 60.—GENTLY DIPPING SEDIMENTARY ROCKS CUT BY NUMEROUS NEAR-VERTICAL FAULTS (UTAH).

[Approximate scale 1 : 63,360. Photographs by Army Map Service]

Sedimentary rocks are indicated particularly by topographic expression. Jointed, resistant sandstone beds stand in bold cliffs, *A*. Soft rocks have lesser angles of slope. Strong photographic tone differences mark contacts of some rock units, as at *B*; locally vegetation changes are suggestive of different rock types, *C*.

Lava flow, *D*, cuts discordantly across formational contacts. Remnant lava flow at *E* appears to have been continuous with flow at *D*. Small cinder cone, *F*, demonstrates use of shape as a recognition element of constructional landforms.

Faults are commonly marked by conspicuous topographic alinements (*G*, *H*). Throw on fault *G* is about 100 feet; on *H* the throw is about 150 feet. Note narrow alinements of vegetation marking faults, *K*.



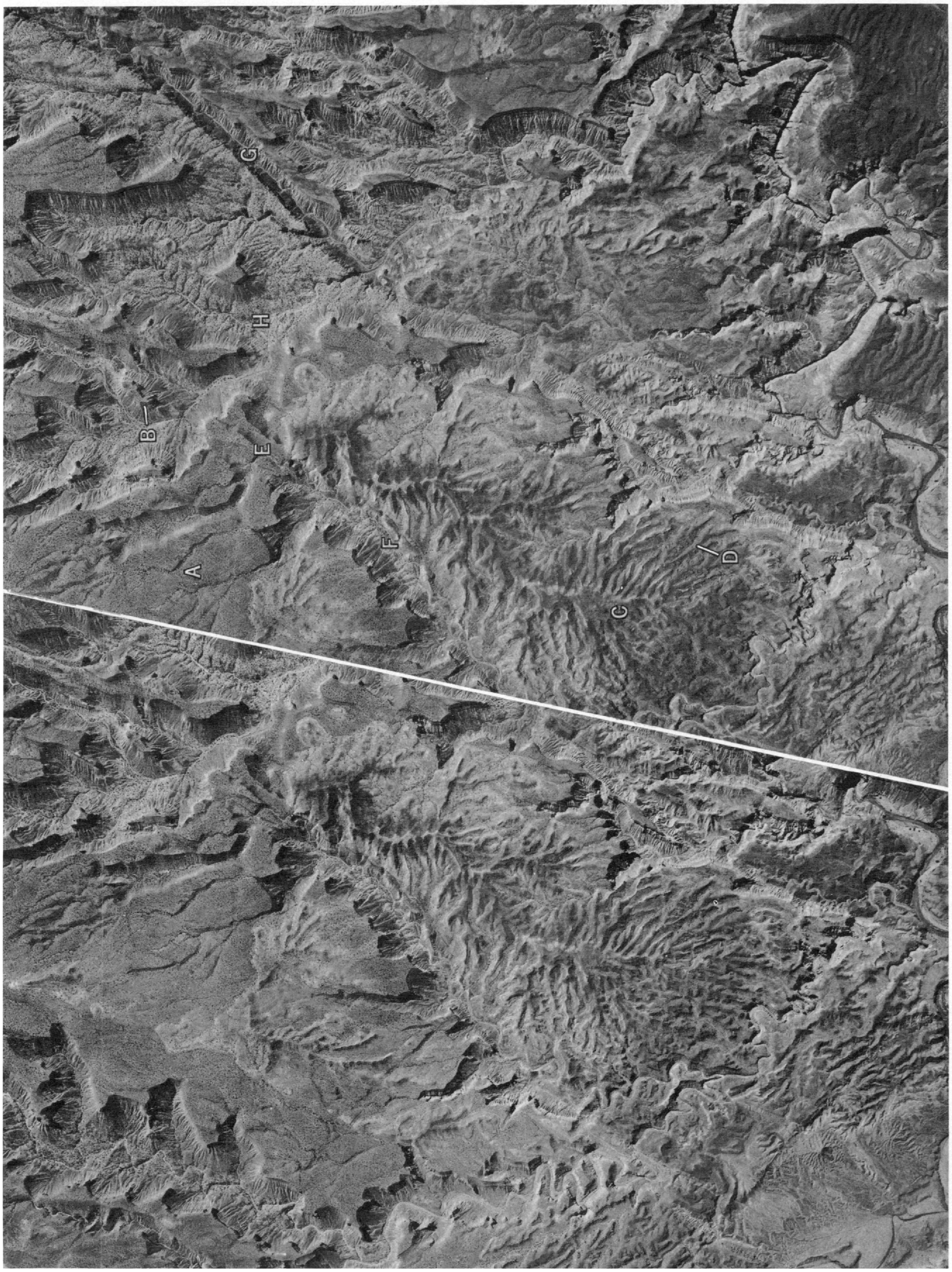
Stereoscopic pair

Approximately 1 mile

FIGURE 61.—FLAT-LYING BEDS OF SANDSTONE, LIMESTONE, AND SHALE (TEXAS).

[Approximate scale 1 : 20,000. Photographs by Commodity Stabilization Service]

Limestone caprock, *A*, shows a concentration of oak trees along rim but not across capping bench, which is covered by a veneer of cherty conglomerate. Sandstone break at *B* also has oak trees. Certain oaks have an affinity for limestone soils and some for sandy soils, but oak types are not distinguishable on conventional black-and-white photographs at a scale of 1:20,000. Shale valleys are covered with mesquite and locally have stock tanks, *C*, which suggest underlying impermeable materials. Note dendritic drainage and distribution of vegetation bands along the topographic contour, which in places form closed loops and suggest flat-lying or nearly flat-lying beds.



Stereoscopic pair

Approximately 1 mile

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Figure 62.—AREA OF FAULTED, GENTLY DIPPING SEDIMENTARY ROCKS (UTAH).

[Approximate scale 1 : 37,000. Photographs by U.S. Geological Survey]

Strong contrasts in drainage densities and in erosional features of the terrain result from different sedimentary rock types. Coarse-textured drainage of little-dissected area, *A*, marks a persistent limestone bed that locally forms bluffs. These bluffs overlie fine-grained sandstone and shale, *B*, which have a lesser angle of slope than the limestone, although the difference in slope angle is masked by the vertical exaggeration of the stereoscopic model. Note that top of limestone and topographic surface coincide permitting ready estimate of the amount of dip. Dark-toned shale and fine-grained sandstone and sandy shale at *C* show fine-textured drainage and erosional topography. Note closely spaced joints in fine-grained sandstone beds at *D*. Vertical offsets of resistant limestone bed at *E* are conspicuous. Drainage along trace of faults is prominent at *F* and *G*. A lower sandstone, *H*, contrasts locally with overlying dark sandstone and shale as a result of its light photographic tone and cover of scattered small trees.

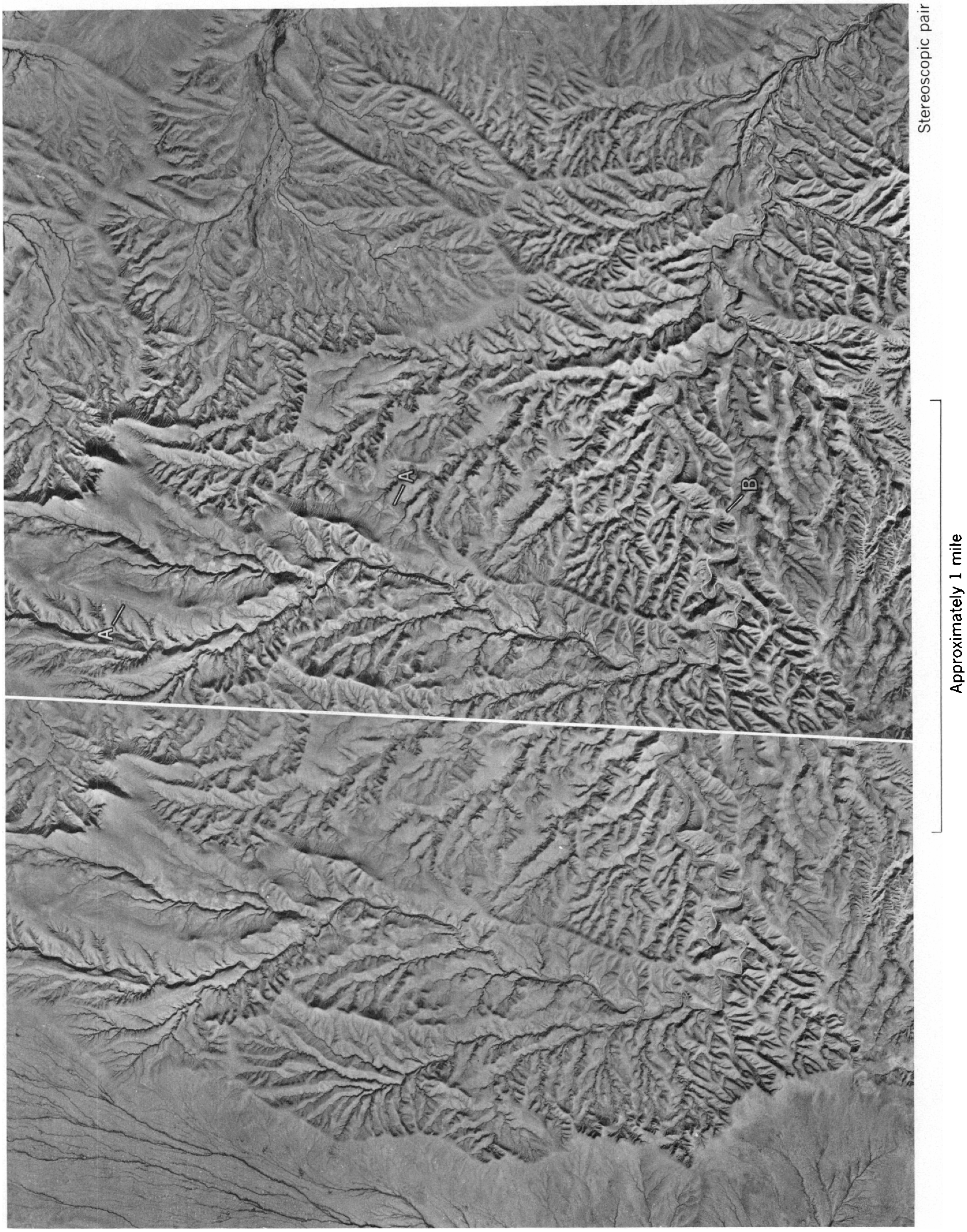

Stereoscopic pair
Approximately 1 mile
A
A
B

FIGURE 63.—SHALE IN SEMIARID CLIMATIC AREA (UTAH).

[Approximate scale 1 : 20,000. Photographs by U.S. Geological Survey]

Fine-textured drainage is typical of shale and other fine-grained clastic rock types. Relief is commonly subdued and divide areas gently rounded. Note that rounding of some divide areas may not be conspicuous because of vertical exaggeration of the stereoscopic model. For example, the relief at *B* is only about 70 feet. The fine-textured drainage and erosional topography suggest plastic soils. The numerous angular crenulations in minor tributaries probably reflect closely spaced joints. Thin light-toned bands, *A*, are expressions of bedding.

Stereoscopic pair

Approximately 1 mile

FIGURE 64.—SHALE AND LIMESTONE IN HUMID CLIMATIC AREA (VIRGINIA).

[Approximate scale 1 : 43,000. Photographs by U.S. Geological Survey]

Gently dipping shale, *A*, shows a fine-textured drainage. Main streams draining shale flow almost directly in the downdip direction. Limestone underlies anticlinal ridge, *B*. Sinkholes are present locally, *C*, but are not conspicuous within the area. In general the limestone areas are less dissected than shale areas because of better internal drainage in limestone. Valley, *D*, is underlain by shale. Note discordance of strike of steeply dipping beds, *E*, with scarp, *F*, which suggests presence of a fault along this topographic break in slope. Thin resistant bed of sandstone, *G*, crops out conspicuously on flank of anticlinal ridge. Trellis drainage in area *D* is typical of folded sedimentary rocks.

Stereoscopic pair

Approximately 1 mile

Figure 65.—AREA OF GENTLY DIPPING LIMESTONE AND SHALE (PENNSYLVANIA).

[Approximate scale 1 : 20,000. Photographs by Commodity Stabilization Service]

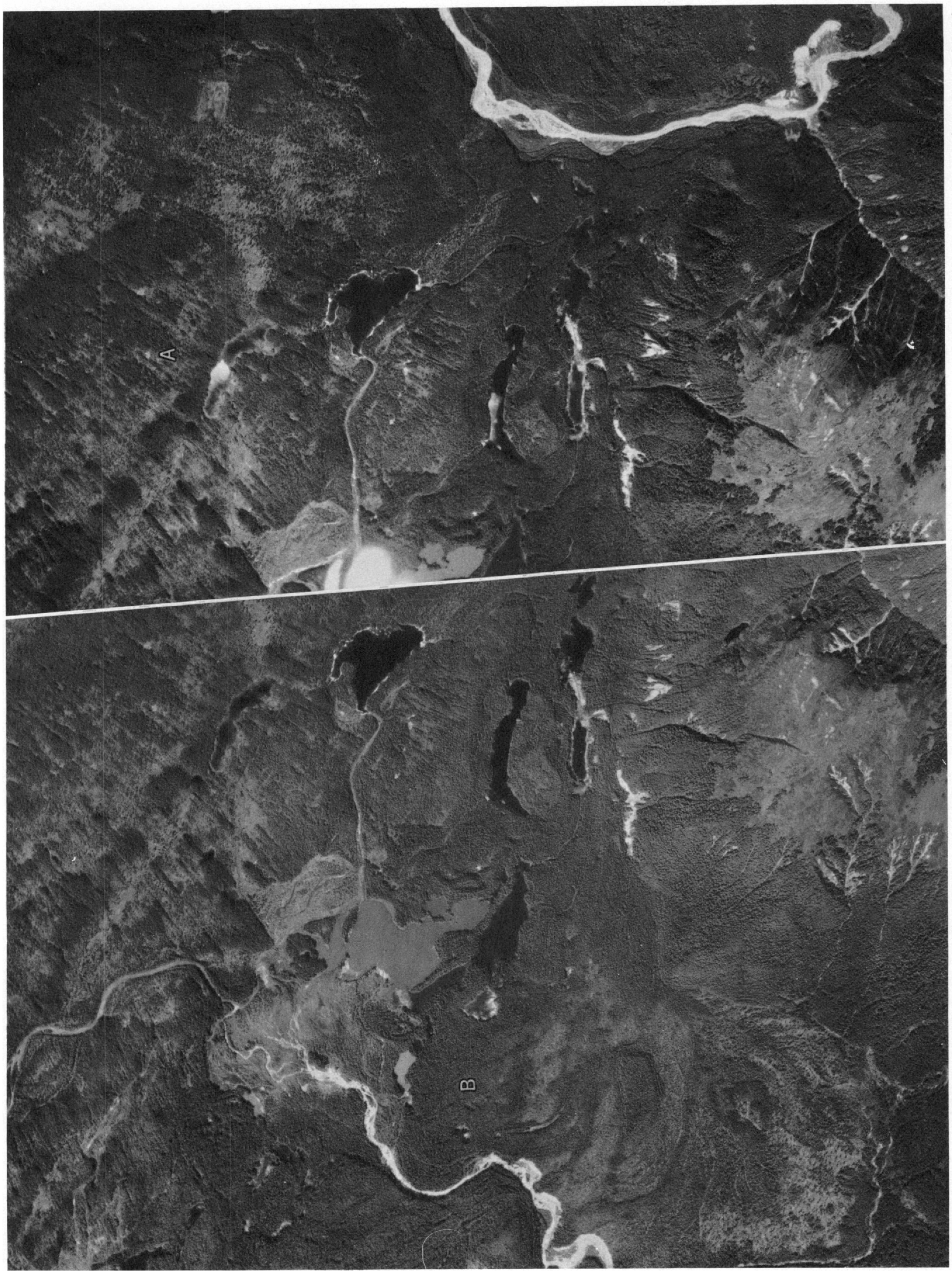
Impermeable shale, *A*, has a greater resistance to erosion than the limestone, *B*, and stands topographically high in this area. The contact of shale and limestone is marked by a pronounced topographic break, as at *C*. The shale has been noticeably dissected by stream erosion in contrast to the limestone in which drainage is in large part internal. Note orchards in well-drained limestone areas. Vegetation along stream valleys in the shale accentuates the drainage contrast of shale and limestone areas. Soil mottling, *D*, in limestone areas occurs where soil cover is thin and allows differences in moisture conditions, believed to result from drainage channels in the limestone bedrock, to stand out. Despite good drainage in the limestone area residual soils developed on limestone may react to engineering tests as a plastic soil and not as a granular soil. Limestone quarry is at *E*.


Stereoscopic pair
A
B
C
Approximately 1 mile

Figure 66.—AREA MANTLED BY GLACIAL DEPOSITS (SOUTH DAKOTA).

[Approximate scale 1 : 60,000. Photographs by Army Map Service]

Topographically high area, *A*, with typical knob-and-kettle topography is covered by morainal material; ponds are common but surface drainage channels are conspicuously absent. Rim of high ground has been noticeably dissected by deep channels. The distribution of these channels, accentuated by dark-toned vegetation, forms a radial pattern similar to that over some subsurface structures in other areas. Drainage disappears in permeable material, *B*, surrounding the high area. Contrast lack of surface drainage rills in moraine at *A*, where drainage is poor, as indicated by ponds, with lack of surface drainage rills in outwash at *B*, where internal drainage is good. Well-drained area, *C*, probably also represents glacial outwash.



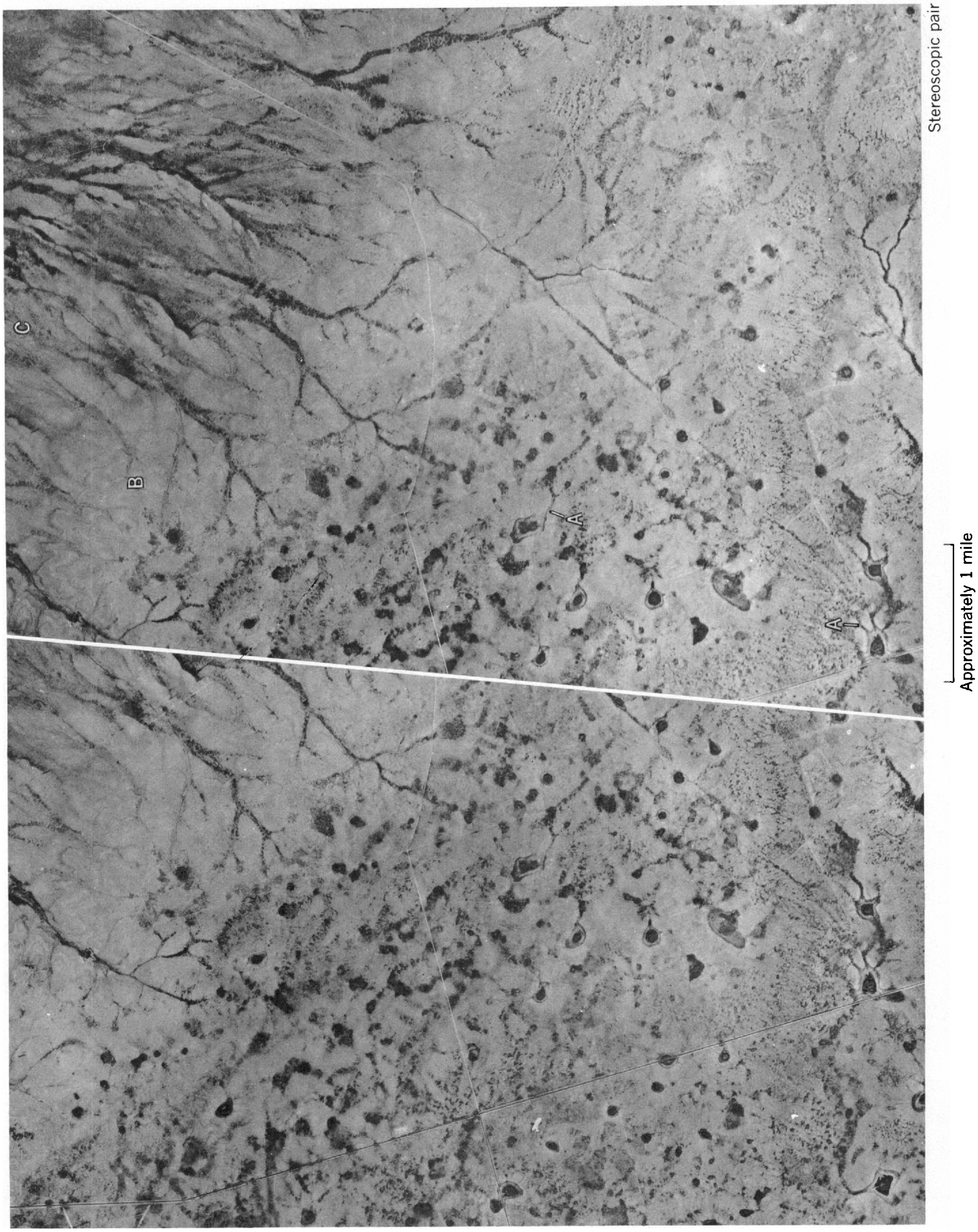
Stereoscopic pair

Approximately 1 mile

FIGURE 67.—GLACIATED AREA IN SOUTHEASTERN ALASKA.

[Approximate scale 1 : 40,000. Photographs by U.S. Navy]

Conspicuous linear trends, *A*, represent glacial grooving. These lineations, except for the fanning out in the direction of ice movement, may appear on photographs similar to lineations that represent foliation in metamorphic rocks. Drumlinoid features that give rise to this linear pattern are generally found in broad, flat, and topographically low areas, such as the floors of broad valleys. Commonly the drumlinoid features are elongated parallel or subparallel to the valley or general topographic grain. Lineations representing foliation on the other hand may transect or parallel the topographic grain; unlike drumlinoid features they are not restricted to any one topographic level. Pock-marked area, *B*, is glacial outwash and probably some glacial lake deposits.


Stereoscopic pair
C
B
A
A
Approximately 1 mile

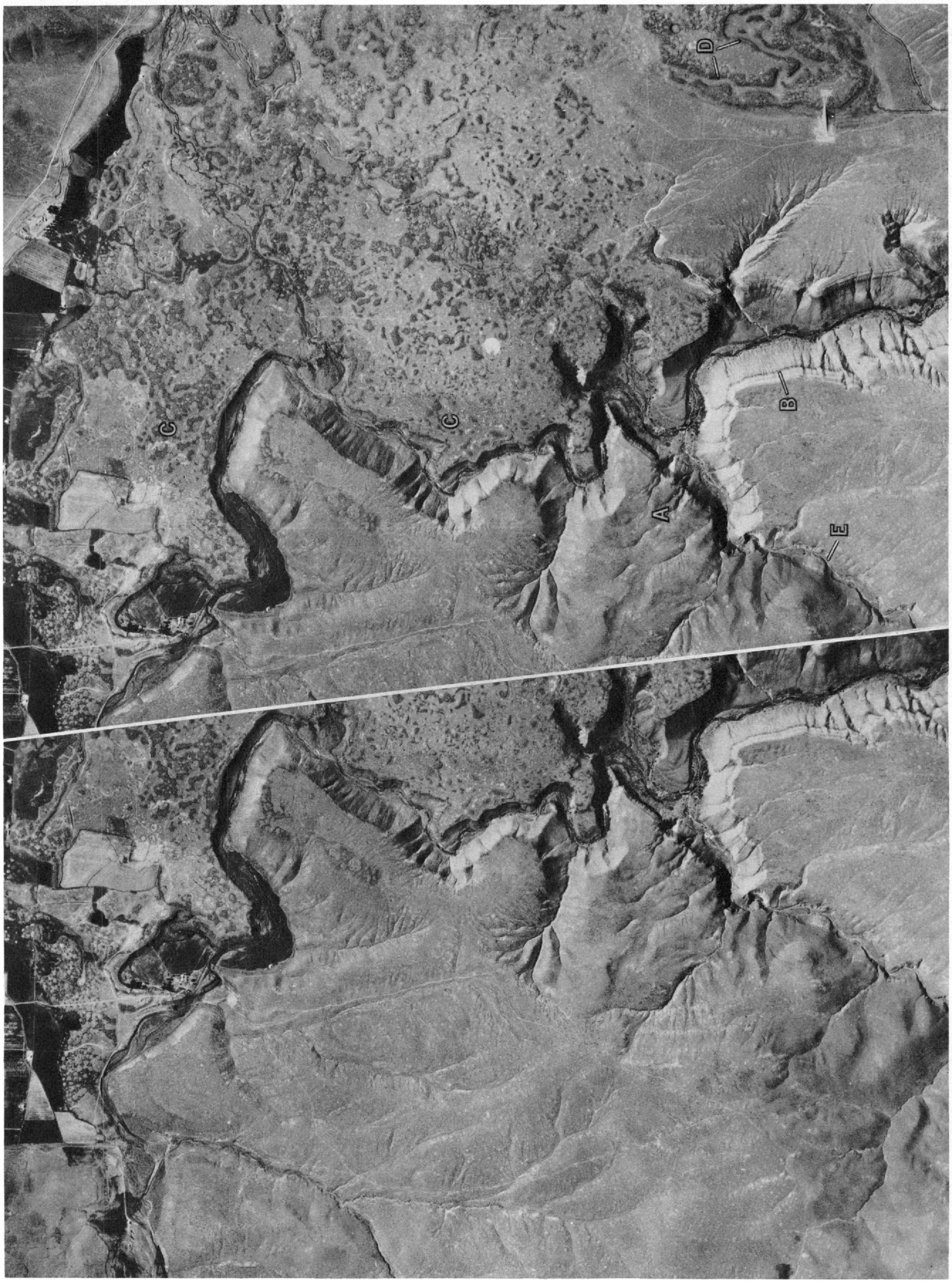
782-139 O - 65 - 12

FIGURE 68.—APPROXIMATELY FLAT-LYING LIMESTONE AND INTERBEDDED SANDSTONE AND MARLSTONE BEDS COVERED LOCALLY BY ALLUVIUM AND WINDBLOWN DEPOSITS (TEXAS).

[Approximate scale 1 : 63,360. Photographs by Army Map Service]

Rounded dark-toned depressions are sink holes that mark area of limestone. Drainage is primarily internal and few surface drainage channels may be seen; a few short surface rills drain into the sink holes, as at *A*.

In contrast to the limestone area, surface drainage is conspicuously developed in the interbedded sandstone and marlstone, *B*, but becomes less well developed in permeable alluvium and windblown deposits, *C*.



Stereoscopic pair

Approximately 1 mile

FIGURE 69.—AREA OF BASALT FLOWS (IDAHO).

[Approximate scale 1 : 20,000. Photographs by Commodity Stabilization Service]

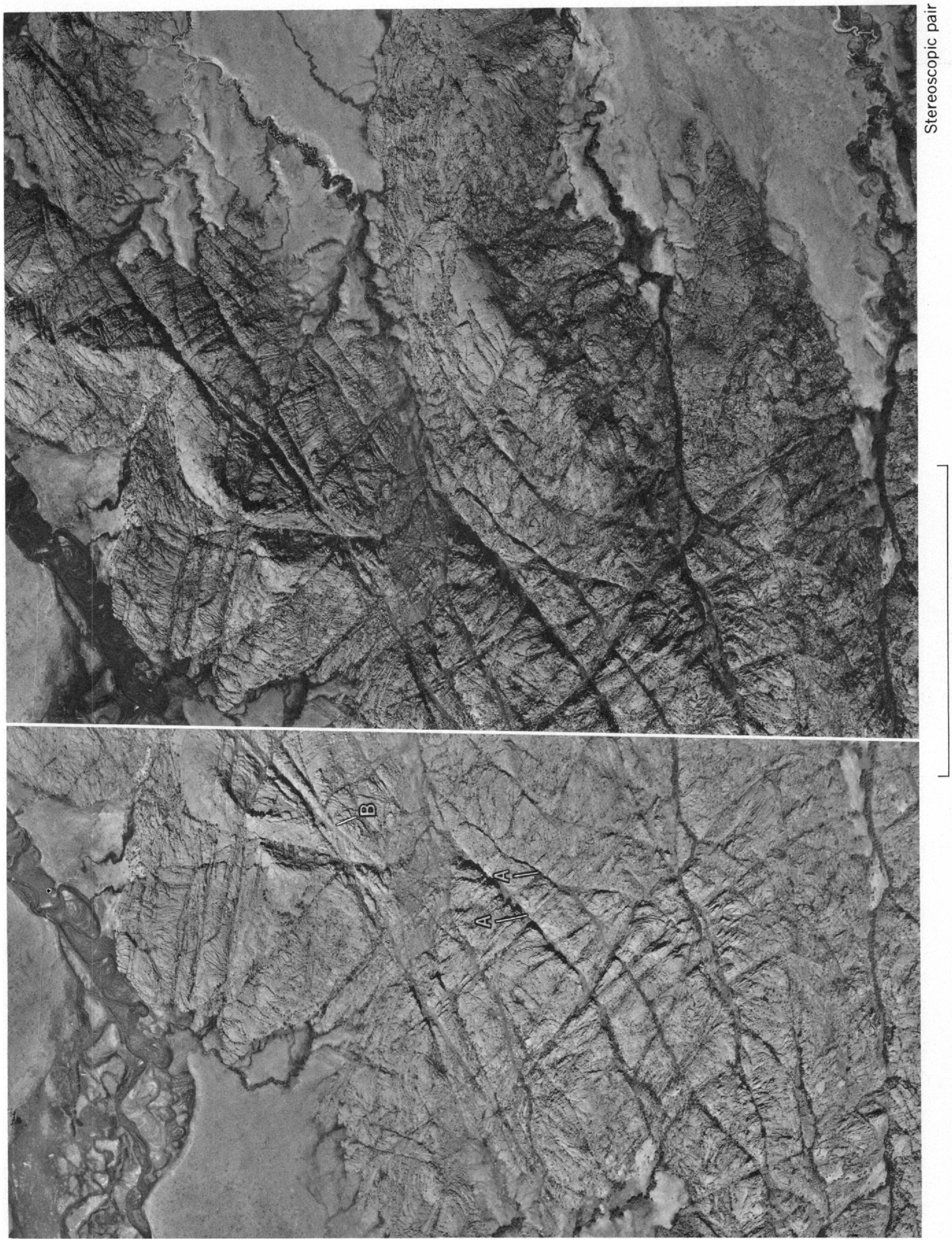
The oldest basalt, *A*, shows subdued rounded topography and well-developed surface drainage. A younger basalt, *B*, is interbedded with light-toned sedimentary rocks. Some surface drainage has developed on the sedimentary rocks. The youngest basalt, *C*, shows a "lizard skin" appearance on aerial photographs; locally a collapse structure may be present as at *D*. Almost no integrated surface drainage is present on the youngest basalt. Stream *E* flows in a fault valley. The fault is younger than, and separates, basalts *A* and *B*; basalt *A* has been upthrown.


Stereoscopic pair
Approximately 1 mile

FIGURE 70.—AREA OF GRANITE (SOUTH DAKOTA).

[Approximate scale 1 : 24,000. Photographs by U.S. Geological Survey]

Dendritic drainage, seen best in stereoscopic view, is typical of many terrains underlain by intrusive igneous rocks or other generally homogeneous rocks. The irregularly spaced joints in several different orientations are characteristic of granite and other intrusive rocks; extremely irregular topography is also common in such terrain. Banding, suggestive of sedimentary or metamorphic rocks, is absent. The occurrence of trees predominantly of one variety and the lack of conspicuous preferred orientation of vegetation is suggestive of uniform composition of bedrock.

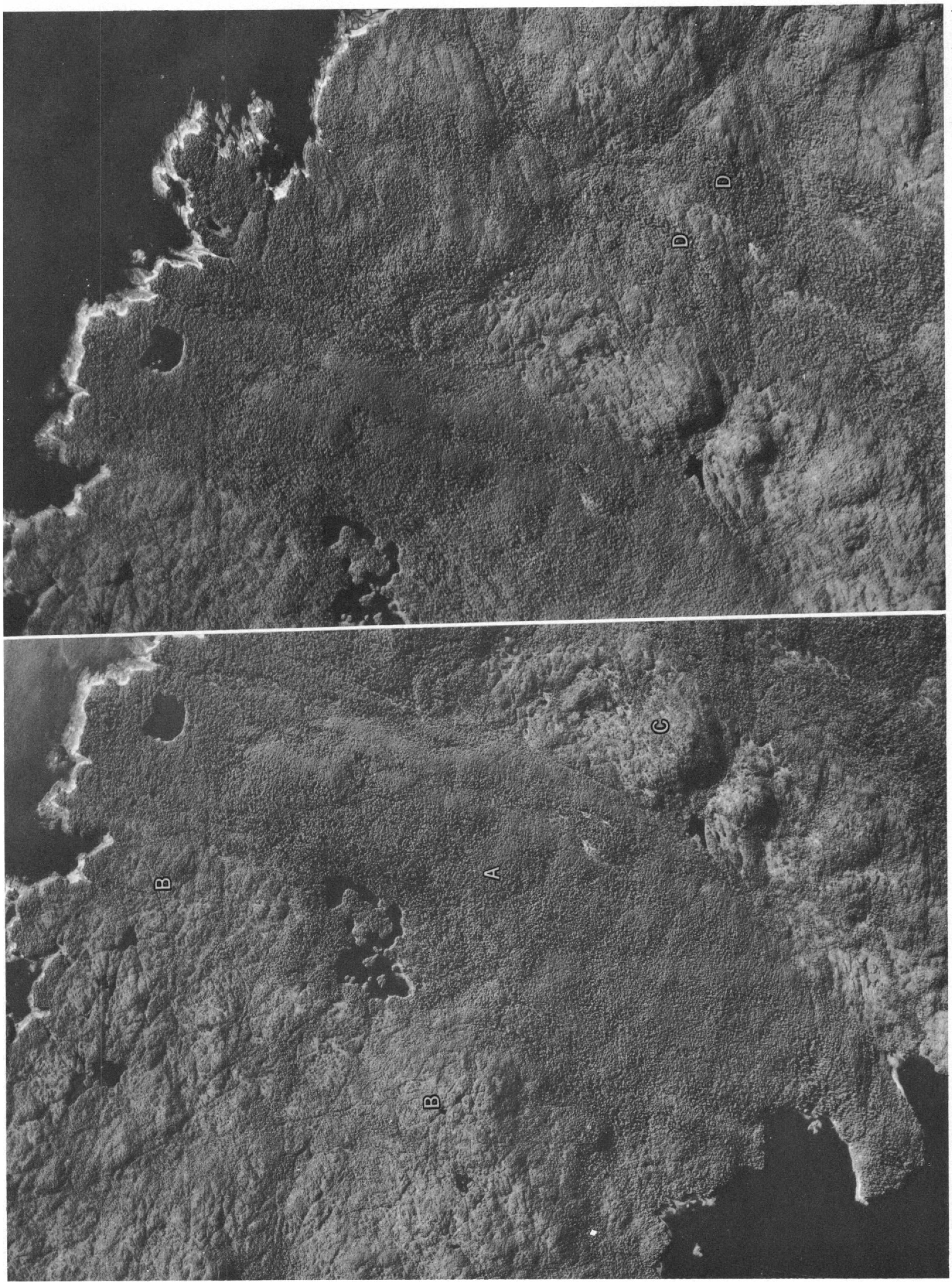


Stereoscopic pair

FIGURE 71.—AREA OF GRANITIC INTRUSIVE ROCKS (WYOMING).

[Approximate scale 1 : 28,000. Photographs by U.S. Geological Survey]

Profuse, irregularly spaced joints in several different orientations are typical, although not necessarily diagnostic, of intrusive igneous rocks. The massive character of the rocks and apparent lack of bedding in turn suggest igneous intrusive rocks, although locally the rocks shown appear similar to some highly fractured massive sandstone. Conspicuous rectilinear depressions, as at *A*, marked by dark-toned vegetation, are shear zones that are more easily eroded than surrounding rock areas, and probably have a higher concentration of moisture that supports vegetation growth. In places, as at *B*, older shear zones have been offset by younger fractures. Note strong control of drainage by faults and joints.



Stereoscopic pair

Approximately 1 mile

FIGURE 72.—AREA SHOWING VEGETATION DIFFERENCES IN IGNEOUS-METAMORPHIC TERRAIN (SOUTHEASTERN ALASKA).

[Approximate scale 1 : 40,000. Photographs by U.S. Navy]

Dense stand of coniferous trees, *A*, is typical of massive marble and related carbonate rocks in this area. Diorite, *B*, has only patchy tree growth but shows typical crisscross joint pattern of short lineations common in many intrusive rocks. Area *C* is schist. The surface expression of the schist is similar to that of the diorite in patchy tree cover and irregular topography but the schist has a dominant lineation direction not present in the intrusive rocks. Vegetation bands, *D*, may cover thin beds of marble. Note that gently curved vegetation bands suggest steeply dipping rock units.

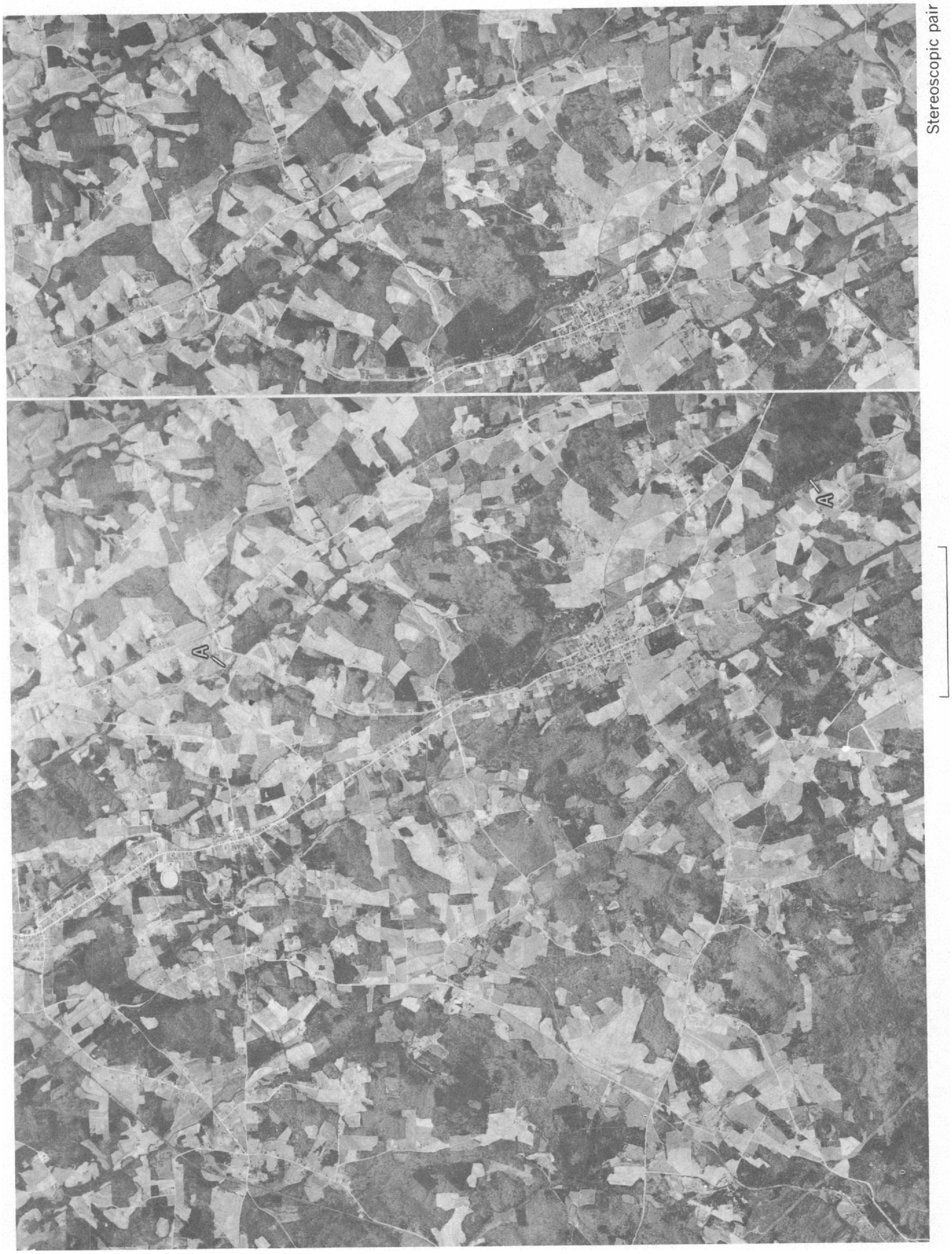
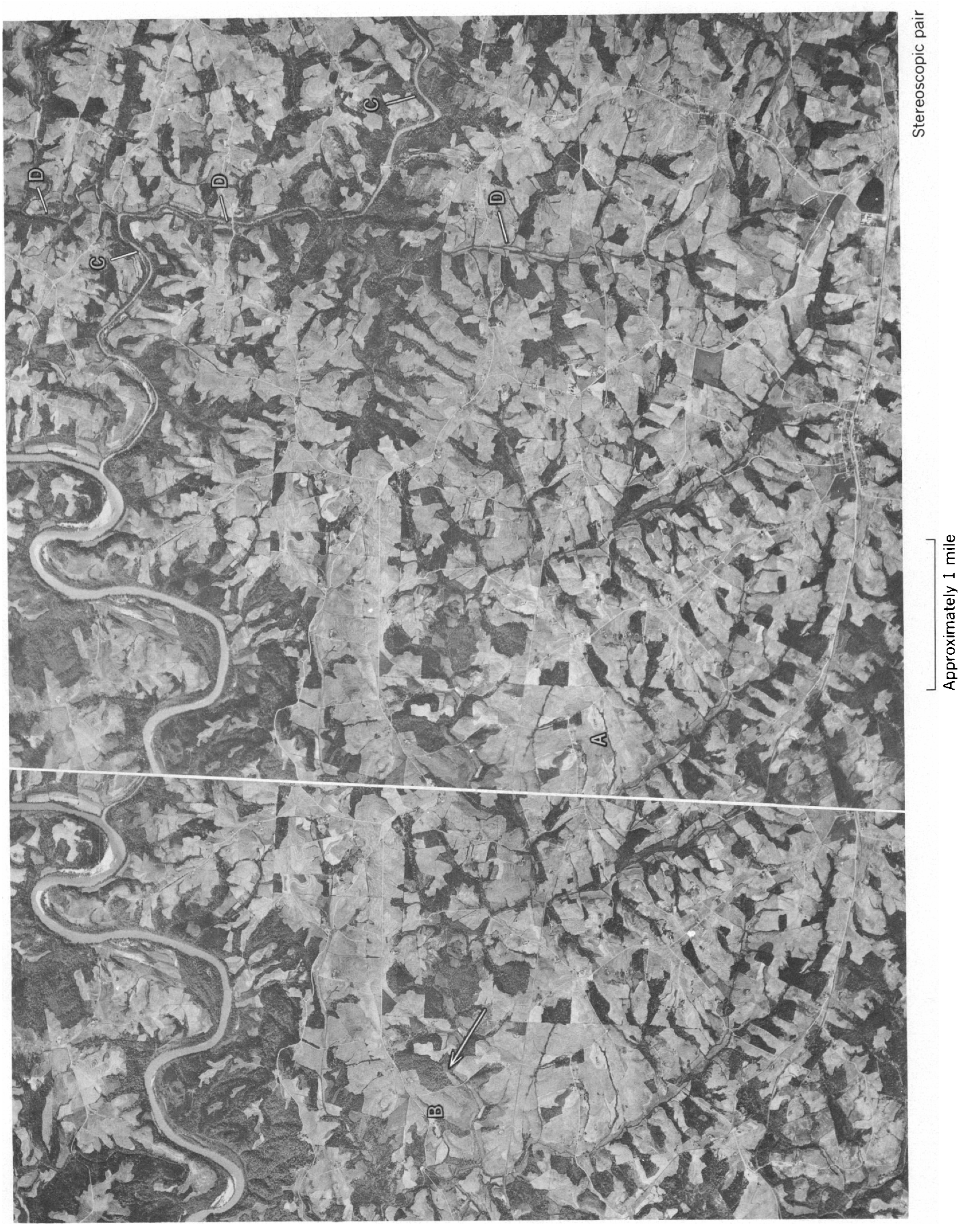

Stereoscopic pair
A
A
Approximately 1 mile

FIGURE 73.—AREA UNDERLAIN BY SILICIC VOLCANIC TUFFS AND FLOWS AND BEDDED ARGILLITE OR SLATE (NORTH CAROLINA).

[Approximate scale 1 : 58,000. Photographs by Army Map Service]

Major streams, A, are developed along the regional cross-joint direction. Roads extending generally parallel to the major streams accentuate the cross-joint direction. Minor tributary streams flow predominantly parallel to the regional structural trend and at right angles to the cross joints. Hills are commonly elongate in the direction of the regional strike, which may represent foliation or flow cleavage rather than bedding. In such low-relief areas the extensive land-use pattern tends to obscure structural trends; commonly the structural trends can be better observed from a mosaic composed of several photographs. Any one stereoscopic pair can only show a small part of the regional geologic structure. Structural interpretation may also be facilitated by study of separate drainage maps, as in figure 8.


Stereoscopic pair
Approximately 1 mile
C
D
D
C
D
A
B

782-139 O - 65 - 13

FIGURE 74.—AREA OF FOLDED, FAULTED, AND HIGHLY METAMORPHOSED ROCKS (NORTH CAROLINA).

[Approximate scale 1 : 57,000. Photographs by Army Map Service]

This pair of photographs illustrates a use of drainage characteristics in the interpretation of geologic structure. Where dips are gentle, tributary streams developed on the updip side of a strike valley commonly will be longer than tributary streams developed on the downdip side of the valley, as at *A*. The direction of dip of strata is thus indicated. Length relations of streams are commonly best studied on a separate drainage overlay (see fig. 7) where vegetation and other obscuring features in the stereoscopic model are not present. In the area shown, a plunging fold is also suggested by the distribution of photographic tones and gentle curvature of streams around the nose, *B*, of the fold. Arrow indicates direction of plunge. Many streams in highly metamorphosed terrain have developed in response to, and therefore reflect, the strike and dip of foliation rather than bedding. Prominent cross joints are expressed by linear segments of major streams, as at *C*, and by alinement of vegetation along some tributary streams. Note conspicuous fault indicated by alinement of stream segments, *D*; this fault is inconspicuous on the ground.

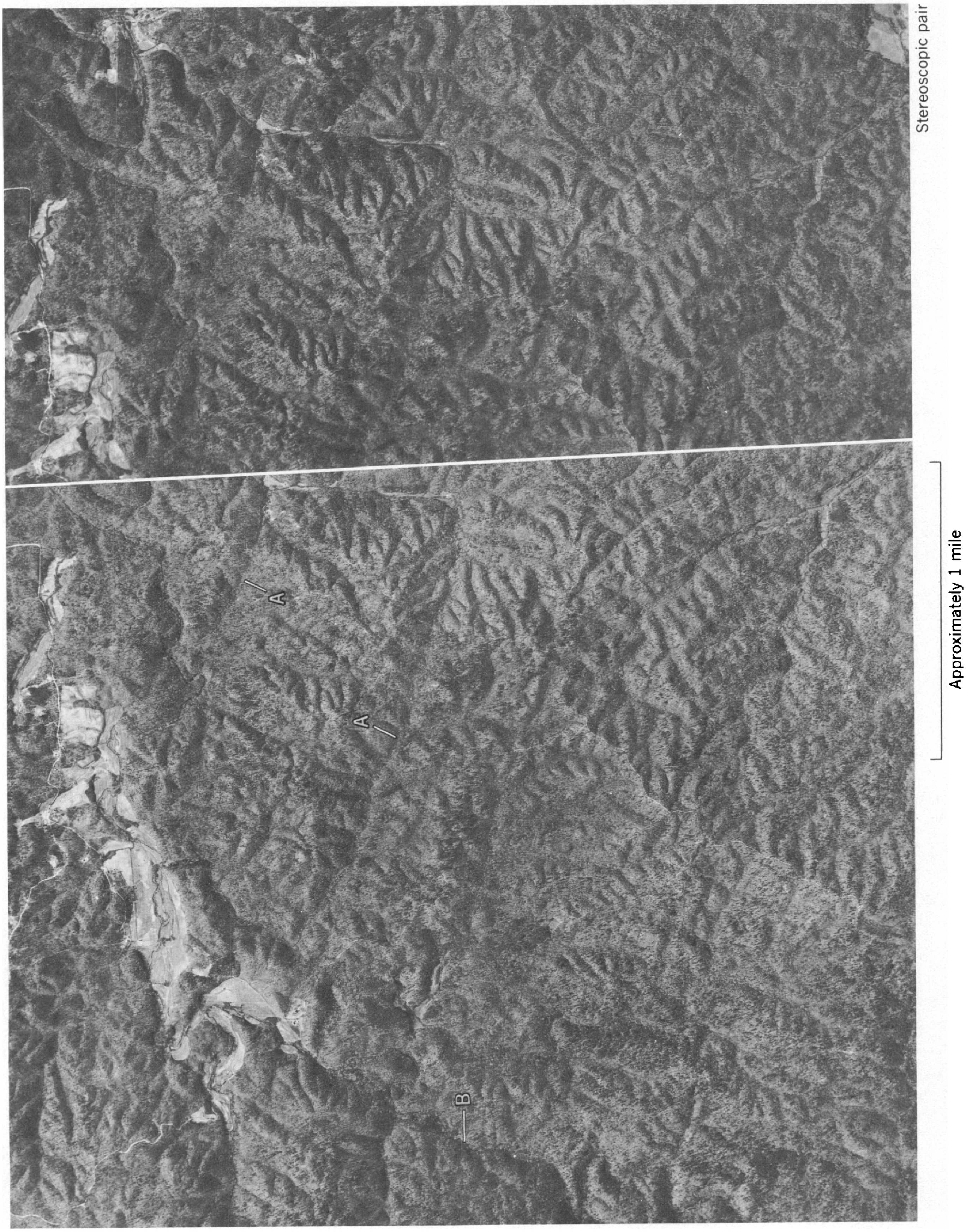
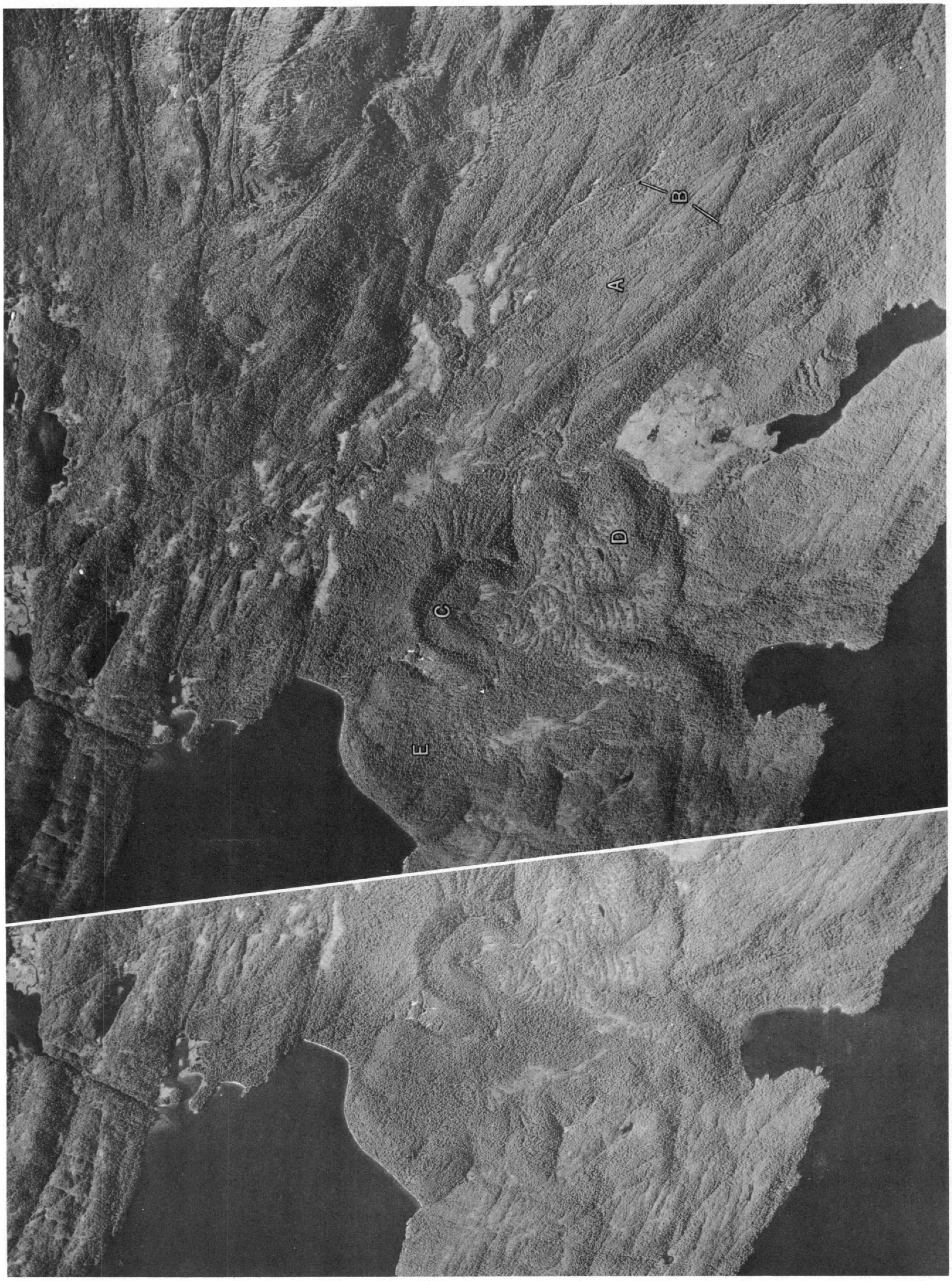

Stereoscopic pair
Approximately 1 mile
A
A
B

FIGURE 75.—AREA UNDERLAIN BY PHYLLITE AND SLIGHTLY METAMORPHOSED SLATY ROCKS (ALABAMA).

[Approximate scale 1 : 29,000. Photographs by U.S. Geological Survey]

Poorly resistant phyllite and slightly metamorphosed slaty rocks here are characterized by fine-textured drainage, commonly found in fine-grained clastic rocks. The area also has a fine-textured erosional topography. Several conspicuous linear trends, *A*, are at right angles to the regional strike of bedding. These trends probably represent regional cross joints. In areas of metamorphic rocks the prominent regional cross joints commonly are widely spaced and streams flow along them. The linear trend of the stream at *B* is parallel to the regional strike of bedding. There is no direct surface manifestation of bedding. Headwater tributaries form a generally dendritic drainage pattern that suggests uniformity of rock type, but principal streams show rectangular drainage probably influenced by bedding and cross joints.



Stereoscopic pair

Approximately 1 mile

Figure 76.—HEAVILY VEGETATED TERRAIN UNDERLAIN BY METAMORPHIC AND EXTRUSIVE VOLCANIC ROCKS (SOUTHEASTERN ALASKA).

[Approximate scale 1 : 40,000. Photographs by U.S. Geological Survey]

Numerous subparallel lineations, *A*, represented primarily by rectilinear depressions that channel the drainage, are expressions of foliation in the metamorphic rocks. Conspicuous rectilinear depressions, *B*, transecting the foliation direction, represent faults. The remnant of a recent volcanic cone, *C*, is recognized by its shape. Note lobate patterns of vegetation, *D*, suggesting areas of flow rocks. Absence of lineations in area *E* suggests that flows also are present there.

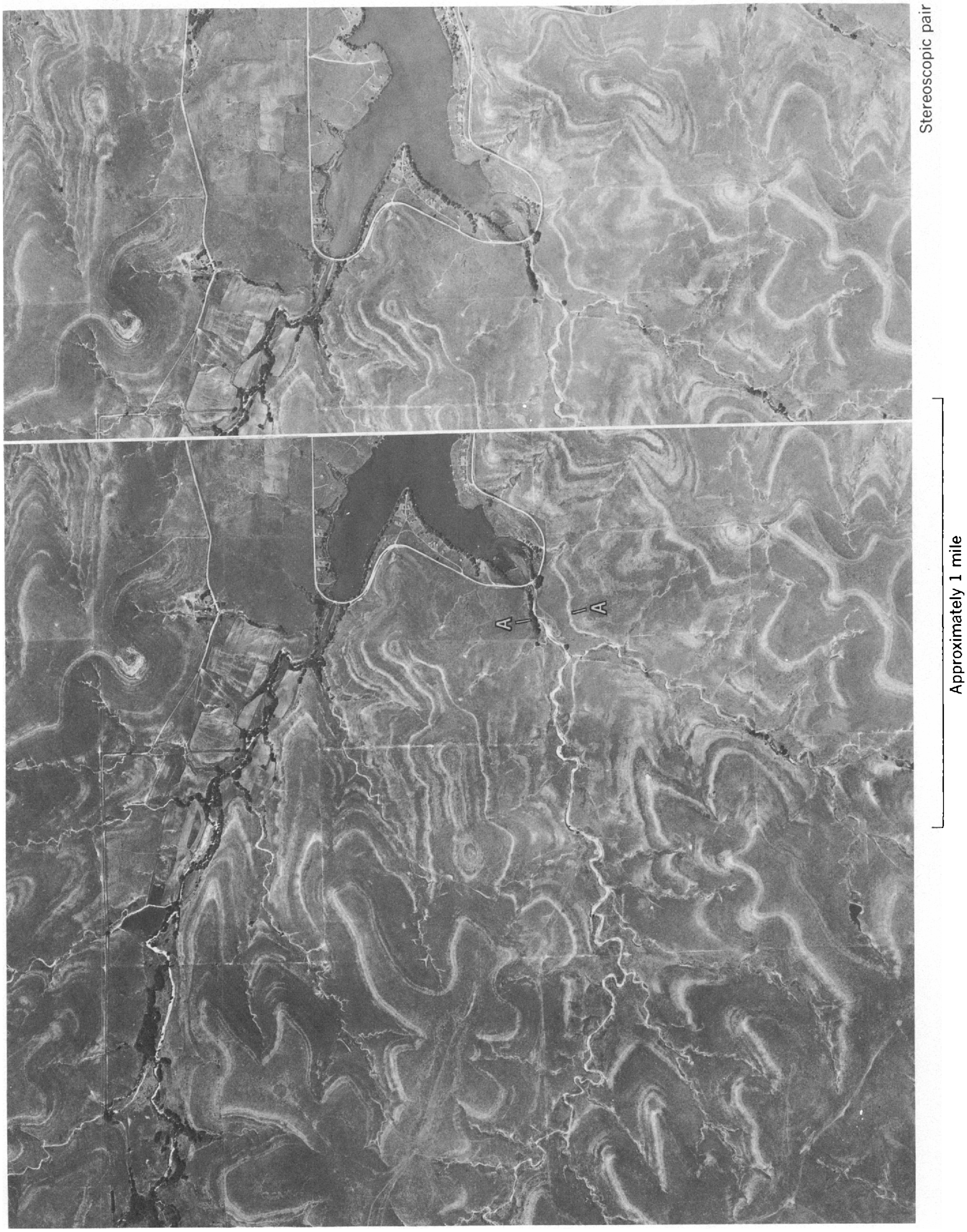
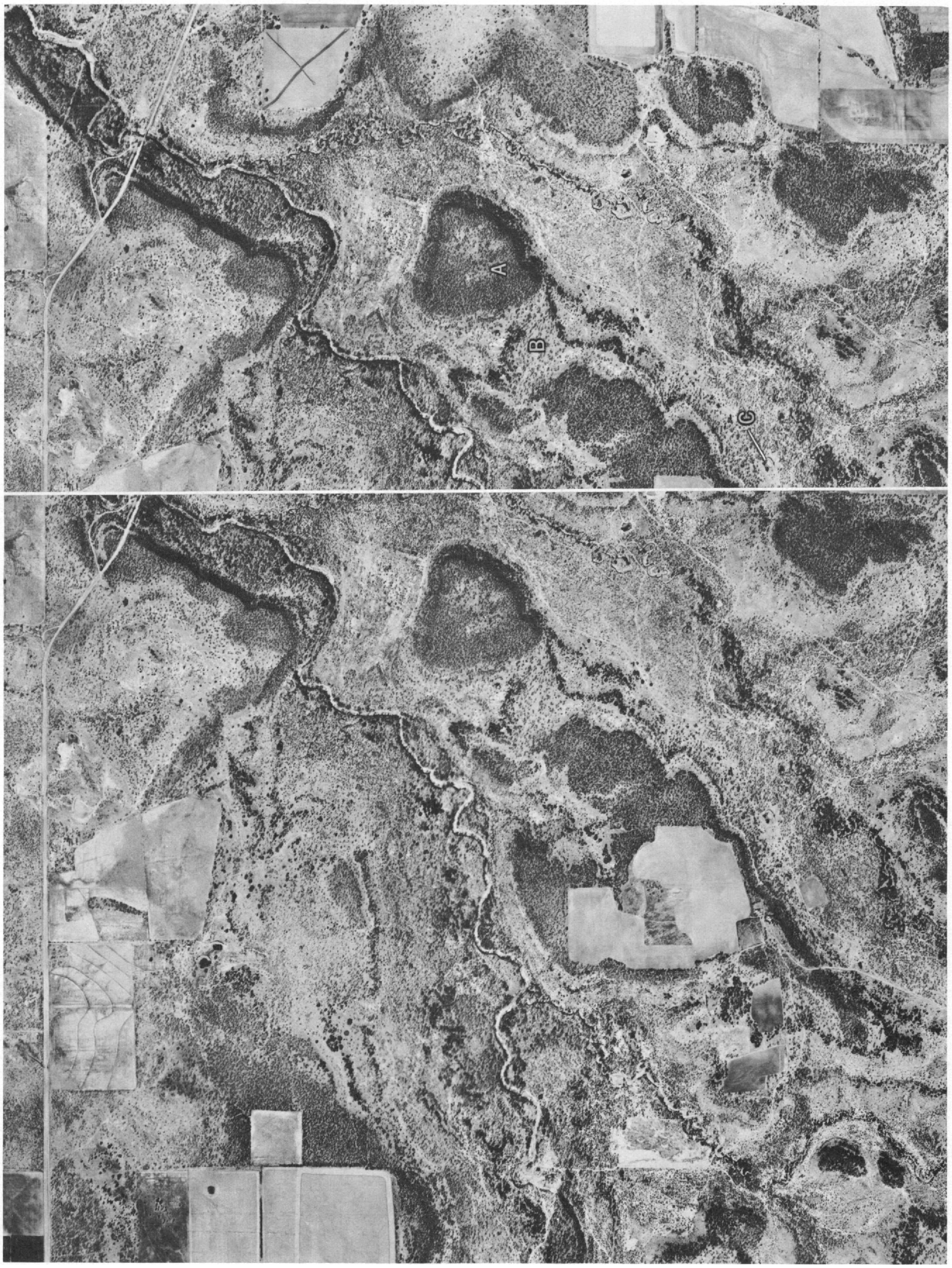

Stereoscopic pair
A
A
Approximately 1 mile

Figure 77.—FLAT-LYING BEDS OF LIMESTONE AND SHALE (KANSAS).

[Approximate scale 1 : 20,000. Photographs by Commodity Stabilization Service]

Strong contrasts in photographic tone result primarily from different lithologic characteristics of underlying formations; dark-toned beds are shale with some grassy vegetation; light-toned beds are limestone. The near-coincidence of bedding traces and topographic contours, closed loops of tonal patterns, as well as the dendritic drainage pattern are typical of flat-lying beds. Small thickness of limestone interbeds is not conducive to development of sink holes. In some places individual limestone beds can be distinguished on the basis of weathering and erosional characteristics; massive cherty limestone benches may show rounded rims, whereas thin platy limestone benches may show a sharp break at the rim. Abundant trees and shrubs along part of bed *A* suggest a plentiful supply of water. Bed *A* is locally an aquifer.



Stereoscopic pair

Approximately 1 mile

FIGURE 78.—FLAT-LYING BEDS OF SANDSTONE, LIMESTONE, AND SHALE (TEXAS).

[Approximate scale 1 : 20,000. Photographs by Commodity Stabilization Service]

Flat-lying beds are indicated by benchlike landform, extension of tonal bands along topographic contour, and by dendritic drainage. Dark photographic tone on sandstone caprock, *A*, results from growth of oak trees. Benches of limestone, *B*, exhibit concentration of oak growth along rims but not across flats. Valley areas are underlain by shale, which is covered predominantly by mesquite growth. Stock tanks, *C*, are common in impermeable material and where present suggest shale in this region.


Stereoscopic pair
A'
A'
Approximately 1 mile

FIGURE 79.—AREA OF SPARSE OUTCROPS UNDERLAIN LARGELY BY GENTLY FOLDED SANDSTONE, CONGLOMERATE, AND SHALE (NORTHERN ALASKA).

[Approximate scale 1 : 20,000. Photographs by U.S. Navy]

Dip slopes are characterized by few streams in contrast to back slopes on which a system of numerous subparallel streams has developed. Drainage in the dip-slope direction is generally coarse textured except for profuse channels developed at heads of tributaries. Drainage on the back slopes is fine textured. The textural difference, or drainage density difference, rather than any specific drainage pattern, stands out. The back slope, with its fine-textured drainage, is predominantly a shale section in contrast to the sandstone and conglomerate of the dip slope. Note horizontal offset of light-toned sandstone beds by near-vertical faults, illustrated at *A*, transverse to the strike.

Stereoscopic triplet

Approximately 1 mile

782-139 O - 65 - 14

FIGURE 80.—GENTLY TO STEEPLY DIPPING SEDIMENTARY ROCKS OVERLYING SCHIST-GNEISS-GRANITE COMPLEX (WYOMING).

[Approximate scale 1 : 59,000. Photographs by Army Map Service]

Striking discordance in dip of beds can be seen between beds at *A* and *B* and between near-vertical beds at *C* and flat-lying beds at *D*. Such a discordance in dip may represent tightly folded structures in some areas but here it represents faulting. Note also the conspicuous discordance in strike between beds at *A* and *C* and between beds at *B* and *C*. The locations of fault traces may be inferred from the positions of discordant beds, but details of fault structure and positions of formation contacts cannot be seen clearly on the photographs of many parts of this complex area. Dark-toned rocks, *E*, lacking bedding or banding are schist-gneiss-granite complex. Light-toned jointed rocks, *F*, are predominantly limestone and dolomite. Where light-toned rocks are cut by a stream, as at *G*, the outcrop pattern forms a V in the direction of dip.

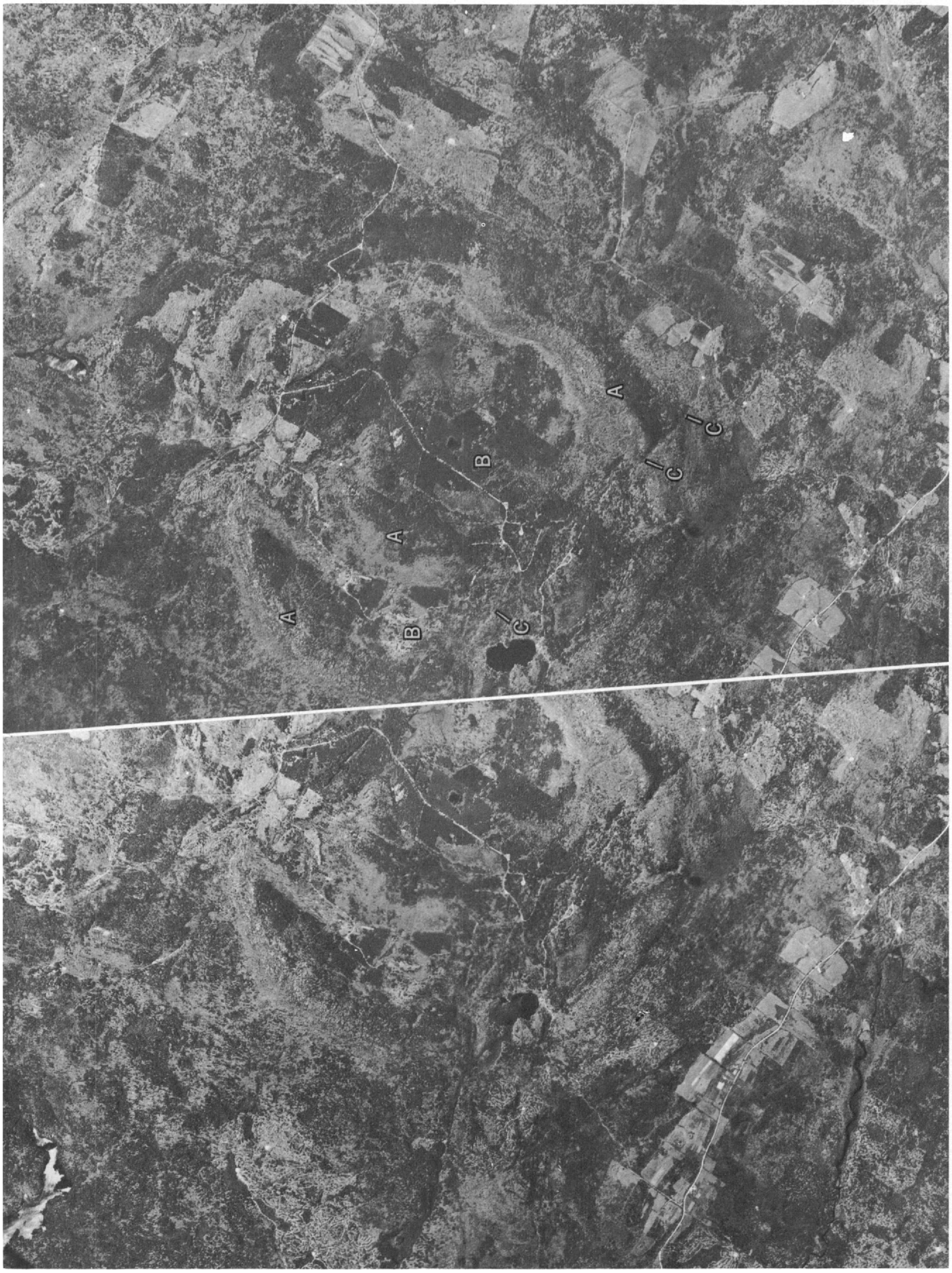
Stereoscopic pair

Approximately 1 mile

FIGURE 81.—GENTLY FOLDED SEDIMENTARY ROCKS (CENTRAL UTAH).

[Approximate scale 1 : 20,000. Photographs by Soil Conservation Service]

Contrasting photographic tones, representing different soil and rock types, strongly outline plunging anticline. Plunge of anticline is also indicated by stream curvature at *A* and *B*. Note that major stream has generally consistent direction of flow until it reaches anticlinal nose at *C*, at which point it is deflected in the direction of plunge of the structure. Outcrop pattern of contact between light- and dark-toned rocks, *D*, along flank of the anticline forms pronounced V's, which point in the direction of dip. Local intrusions of basalt dikes, *E*, stand in topographic relief above softer surrounding rocks.



Stereoscopic pair

FIGURE 82.—RING DIKE IN NEW HAMPSHIRE.

[Approximate scale 1 : 34,000. Photographs by U.S. Geological Survey]

The ring dike, composed of several types of igneous rock, is the most conspicuous feature of the terrain. Different rock types in places are reflected in the topographic expression of terrain. An outer ring and partial inner ring, *A*, composed of monzonite stand in conspicuous topographic relief. Hornblende diorite, in places foliated, forms the low areas, *B*. Some geologic contacts may be located on the basis of topography. However, specific placement of contacts cannot be made from the stereoscopic model; but in igneous terrain, where one rock type may grade into another, contacts are difficult to select in the field. The ring dike is cut by several faults, ***C***, indicated by alinements of scarps, depressions, and vegetation.

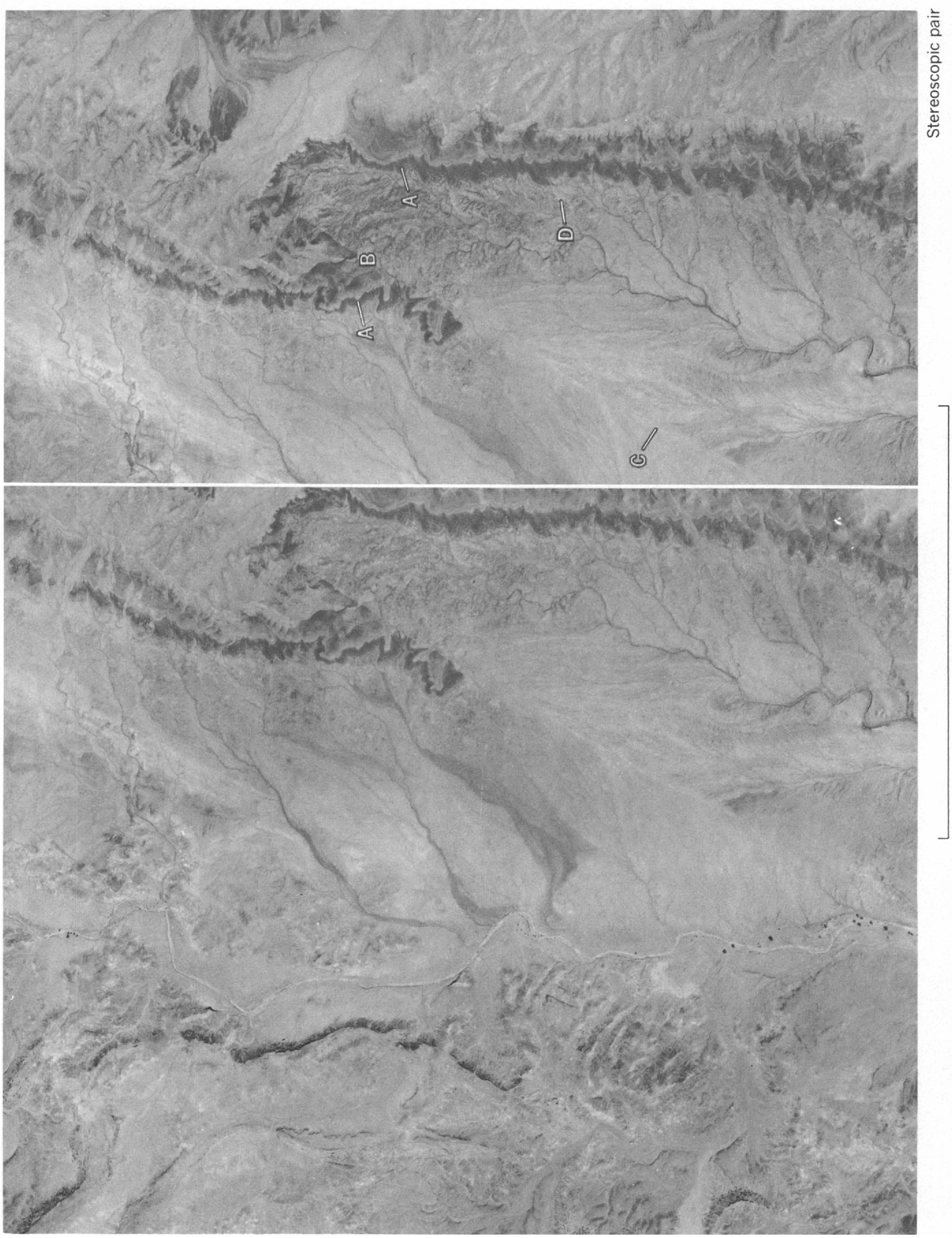
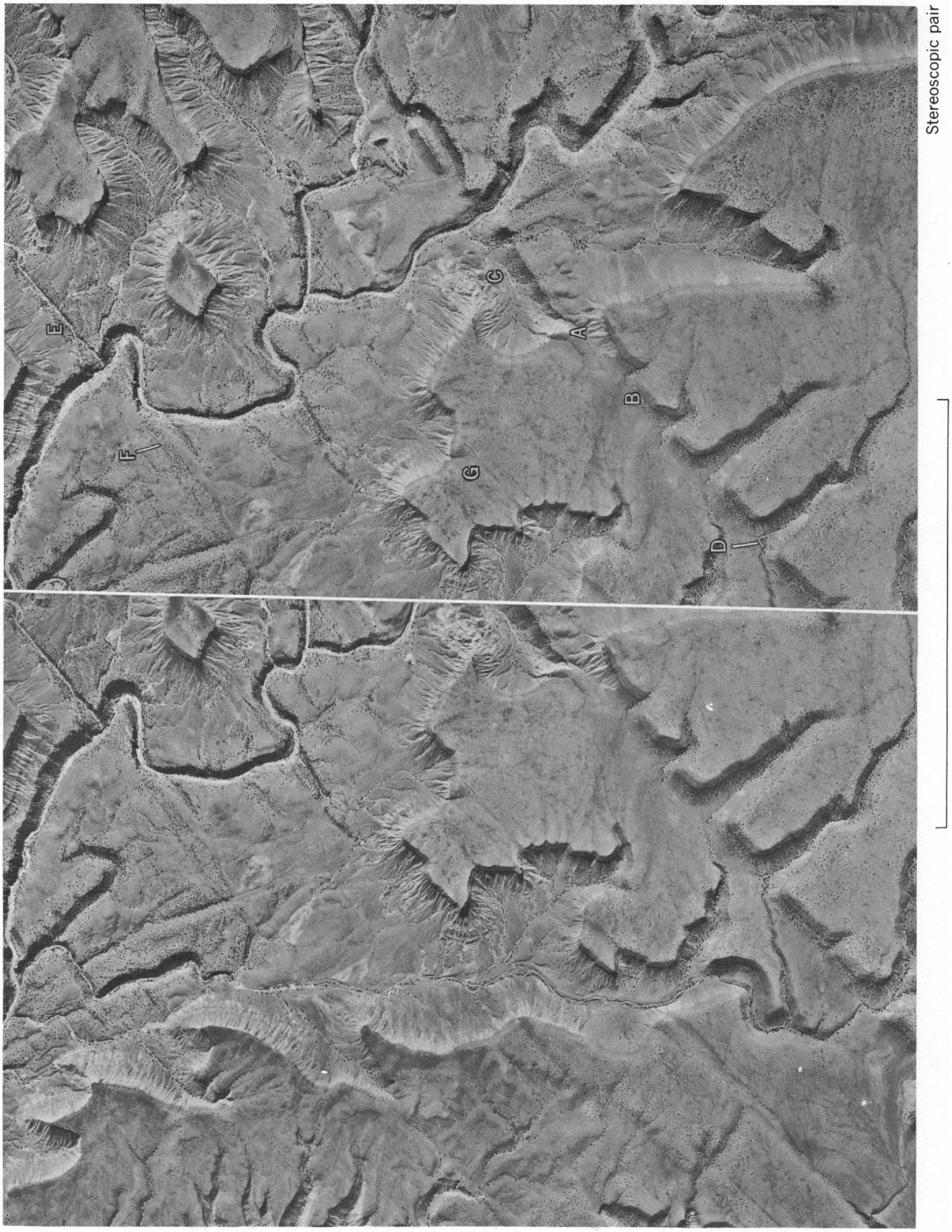

A
B
A
D
C
Stereoscopic pair
Approximately 1 mile

FIGURE 83.—GENTLY DIPPING SEDIMENTARY ROCKS OFFSET BY NEAR-VERTICAL FAULT (UTAH).

[Approximate scale 1 : 20,000. Photographs by U.S. Geological Survey]

Line separating areas of contrasting photographic tones is trace of fault. The straightness of the fault trace indicates that the fault has approximately a vertical dip. Note vertical offset of dark-toned shale bed, *A*, and difference in erosional character of topography on opposite sides of fault at *B*. Faint trace of fault in alluvium at *C* is locally marked by differences in drainage on opposite sides of the fault. Light-toned sandstone interbeds, *D*, cap local areas and exhibit serrated margins as a result of closely spaced joints. Fine-textured drainage is typical of the poorly resistant shale and thin sandstone interbeds.



Stereoscopic pair

FIGURE 84.—FAULTED, GENTLY DIPPING SEDIMENTARY ROCKS (UTAH).

[Approximate scale 1 : 20,000. Photographs by U.S. Geological Survey]

Conspicuous high-angle faults offset beds in many places, as at *A*, where limestone caprock is down-faulted about 125 feet. Note the effect of vertical exaggeration in the stereoscopic model on the amount of offset. Fault is indicated by scarp, *B*, and its alinement with stream at *C*. Note right-angle bend in stream at *D* along trace of fault. Another fault is indicated by alinement of stream *E* and break in vegetation *F*. Several other faults with only small displacements are shown by alinements at *G*. Resistant limestone caprock stands in vertical bluffs overlying less resistant shale and shaly siltstone that have a lesser angle of slope.

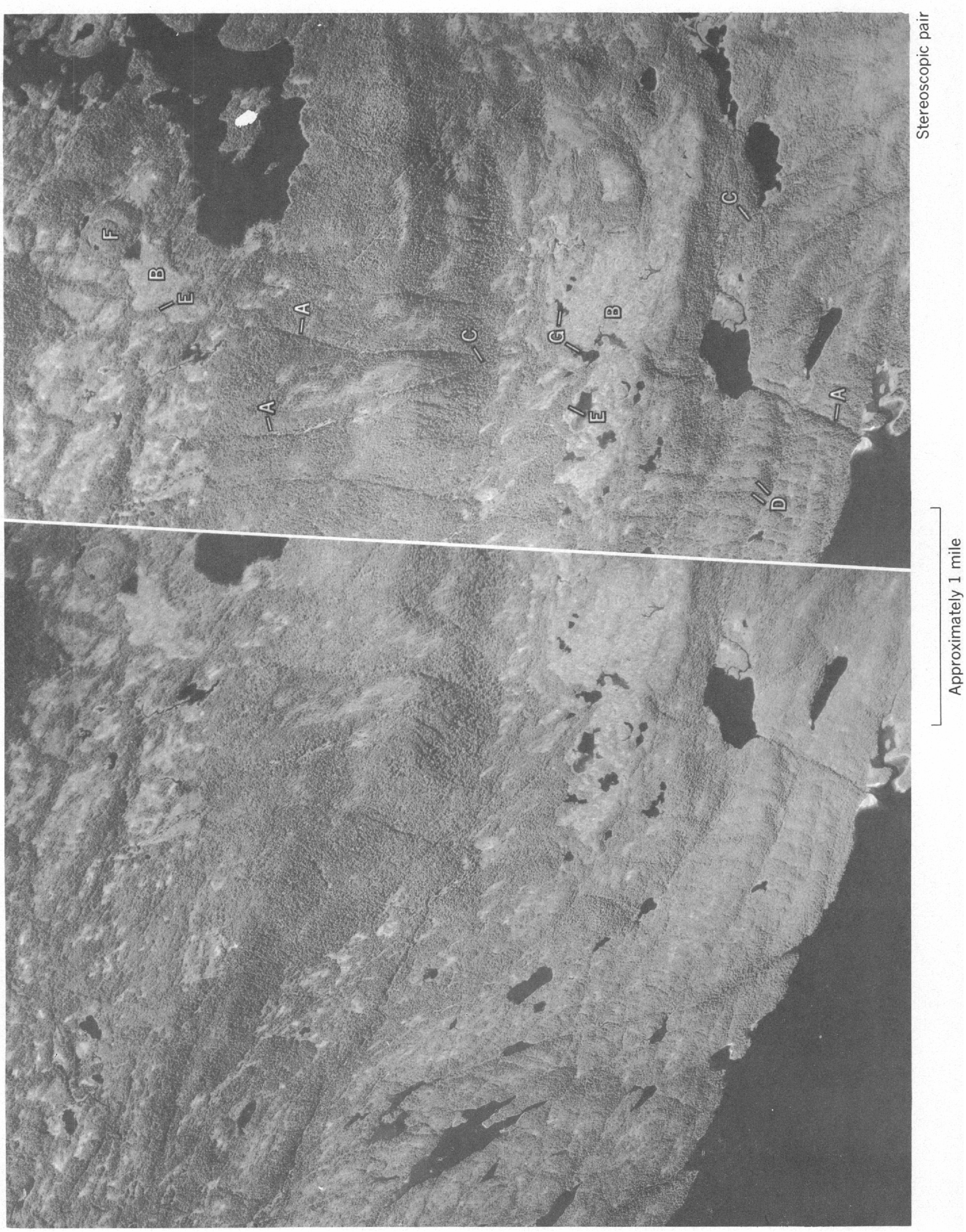
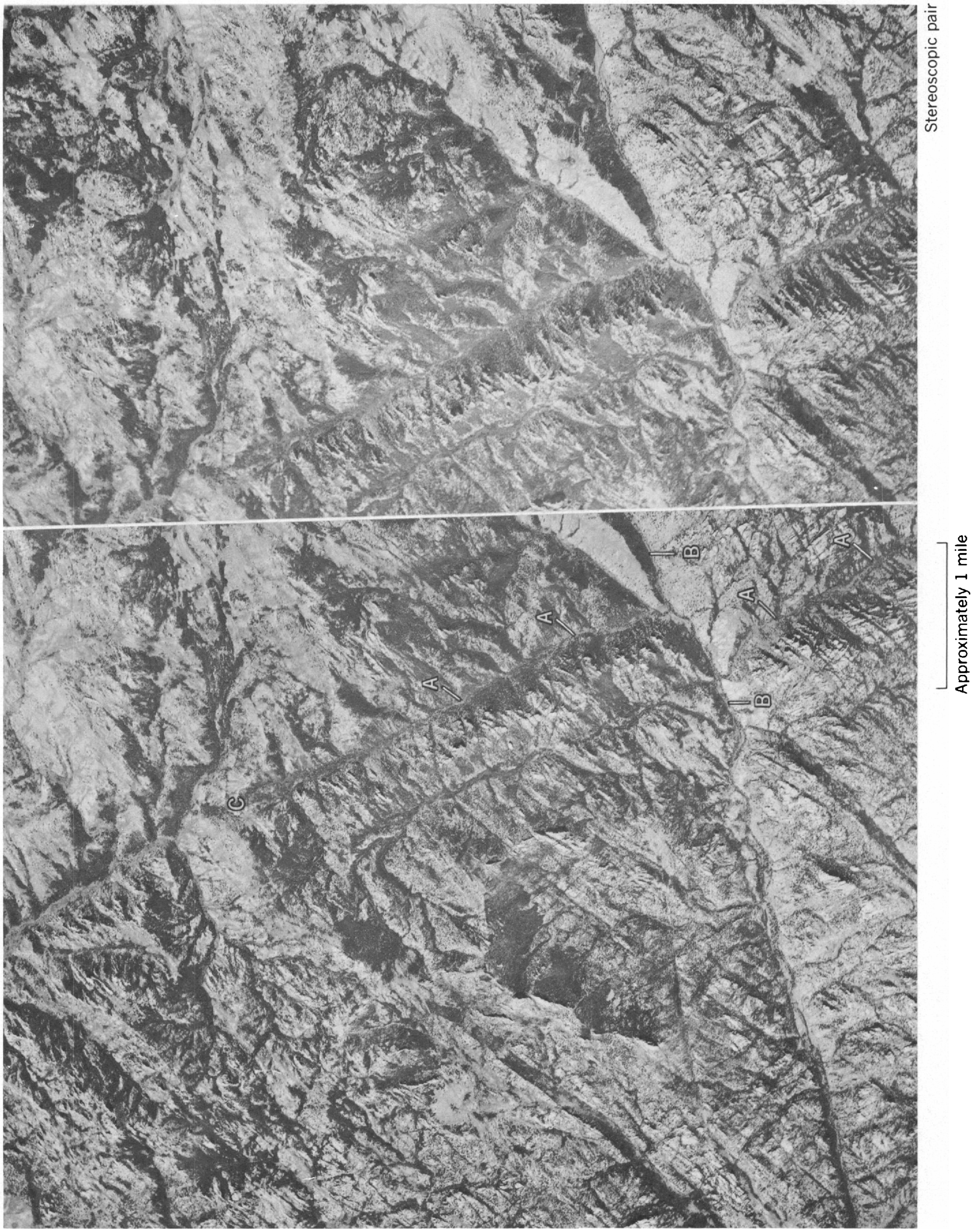

F
B
E
A
A
C
A
G
B
E
C
D
A
Stereoscopic pair
Approximately 1 mile

FIGURE 85.—VEGETATED TERRAIN UNDERLAIN BY IGNEOUS AND METAMORPHIC ROCKS LOCALLY COVERED BY BASALT FLOWS (SOUTHEASTERN ALASKA).

[Approximate scale 1 : 40,000. Photographs by U.S. Navy]

A significant contrast between the igneous and metamorphic complex and younger volcanic flows is shown in the distribution of faults and vegetation. Faults, indicated primarily by rectilinear depressions, *A*, are common in the igneous and metamorphic rocks, but are absent from the area of lava flows, *B*. Note that certain faults, as at *C*, may be traced up to the lava flows and that continuations of these faults may be picked up on the opposite side of the flow area. Some of the shorter lineations, as at *D*, probably represent wide-spaced joints. Lobate patterns of dark-toned vegetation, *E*, commonly delineate the edges of individual lava flows. Small cone at *F* is suggested by shape of constructional landform. Relatively flat, muskeg-covered flows are generally poorly drained and locally contain numerous shallow ponds, *G*, that lack any integrated drainage. The muskeg areas have a relatively light photographic tone because of the mossy vegetation and do not appear dark despite the abundance of moisture. The photographic texture of the muskeg areas is also distinctive.

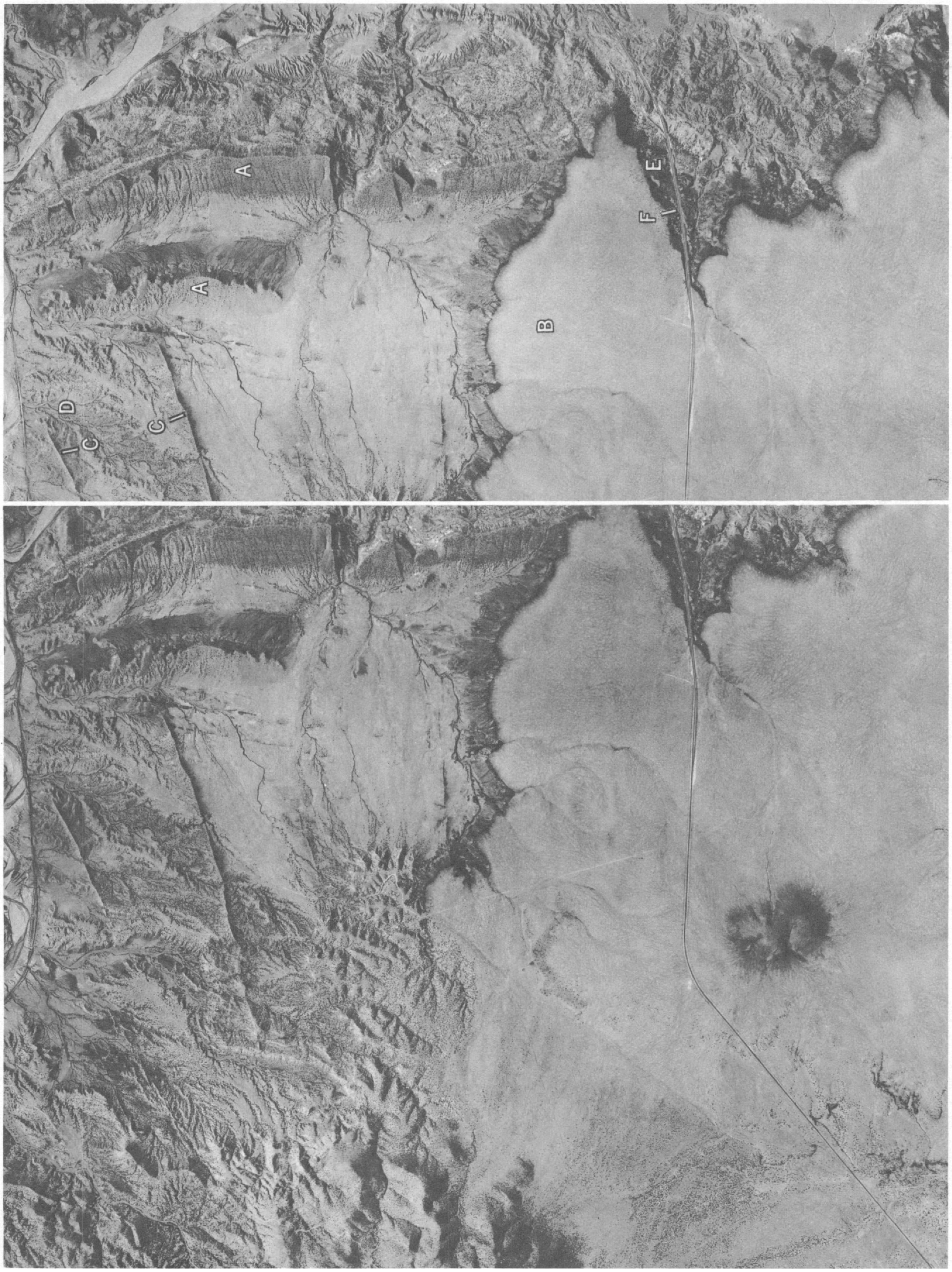

Stereoscopic pair
A
A
A
A
B
B
C
Approximately 1 mile

782-139 O - 65 - 15

FIGURE 86.—AREA OF CRYSTALLINE ROCKS (WYOMING).

[Approximate scale 1 : 60,000. Photographs by Army Map Service]

Numerous widely spaced joints, typical of many intrusive masses, are conspicuous, although widely varying orientations of joints, found in most plutonic rocks, are not prominent. Drainage is markedly controlled by faults and joints; the dendritic drainage that is normally characteristic of crystalline masses is thus subdued. Although the rocks shown here are locally gneissic, evidence of bedding of original sediments or gneissic structure is generally lacking. Major fault, *A*, marked by stream alinement, is offset by younger fault, *B*, also delineated by stream alinement. Note alinement of streams on opposite side of divide, *C*.



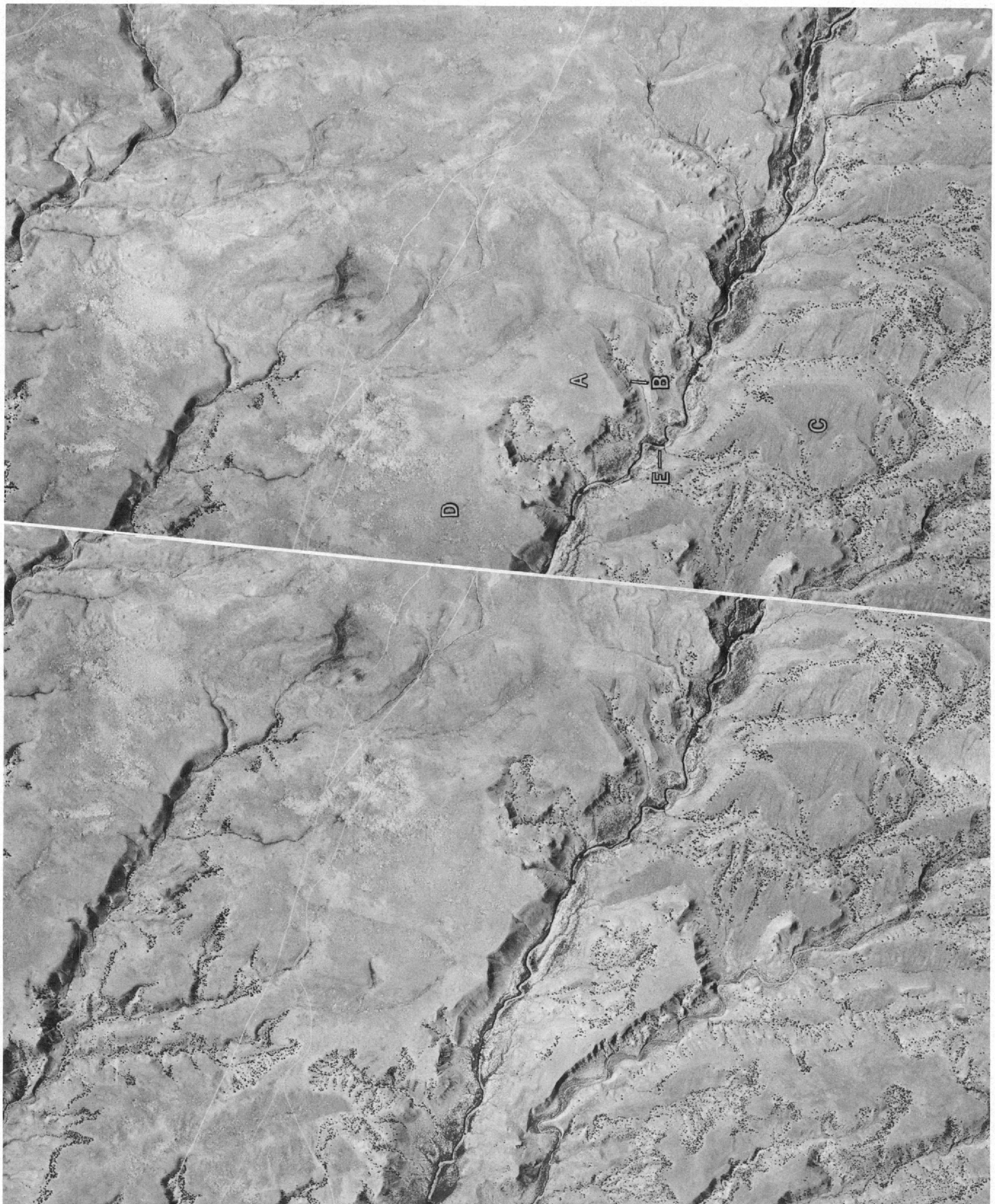
Stereoscopic pair

Approximately 1 mile

FIGURE 87.—LAVA FLOW LYING UNCONFORMABLY ON GENTLY DIPPING SEDIMENTARY ROCKS (NEW MEXICO).

[Approximate scale 1 : 54,000. Photographs by Army Map Service]

Resistant sandstone beds, *A*, dipping 15° are truncated by overlying lava flow, *B*. Bedding stands out where topographic and bedding surfaces coincide. Hogback landform is also prominent where resistant sandstone beds and intervening shale areas have been etched by erosion. Note how vertical exaggeration of dip causes unconformable relation between sedimentary beds and overlying lava flow to stand out. Surface of lava flow has mottled appearance that is typical of basalt flows in many areas. Basaltic dikes, *C*, stand in topographic relief above soft shale shown by fine-textured drainage at *D*. Some landsliding has taken place at *E* where resistant lava overlies less resistant rocks. Road alinement *F* is subject to potential destructive action of additional slides.



Stereoscopic pair

Approximately 1 mile

FIGURE 88.—GENTLY DIPPING SEDIMENTARY ROCKS OVERLAIN IN PART BY RIVER GRAVELS (UTAH).

[Approximate scale 1 : 20,000. Photographs by Commodity Stabilization Service]

Flat-lying gravel cap, *A*, truncates underlying sedimentary rocks. Traces of bedding below granular material of gravel cap are indicated by minor breaks in slope, *B*, accentuated by shadows. Surface drainage is conspicuously absent from well-drained broad gravel flat, *D*, which represents a younger, lower and less dissected terrace than *A*. Gullies in silty valley-fill, *E*, exhibit near-vertical slopes where recent stream dissection has taken place. Note effect of vertical exaggeration in the stereoscopic model. True dip of beds at *C* is about 6°.

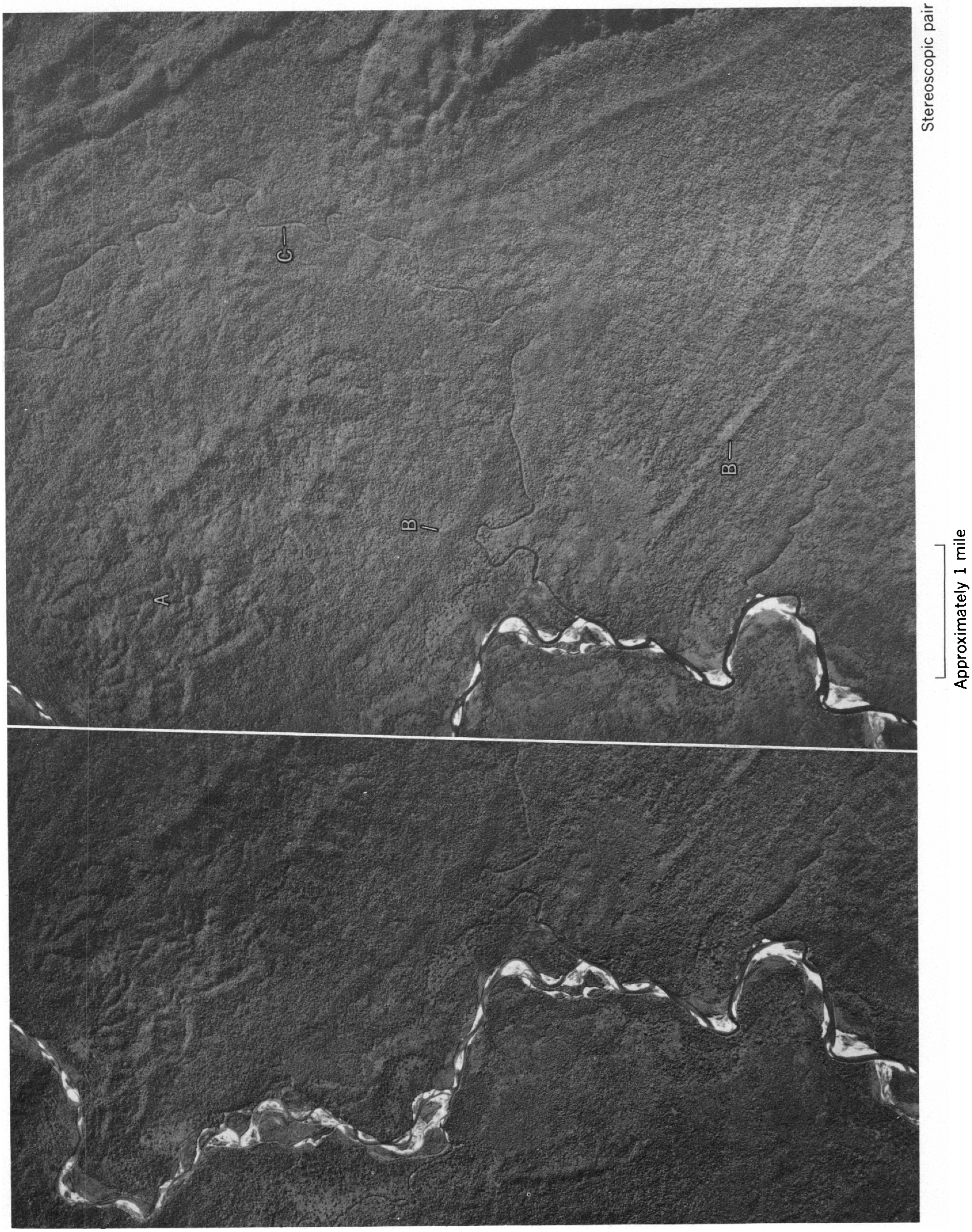
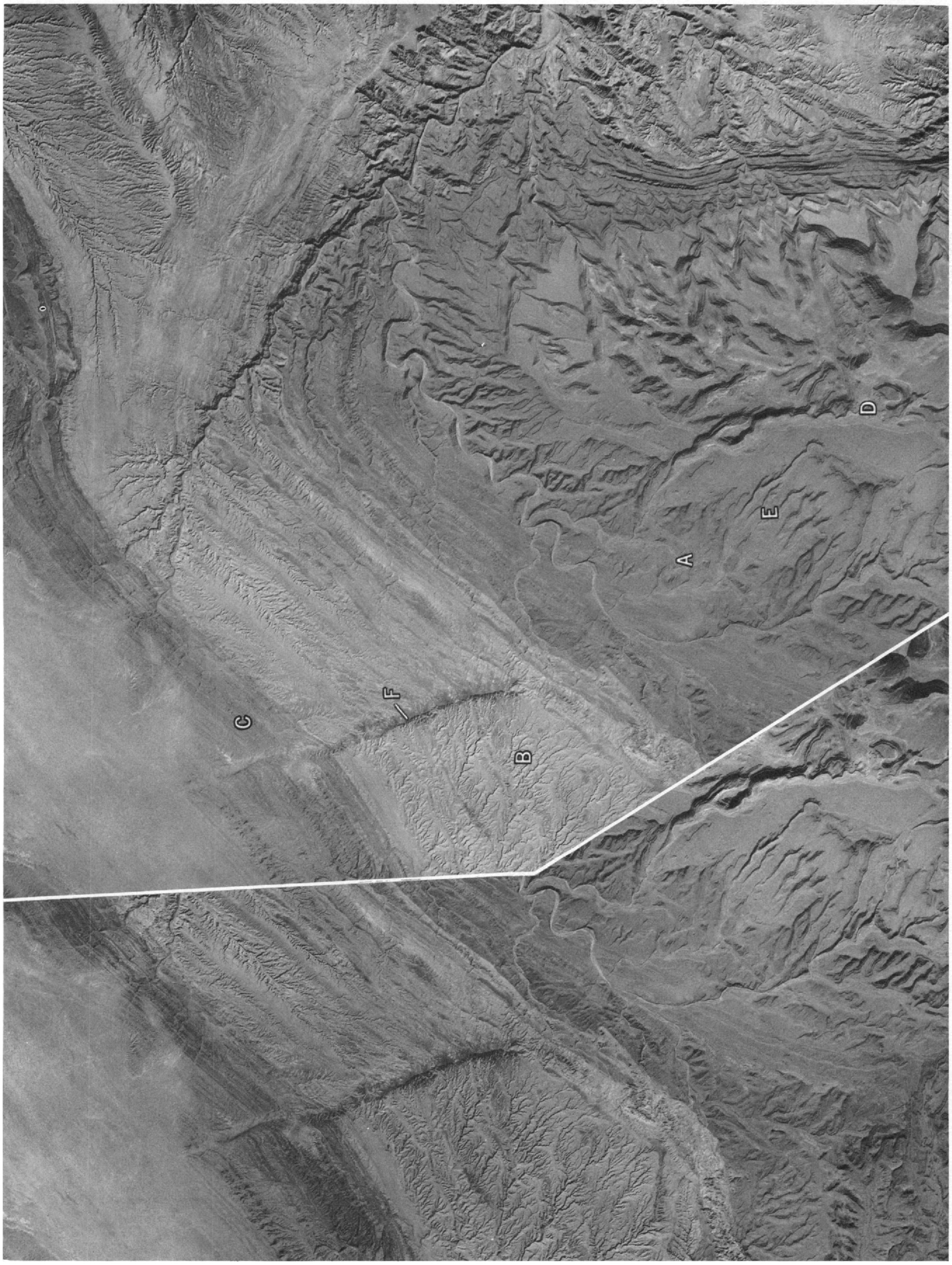

Stereoscopic pair
Approximately 1 mile
A
B
B
C

FIGURE 89.—GENTLY FOLDED SEDIMENTARY ROCKS IN HEAVILY VEGETATED AREA (NORTHERN GUATEMALA).

[Approximate scale 1 : 65,000. Photographs by Army Map Service; published with permission of the Guatemala Government]

Anticlinal structural feature in heavily vegetated jungle area is indicated by erosional characteristics of terrain and by drainage. Core of anticline, *A*, is topographically higher than surrounding area and is somewhat more dissected. Bedding and direction of dip are suggested by the topographically high bands of ground at *B*; note that tree crowns appear to fall in a dipping plane. Stream, *C*, has been deflected around the nose of the anticline; the convex side of the curve indicates the direction of plunge, but the major stream of the area has maintained its course across the anticline.



Stereoscopic pair

Approximately 1 mile

Figure 90.—PLUNGING ANTICLINE IN GENTLY FOLDED ROCKS (SOUTHERN UTAH).

[Approximate scale 1 : 37,000. Photographs by U.S. Geological Survey]

Distribution of rock types and characteristics of drainage clearly outline plunging anticline. Note that major stream curves around nose of the anticline and the convex side of the curve indicates the direction of plunge. Lithologic differences between formations are conspicuously shown by contrasts in photographic tone and erosional characteristics of terrain. Dark-toned formation, *A*, is an interbedded sequence predominantly of red sandstone and some mudstone and shale. Light-toned formation, *B*, is made up of a rather uniform weakly cemented massively bedded sandstone showing a fine-textured dendritic drainage. Drainage rills in formation *A* and *C* are controlled in part by hard, resistant sandstone interbeds that locally channel the drainage along the interbeds. Formation *C* largely comprises a series of red to brown silty sandstone and shale. Rocks at *D* include predominantly thin-bedded red sandstone and limestone interbeds. Bedding is prominently shown because topographic surfaces and bedding surfaces coincide in many places. Dip of sedimentary beds is exaggerated as in most stereoscopic models. True dip at *E* is 5°. Dark-toned resistant basalt dike, *F*, stands in relief above light-toned rocks.

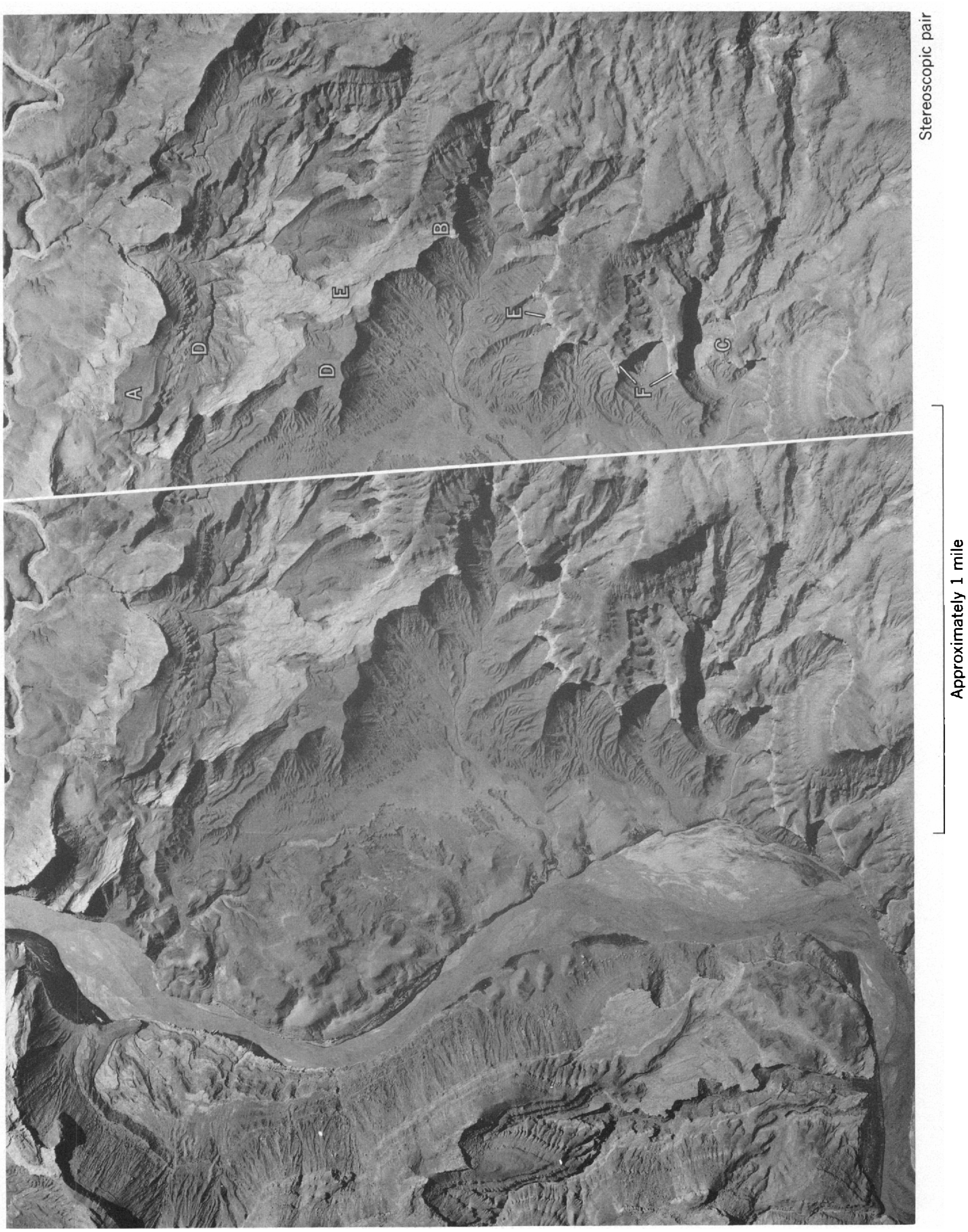
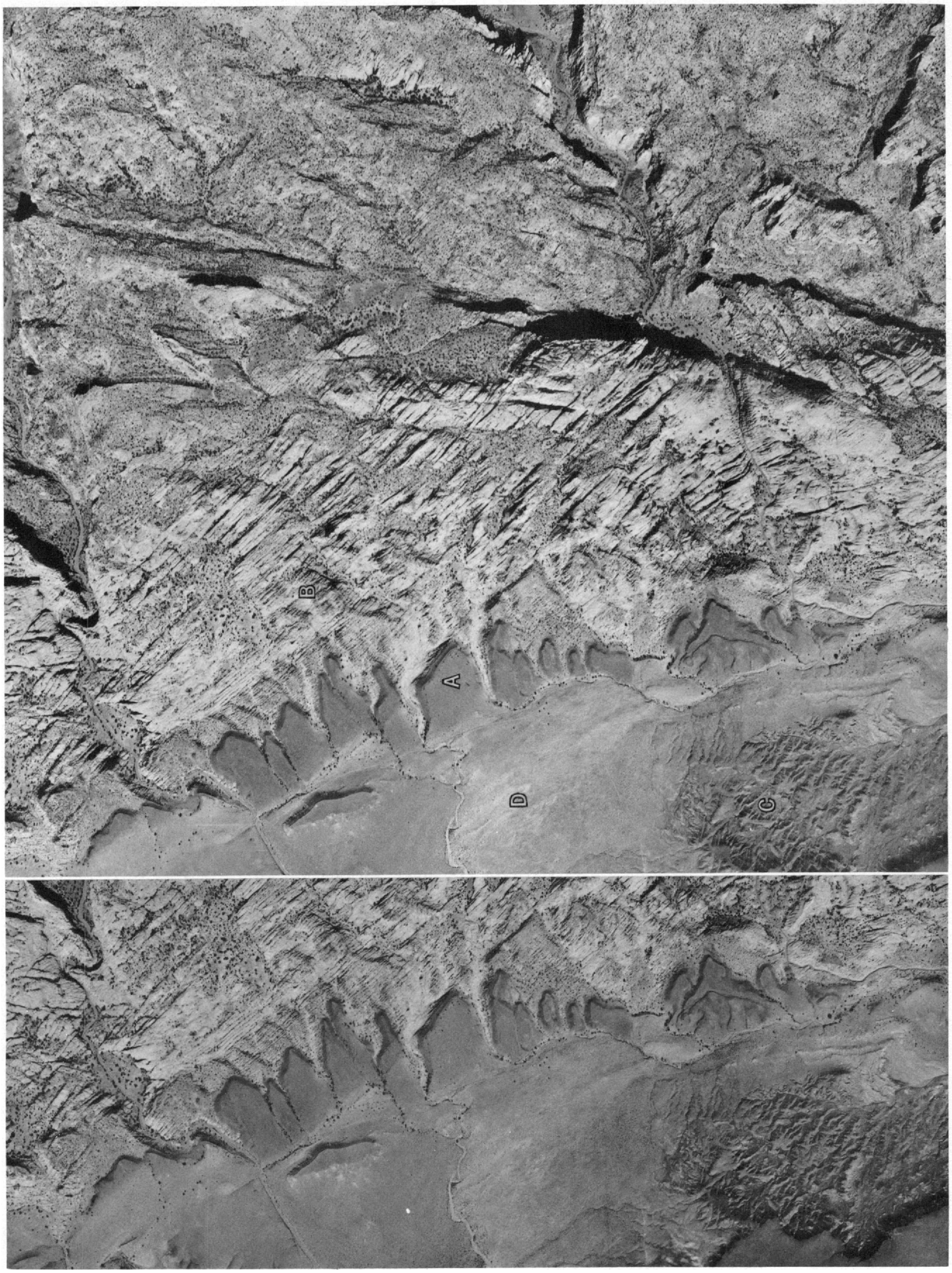

Stereoscopic pair
A
B
C
D
D
E
E
F
Approximately 1 mile

FIGURE 91.—STRATIGRAPHIC SECTION ACROSS GENTLY FOLDED ANTICLINE (UTAH).

[Approximate scale 1 : 20,000. Photographs by U.S. Geological Survey]

Breaching of anticline by major river has exposed cross section of the fold. Bedding is clearly represented at *A* where bedding surfaces coincide with topographic surfaces. Effect of vertical exaggeration on dip is shown on both flanks of the anticline. True dip at *A* is about 20° ; at *B* the beds are horizontal; at *C* the dip is about 4°. Shale, siltstone, and fine-grained sandstone, *D*, exhibit dark photographic tones; relatively closely spaced joints may be seen locally. Coarse sandstone with some conglomerate, *E*, has light photographic tone; widely spaced joints are present as at *F*. The coarse-grained rocks characteristically form cliffs. Where beds are nearly horizontal the fine-grained rocks have slopes that are less steep than those of the coarse-grained rocks. Where beds are dipping, the softer rocks are in many places etched out by erosion leaving hogbacks of resistant rock types.



Stereoscopic pair

Approximately 1 mile

782-139 O - 65 - 16

FIGURE 92.—GENTLY DIPPING SEDIMENTARY ROCKS ON EAST SIDE OF SAN RAFAEL SWELL (UTAH).

[Approximate scale 1 : 20,000. Photographs by U.S. Geological Survey]

Bedding on flank of fold is clearly shown by photographic tone differences and hogback landform where dip surfaces and topographic surfaces coincide. Note effect of vertical exaggeration on dip in the stereoscopic model; beds at *A* have true dip of 6°. Massive crossbedded sandstone, *B*, has light photographic tone and widely spaced joints oriented predominantly in one direction; locally its appearance on aerial photographs is similar to some igneous rocks. Dark-toned resistant beds, *A*, are red mudstone and lenticularly bedded medium-grained sandstone. Poorly resistant interbedded red limy sandstone, mudstone, and limestone, *C*, is easily eroded and has fine-textured drainage. Beds at *C* are flat lying. Windblown sand, *D*, is marked by absence of surface drainage channels.

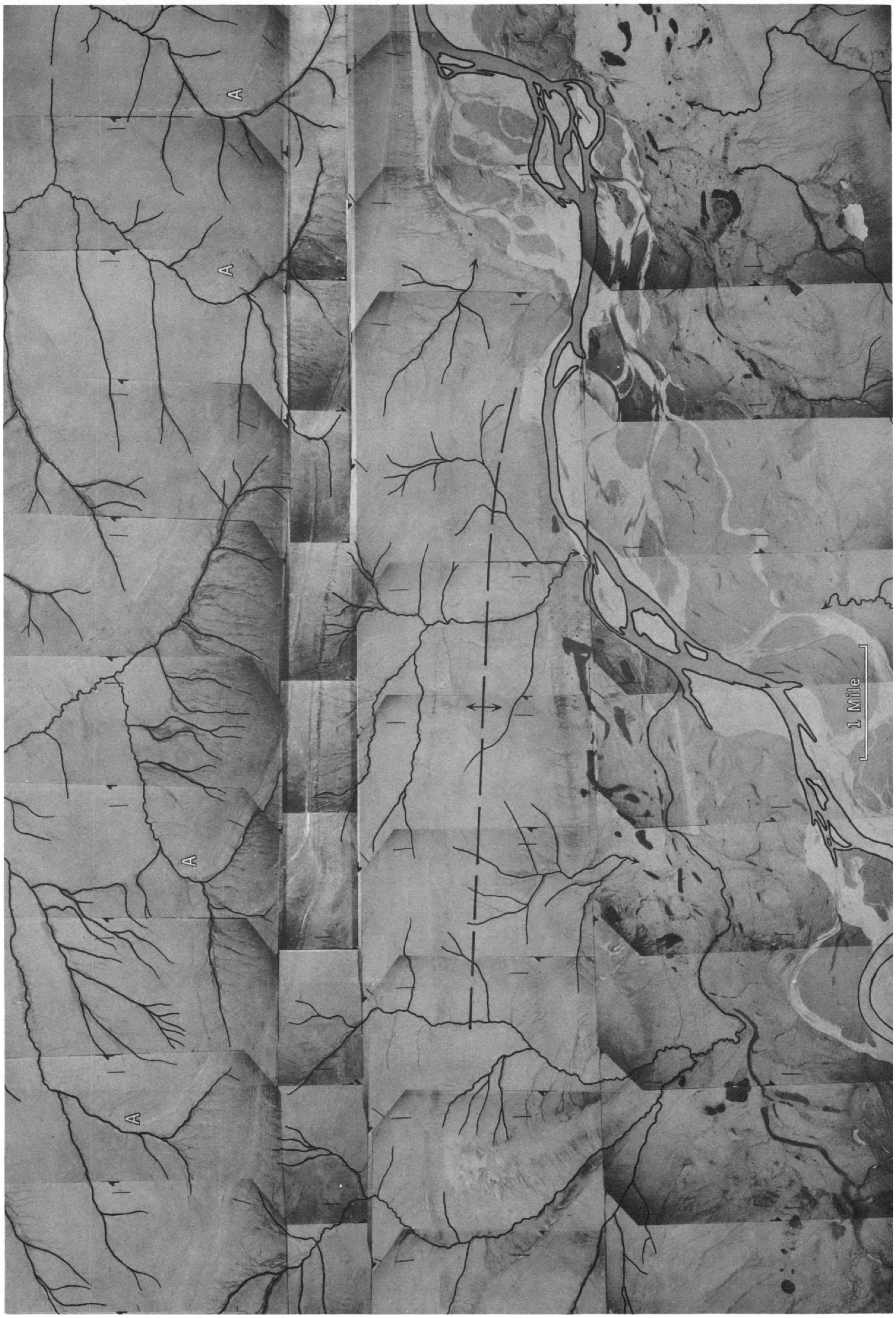
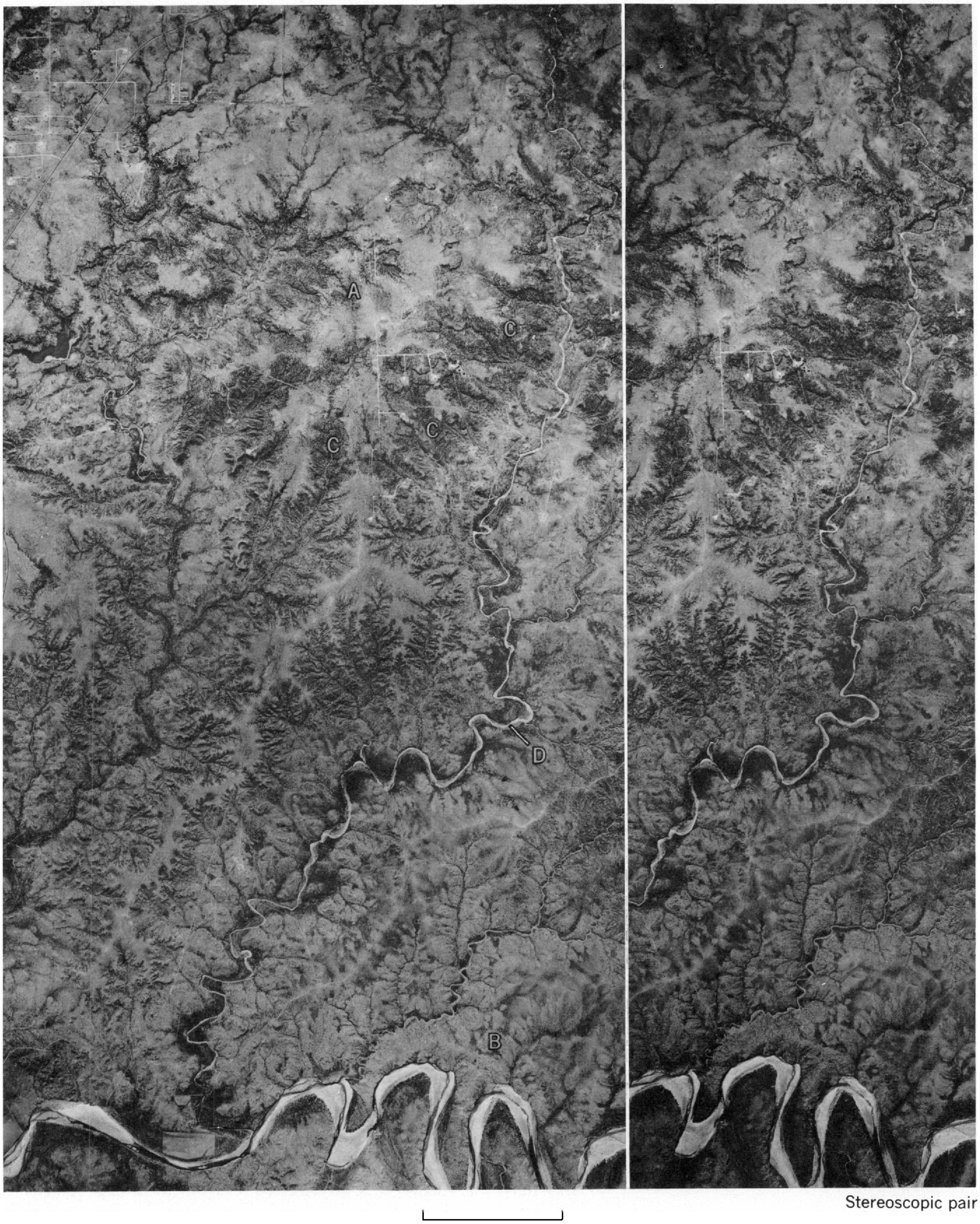

A
A
A
A
1 Mile

FIGURE 93.—UNCONTROLLED MOSAIC OF UMIAT ANTICLINE AREA, NORTHERN ALASKA, UNDERLAIN BY SHALE, SANDSTONE, CONGLOMERATE, AND GRAYWACKE.

[Photographs by U.S. Navy]

Curvature of streams, *A*, has developed on flank of anticline where hard and soft interbeds are exposed. Anticline has been breached into soft shale permitting streams developed on the more resistant dip slope to curve along soft interbeds and not across the axis of the fold. Contrast figure 81 where stream curvature indicates position of structural axis and direction of structural plunge.



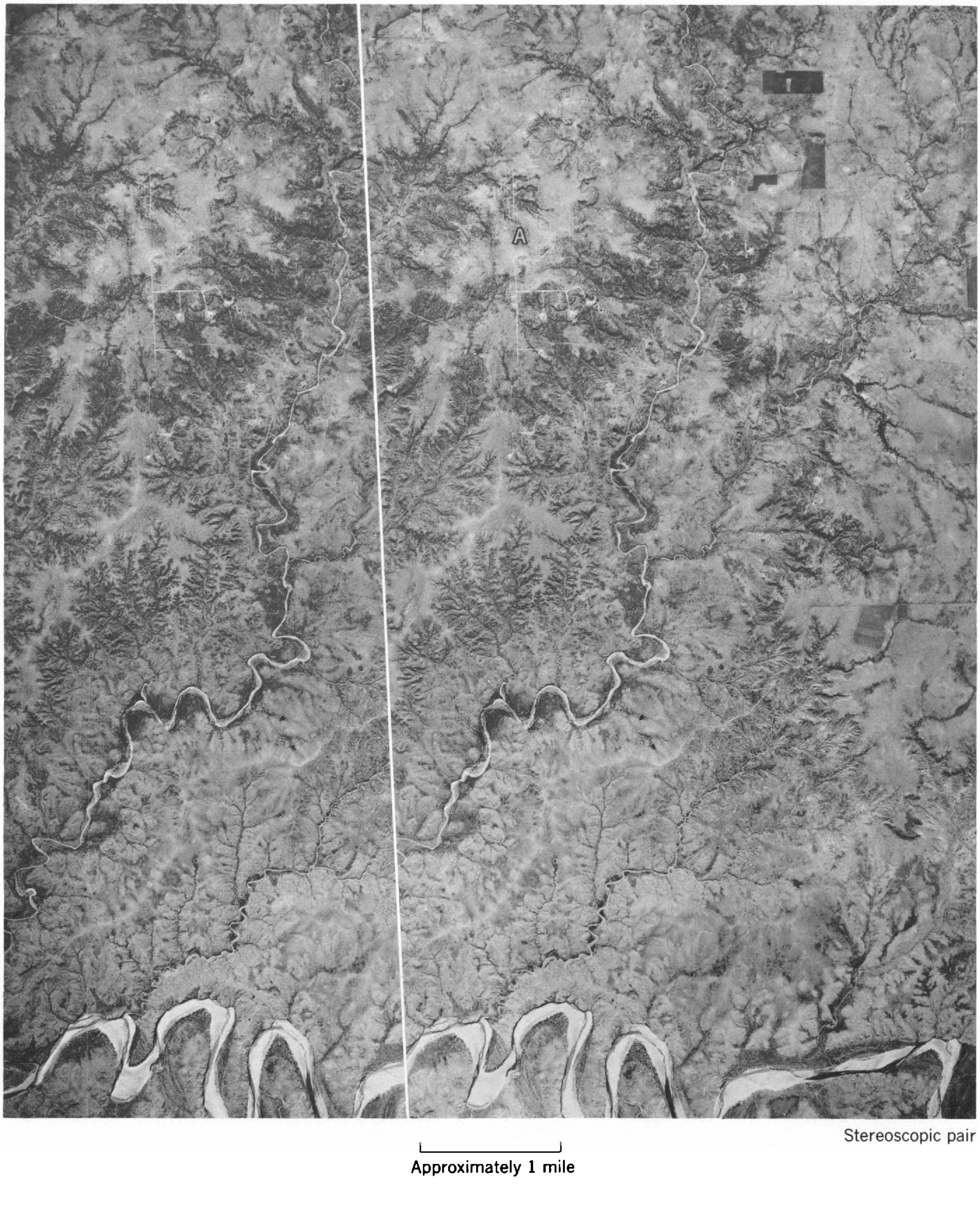
Stereoscopic pair

Approximately 1 mile

FIGURE 94.—SUBSURFACE STRUCTURE REFLECTED IN SURFACE DRAINAGE CHARACTERISTICS (TEXAS).

[Approximate scale 1 : 63,360. Photographs by Army Map Service]

Subsurface structures at *A* and *B* are suggested by drainage characteristics of the area. Streams flanking the structure at *A* curve around the structure in their headwater portions. Tributary streams drain radially off the structure (see figures 9 and 95). In addition, the crudely circular pattern of more highly dissected ground and the pattern of dark photographic tone, *C*, which results from a concentration of vegetation, suggest subsurface structure. Compressed meanders are present over a subsurface structure at *B*. Also note stream deflection downstream from *D* which is a further suggestion of subsurface structure in area *B*.



Stereoscopic pair

FIGURE 95.—SAME PHOTOGRAPHS AS FIGURE 94, BUT REVERSED TO SHOW PSEUDOSCOPIC EFFECT AS AN AID TO INTERPRETATION.

[Approximate scale 1 : 63,360. Photographs by Army Map Service]

Reversal of the positions of two aerial photographs of a stereoscopic pair produces the well-known pseudoscopic effect, in which stream valleys appear as ridges and hills look like depressions. This unnatural view of the terrain commonly accentuates stream characteristics, which may be significant indicators of subsurface structure, as at *A*. The pseudoscopic view also commonly facilitates plotting of drainage.


KUGRUA RIVER
KUNGOK RIVER
70°45'
70°30'
N
2 Miles

FIGURE 96.—UNCONTROLLED MOSAIC OF WAINWRIGHT AREA, NORTHWESTERN ALASKA.

[Photographs by U.S. Navy]

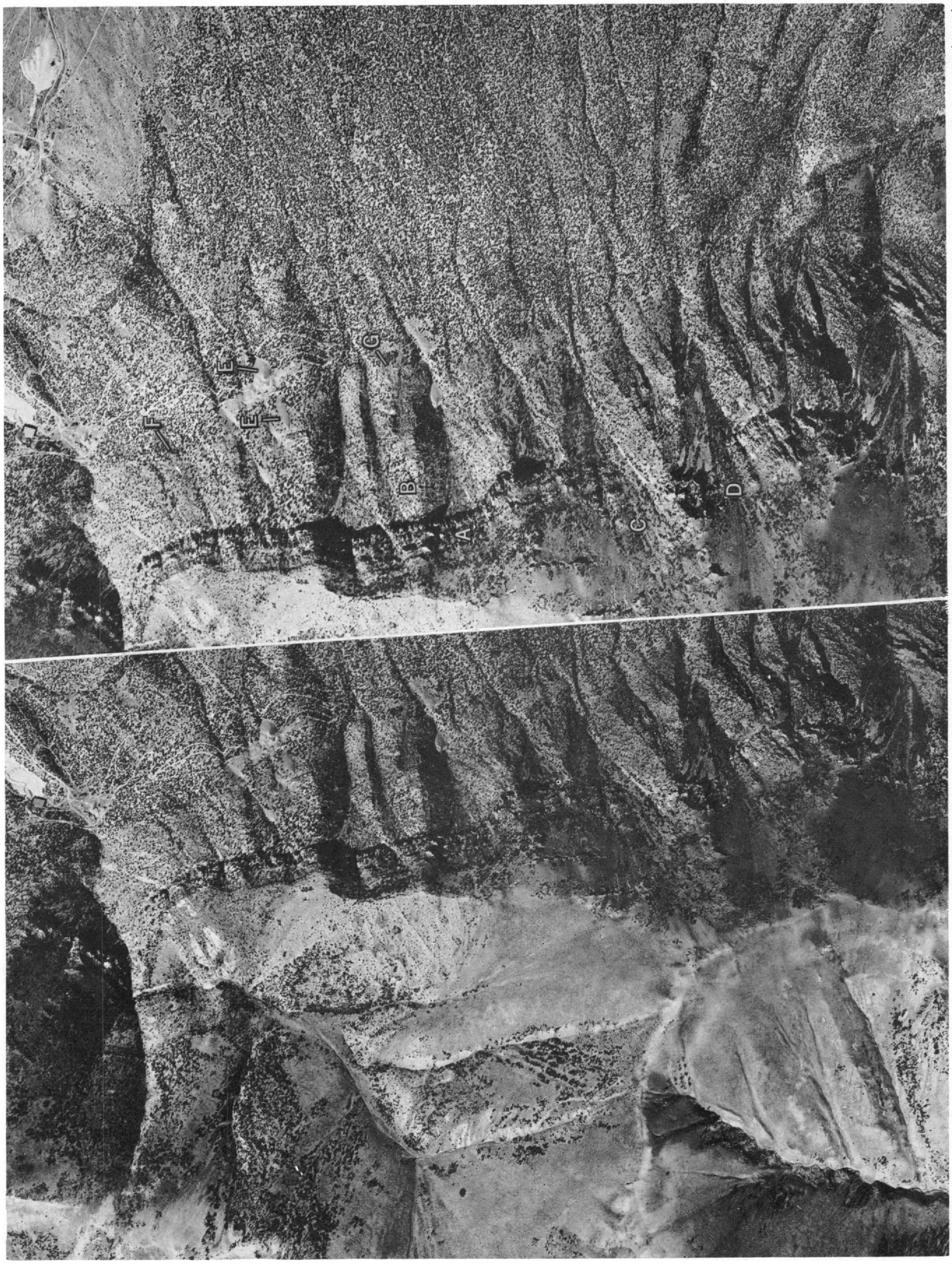
The radial-dendritic drainage pattern shown is anomalous to the Arctic coastal plain where northward-flowing streams predominate. Local relief across the area is only a few feet per mile. The radial drainage pattern, suggestive of subsurface structure, is readily seen on the small-scale mosaic but could be easily overlooked on single photographs or individual stereoscopic pairs. Note the northward deflection of the Kugrua River; the abrupt change in direction of streamflow is believed due to subsurface structure. Seismic work indicates a structural nose plunging southeast in the north-central part of the area. Outcrops are sparse in the area and surface indications of structure, other than drainage pattern, are generally lacking. The drainage pattern of this area is similar to that of an area to the southeast where gas was found in a subsurface structure that had been defined by geophysical methods.


C
C
A
B
B
Stereoscopic pair
Approximately 1 mile

FIGURE 97.—AREA UNDERLAIN PREDOMINANTLY BY GENTLY DIPPING SANDSTONE AND SHALE (NORTHERN ALASKA).

[Approximate scale 1 : 20,000. Photographs by U.S. Navy]

Sandstone beds stand out because of photographic tone, relief, and vegetation changes, as at *A*. As these sandstone beds are traced across the area they lose their topographic expression, as at *B*, and are replaced by shale of the underlying formation. The rate of "shaling" or change of facies from sandstone to shale can be calculated from quantitative studies of the aerial photographs, and the direction of maximum thinning of the sandstone section determined. Note the effect of vertical exaggeration on dip of resistant sandstone beds; true dip is 7° to 8° in this area. Effect of vertical exaggeration is also shown at *C* where minor topographic breaks in slope, accentuated by shadows, reflecting thin resistant beds stand out.



Stereoscopic pair

Approximately 1 mile

782-139 O - 65 - 17

FIGURE 98.—GENTLY DIPPING SEDIMENTARY ROCKS CUT BY HIGH-ANGLE FAULTS (NEVADA).

[Approximate scale 1 : 20,000. Photographs by Soil Conservation Service]

Topographic expression of resistant, jointed quartzite bed, *A*, permits differentiation of quartzite and underlying carbonate sequence of rocks, *B*. High-angle faults, transverse to the strike of bedding are shown at *C* and *D* by the vertical offset of the quartzite bed. The contact of quartzite and underlying carbonate rocks is the locus of polymetal sulfide veins, but the veins cannot be seen in the stereoscopic model. Note mine dumps, *E*, marking location of crosscuts to base of the quartzite, which dips into the slope about 20° to 25°. Direction of dip is clearly indicated by V in outcrop pattern of quartzite bed where major stream cuts through the ridge. Trace of a major fault with several thousand feet displacement is only weakly shown parallel to slope at *F* and *G* where density of vegetation is slightly greater on the downhill side of the fault trace.


Stereoscopic pair
Approximately 1 mile
A
B
C

FIGURE 99.—COMPLEXLY FOLDED AND FAULTED AREA OF GREENSTONE, SCHIST, LIMESTONE AND MARBLE (SOUTHEASTERN ALASKA).

[Approximate scale 1 : 40,000. Photographs by U.S. Navy]

Relatively dark-toned highly fractured rocks, *A*, are greenstone and greenstone schist. Light-toned profusely fractured rocks, *B*, are limestone and marble. Prominent lineations, *C*, are representative of faults along which rich gold-quartz veins have been found in this area. Note that fault lineations characteristically are rectilinear depressions.

Stereoscopic pair

Approximately 1 mile

FIGURE 100.—IGNEOUS AND METAMORPHIC TERRAIN (SOUTHEASTERN ALASKA).

[Approximate scale 1 : 40,000. Photographs by U.S. Navy]

In this area lead and silver deposits are found locally along the contact of intrusive quartz diorite and metamorphic rocks. Smooth slopes, *A*, are underlain by metamorphic rocks. The closely spaced parallel ridges and depressions, *B*, reflect foliation in the metamorphic rocks. Depressions, *C*, probably represent solution cavities in carbonate interbeds. Lineations, *D*, transecting the foliation direction are believed to be expressions of faults. The uneven surface, *E*, cut by a crisscross of joints is underlain by quartz diorite. This pattern of lines representing joints is typical, but not necessarily diagnostic, of intrusive rocks. The contact of igneous and metamorphic rocks is in the conspicuous saddle between *A* and *E*.

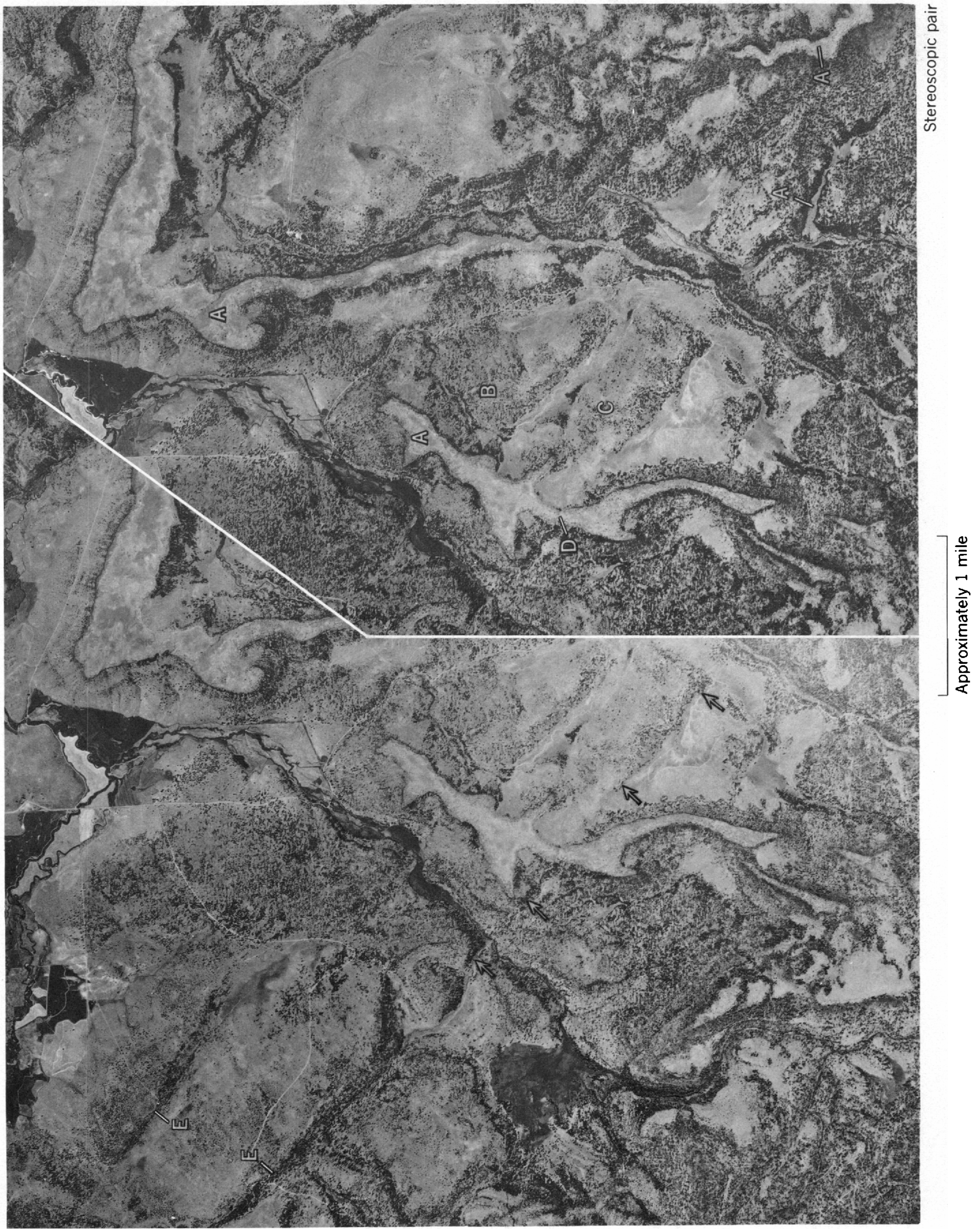
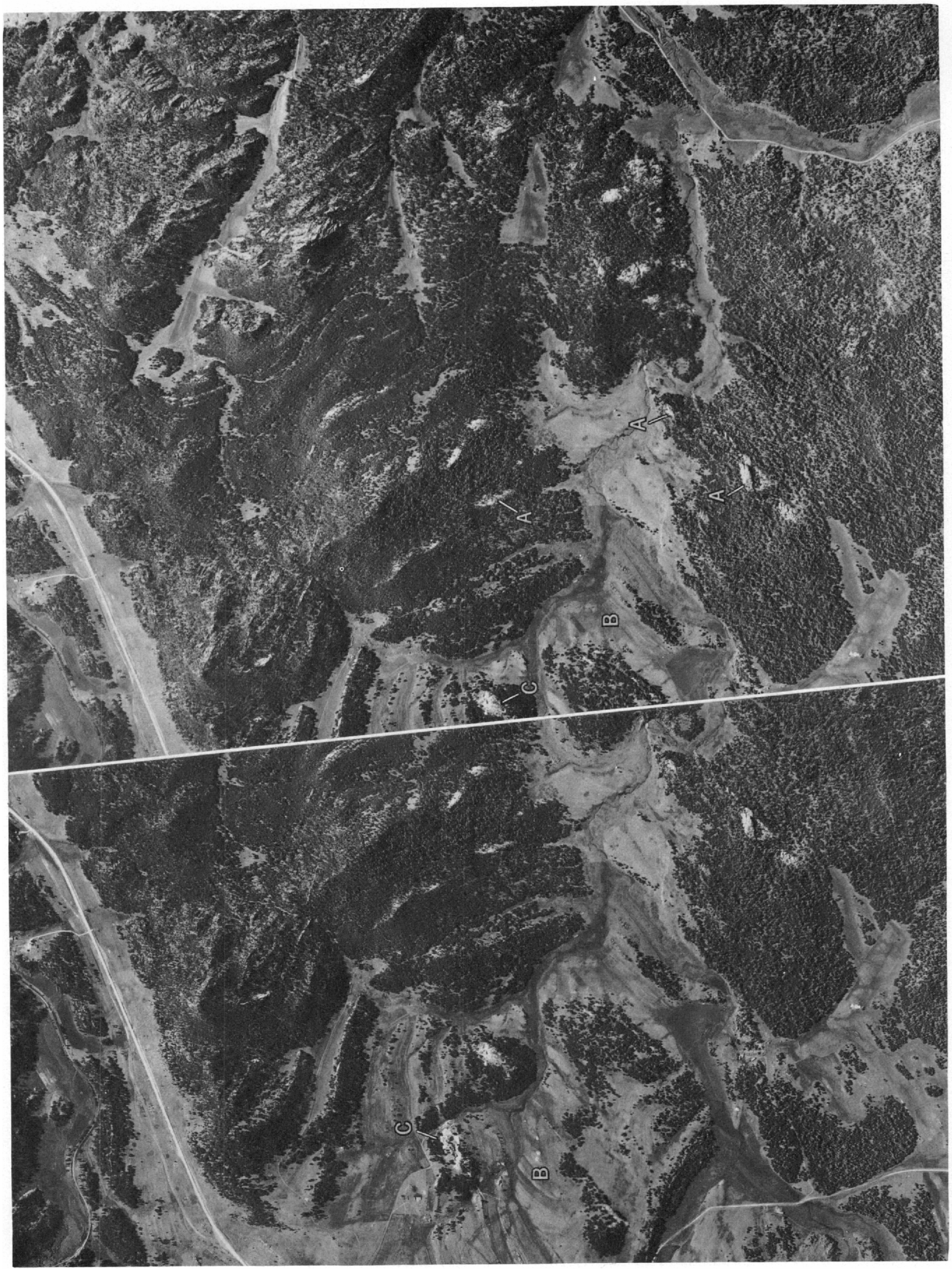

Stereoscopic pair
A
A
A
A
B
C
D
E
E
Approximately 1 mile

Figure 101.—GENTLY TILTED AND FAULTED LAVA FLOWS (OREGON).

[Approximate scale 1 : 54,000. Photographs by Army Map Service]

Perched remnants of basaltic lava, *A*, form skeletal dendritic pattern, which suggests that lava filled former stream valleys. In some areas perched lava remnants are known to cover older auriferous stream gravel. Several faults are indicated by alinements of stream segments, vegetation lines, and photographic tone contrasts (see alinement of arrows). Dip on flow surfaces, as at *B*, may be readily estimated or measured from aerial photographs because of the relatively large area examined in a single view, and because of vertical exaggeration of the dip slope. Note that the younger flow, *A*, has a gentler dip than the older flows, *B* and *C*. Surfaces *B* and *C* may be correlative and separated by a fault in the intervening valley. At point *D* the younger perched lava flows are also faulted, but throw is considerably less than where older lava flows are displaced by the same fault. In some areas faults displace only the older rocks and do not offset the most recent flows. A long period of fault activity is thus suggested. Note that in monoscopic view fault alinements, *E*, accentuated by vegetation, are striking.



Stereoscopic pair

Approximately 1 mile

Figure 102.—AREA OF PEGMATITE DIKES (SOUTH DAKOTA).

[Approximate scale 1 : 24,000. Photographs by U.S. Geological Survey]

Pegmatites in the area shown are generally concordant with schistosity and bedding of quartz-mica schist country rock. In many places the pegmatite dikes stand in topographic relief above the surrounding schist, as at *A*. The massive, jointed character of the larger pegmatite dikes is similar to other intrusive rocks and contrasts with the thin-bedded schistose rocks. Thin pegmatite dikes commonly cannot be distinguished in the aerial photographs and only general contact areas can be mapped for most of the wide pegmatite dikes because of the vegetation cover. Locally steeply dipping schist also stands in topographic relief; these rocks can be distinguished by the sheeted character of the outcrops. General structural trends are reflected in topographic expression of parallel ridges and in photographic tones of vegetation in fields, *B*. Note mining activity in pegmatite at *C*.

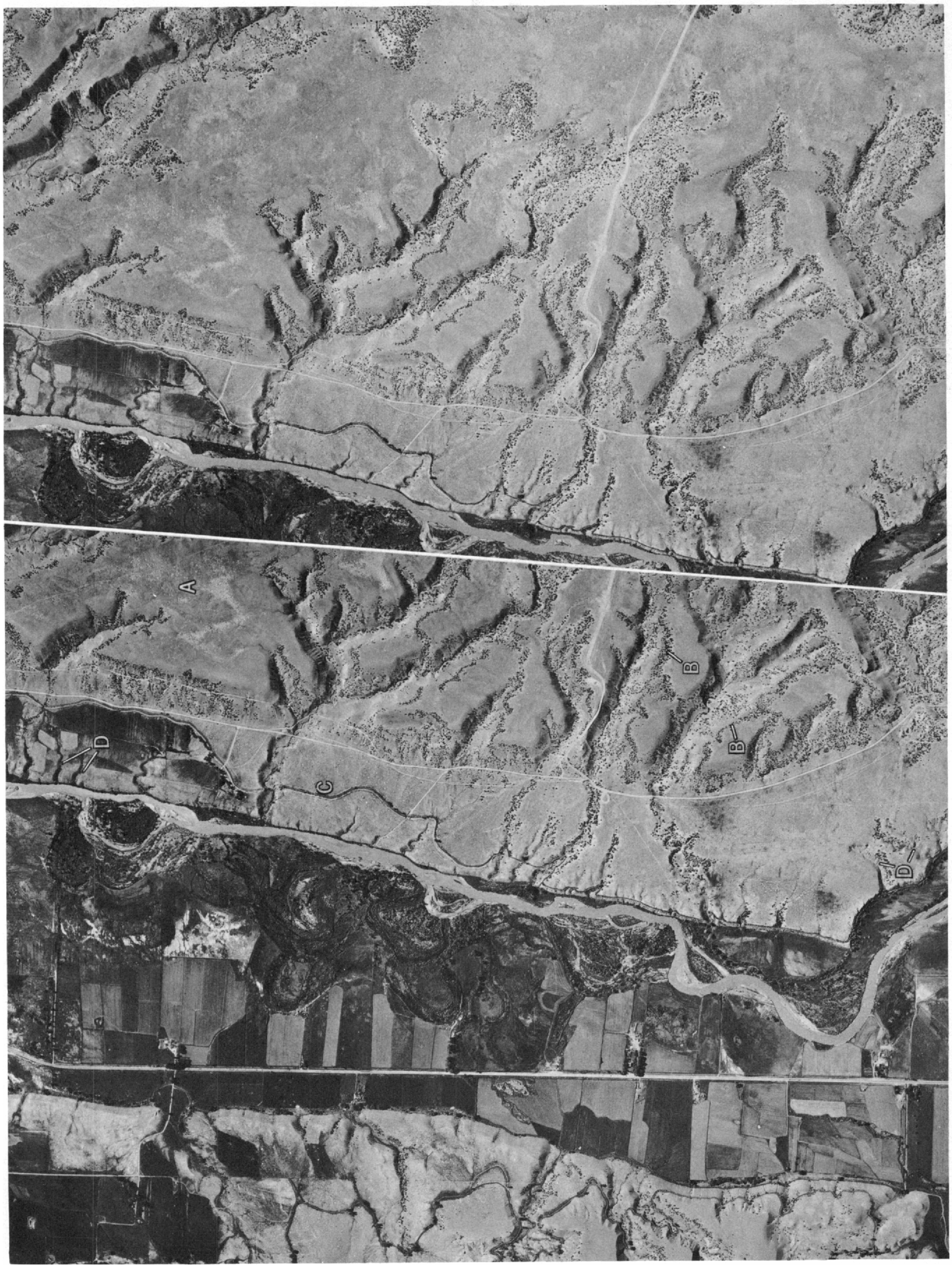
Stereoscopic pair

Approximately 1 mile

FIGURE 103.—METAMORPHOSED SEDIMENTARY ROCKS INTRUDED BY QUARTZ MONZONITE (CALIFORNIA).

[Approximate scale 1 : 47,000. Photographs by U.S. Geological Survey]

Metamorphic rocks here are generally dark toned, as at *A*, and locally show prominent banding; joints are closely spaced and are not conspicuously shown on the photographs. Quartz monzonite, *B*, is relatively light toned and lacks banding, but like most intrusive igneous rocks it has a strong development of irregularly and widely spaced joints that are readily seen in the stereoscopic model. Light-toned streaked, prominent talus slopes, *C*, have formed where the fine-grained metamorphic rocks are present. In areas of igneous rocks the talus slopes are less well developed; locally large individual talus blocks can be observed at the bases of slopes. A fault trace is suggested by conspicuous linear feature, *D*. Note alinement of short straight linear segments, *E*, on opposite sides of divide; these linear traces may represent the trace of a fault or the prominent development of joints.



Stereoscopic pair

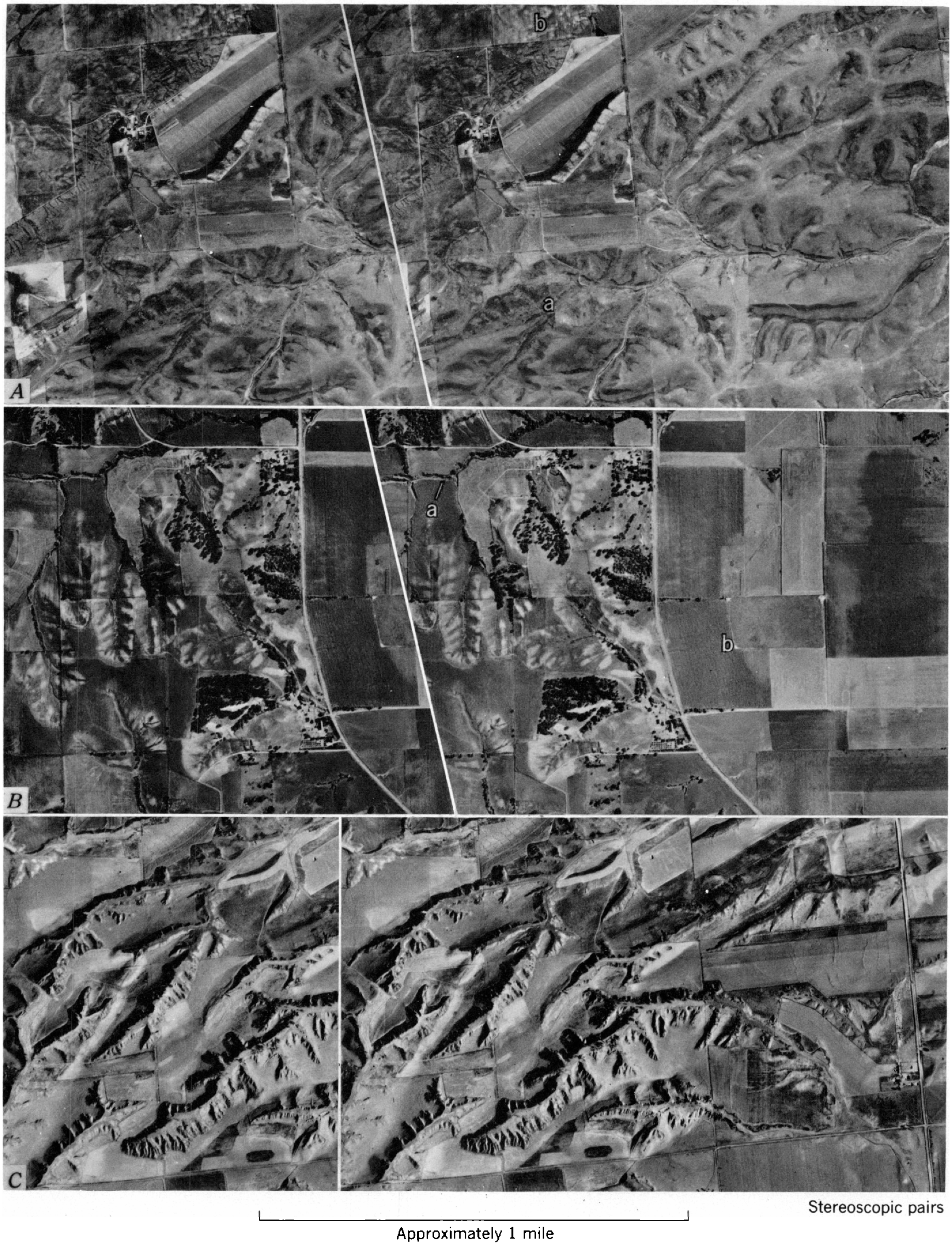
Approximately 1 mile

782-139 O - 65 - 18

FIGURE 104.—DISTINCTIVE LANDFORM OF GRAVEL TERRACES ALONG A MAJOR STREAM (NORTHEASTERN UTAH).

[Approximate scale 1 : 20,000. Photographs by Commodity Stabilization Service]

The steplike landform of terraces is conspicuous. Other elements of the soil pattern—vegetation, drainage, and erosional characteristics—provide significant information to the photointerpreter. Absence of surface drainage, as at *A*, suggests well-drained materials. At *A* the material is composed of coarse bouldery gravel that has good internal drainage. Vegetation, *B*, is prominent along edges of upper terrace gravel cap where water emerges from the gravel. Lower terraces, as at *C*, are more continuous and less dissected than the older terraces at higher altitudes, although recent streams in conspicuous V-shaped gullies, *D*, dissect the edge of the terrace. Terrace deposits commonly are favorable reservoirs for ground-water storage; in addition they provide a ready source of some materials used by the construction engineer.



Stereoscopic pairs

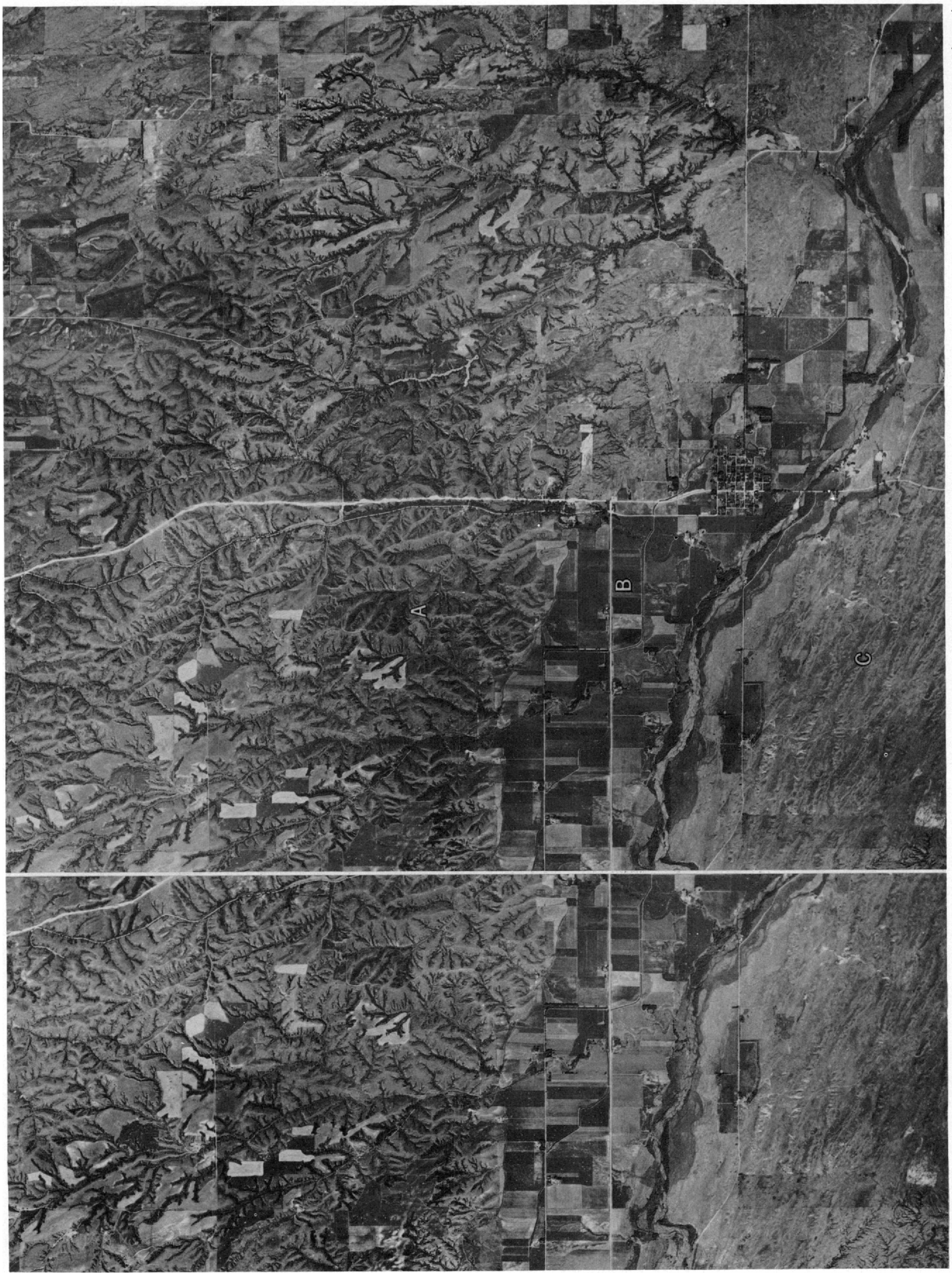
FIGURE 105.—AREAS SHOWING DRAINAGE CHARACTERISTICS IN SURFICIAL MATERIAL THAT IS PREDOMINANTLY LOESS.

[Approximate scale 1 : 20,000. Photographs by Commodity Stabilization Service]

Figure *A*. Contrasting drainage characteristics and differences in photographic tones in areas *a* and *b* suggest differences in character of the surficial materials. The modified dendritic drainage and scoop-shaped valley heads are typical of dissected loess areas, *a*. Lack of surface drainage rills is a feature of sand dune areas, *b*, where materials are coarse-grained, highly permeable, and drainage is largely internal. Note light-and-dark mottled soils in sand dune area. The fine-grain size of loess is believed responsible for the fine-textured drainage (Iowa).

Figure *B*. As in area shown in figure *A*, the dissected loess hills exhibit a modified dendritic drainage pattern. Recent erosion has cut deep narrow and sharply defined channels in the bottoms of broad valleys, as at *a*. Gully walls are essentially vertical. Note characteristic scoop shape of side drainage and serrated ridges along some divides. Light streaks due to thin grass cover or to cultivation are typical of many loess areas. Broad, flat river flood plain, *b*, has good internal drainage and exhibits a lack of visible surface drainage channels (Nebraska).

Figure *C*. Deeply dissected loess hills have drainage pattern similar to areas shown in figures *A* and *B*, but erosion may have proceeded more rapidly than in other areas. Valley walls are sharply defined. Steep valley walls commonly characterize loess (Nebraska).



Stereoscopic pair

Approximately 1 mile

FIGURE 106.—AREA OF SURFICIAL DEPOSITS, PRIMARILY WINDBLOWN (CENTRAL NEBRASKA).

[Approximate scale 1 : 67,000. Photographs by Army Map Service]

Highly dissected loess hills, *A*, abut against well-drained alluvial terraces, *B*. Extensive dissection of loess has resulted in a fine texture of erosional topography and fine-textured drainage. Bottoms of many valleys in loess are notched by recent stream dissection. The modified dendritic drainage pattern is typical of loess area. Note absence of surface drainage rills in terrace alluvium, *B*, and elongate windblown sand hills, *C*, indicating the highly permeable nature of the underlying materials. Loess is generally considered well drained internally and is thus an exception to the general association of fine-textured drainage and impermeable soils. The fine-textured drainage in loess is believed to be a result of the fine grain size. Contrast appearance here of drainage density in loess with drainage density on large-scale photographs of figure 105.

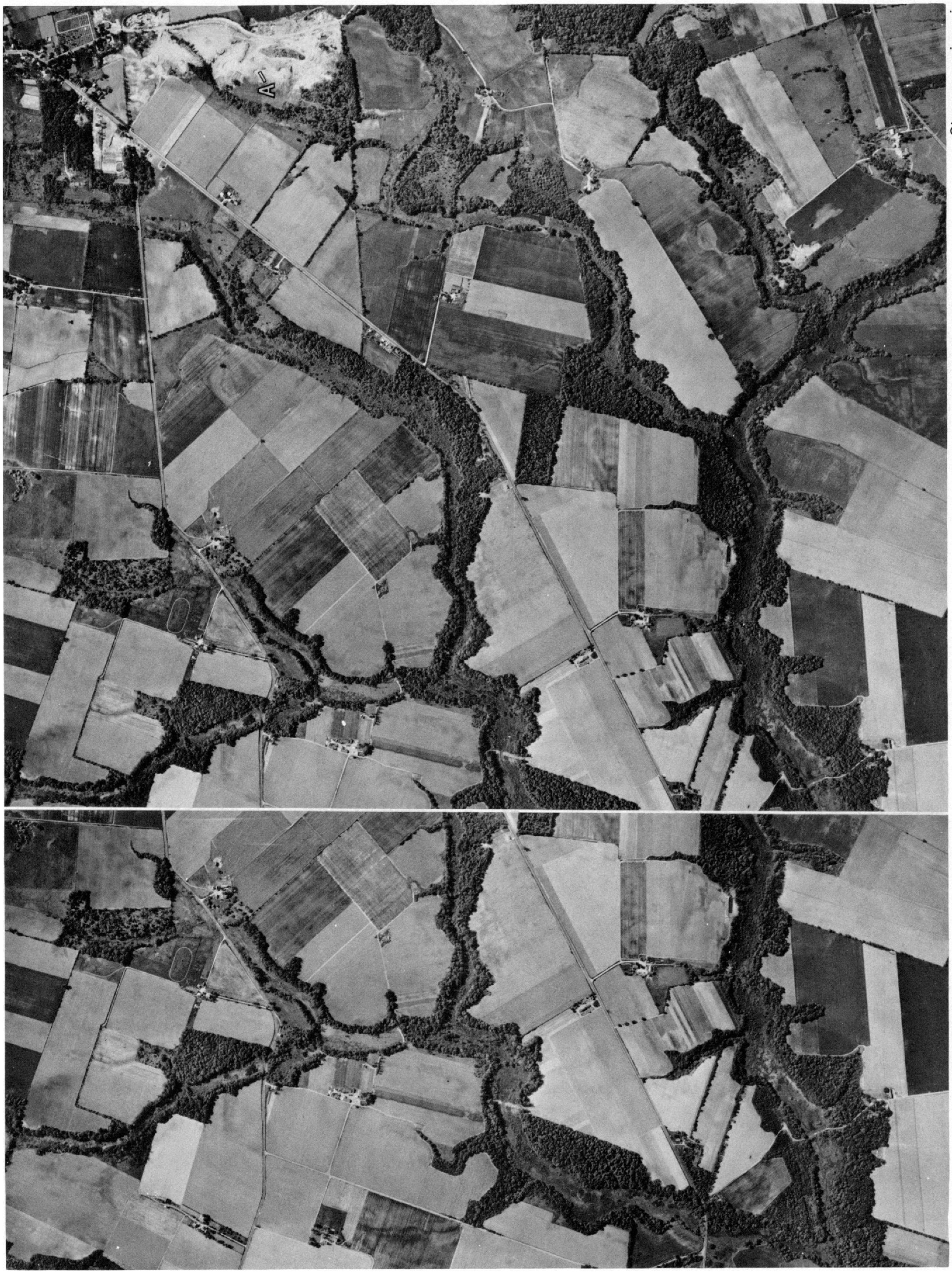
Stereoscopic pair

Approximately 1 mile

FIGURE 107.—MOTTLED SOILS OF DRIFT PLAIN (IOWA).

[Approximate scale 1 : 27,000. Photographs by U.S. Geological Survey]

Light-toned areas are generally slightly higher than surrounding dark-toned areas. High areas of light photographic tone are somewhat better drained than the intervening dark areas, and generally contain silty soils with a lesser accumulation of organic material than the depressions. Clay materials and humus have accumulated in depressions to impart dark photographic tone. Linear pattern of light-toned areas may represent minor recessional moraines. They trend across the direction of movement of ice. Near major streams the reworked glacial drift may be better sorted and locally an important source of borrow material for the construction engineer.



Stereoscopic pair

Approximately 1 mile

Figure 108.—COASTAL PLAIN UNDERLAIN BY CLAY, SAND, AND GRAVEL (NEW JERSEY).

[Approximate scale 1 : 20,000. Photographs by Commodity Stabilization Service]

Cultivated areas are thin cappings of sand and gravel overlying clay formation. Lack of surface drainage rills in sand and gravel indicate that the capping material is well drained internally. Except for dark-toned crop vegetation the cultivated areas also have the general light tones commonly associated with well-drained materials. Note borrow pit in granular material at *A*. Streams flow in clay. The steep walls and flat bottoms of gullies may not be typical of plastic clays in humid regions, however. Headward extent of small gullies generally ends abruptly against contact of clay with overlying sand and gravel. Vegetation growth is conspicuous along steep sides of gullies where trees have not been cleared for cultivation. Vegetation growth is locally favored by relatively constant supply of water that flows to surface along contact of clay with overlying sand and gravel.

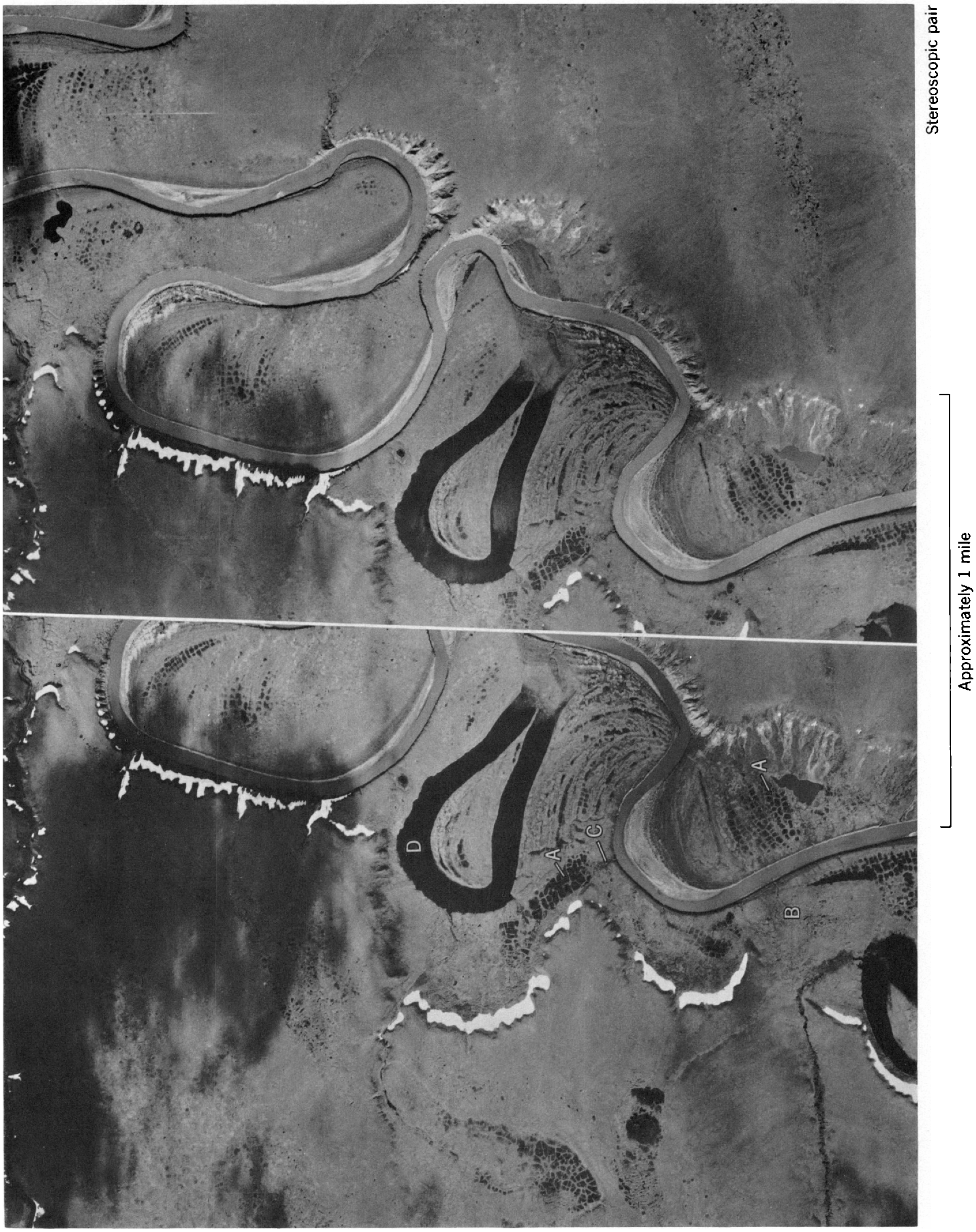

Stereoscopic pair
Approximately 1 mile
A
A
C
D
B

FIGURE 109.—POLYGONALLY PATTERNED GROUND IN PERMAFROST AREA ALONG MAJOR STREAM (NORTHERN ALASKA).

[Approximate scale 1 : 20,000. Photographs by U.S. Navy]

The susceptibility of low, poorly drained areas to the development of polygonally patterned ground resulting from ice-wedge formation is shown conspicuously along this major stream valley. Development of polygons, primarily low-center polygons, *A*, shown with relatively dark-toned centers and light-toned marginal ridges, has followed old channel scars representative of old slip-off slopes. Some high-center polygons, *B*, are also present. The angular gully pattern, *C*, is commonly found where ice wedges are melting out of polygonally patterned ground. Also note serrated edges of oxbow lake, *D*, and rim of river terraces were ice wedges in polygonally patterned ground have melted out. Contrast appearance of poorly drained river terraces here with river terraces in nonpermafrost areas where internal drainage is generally good. The conspicuous tilt of the oxbow lake and up-hill flow of stream meanders indicate that tilt is present in the aerial photographs.

Stereoscopic pair

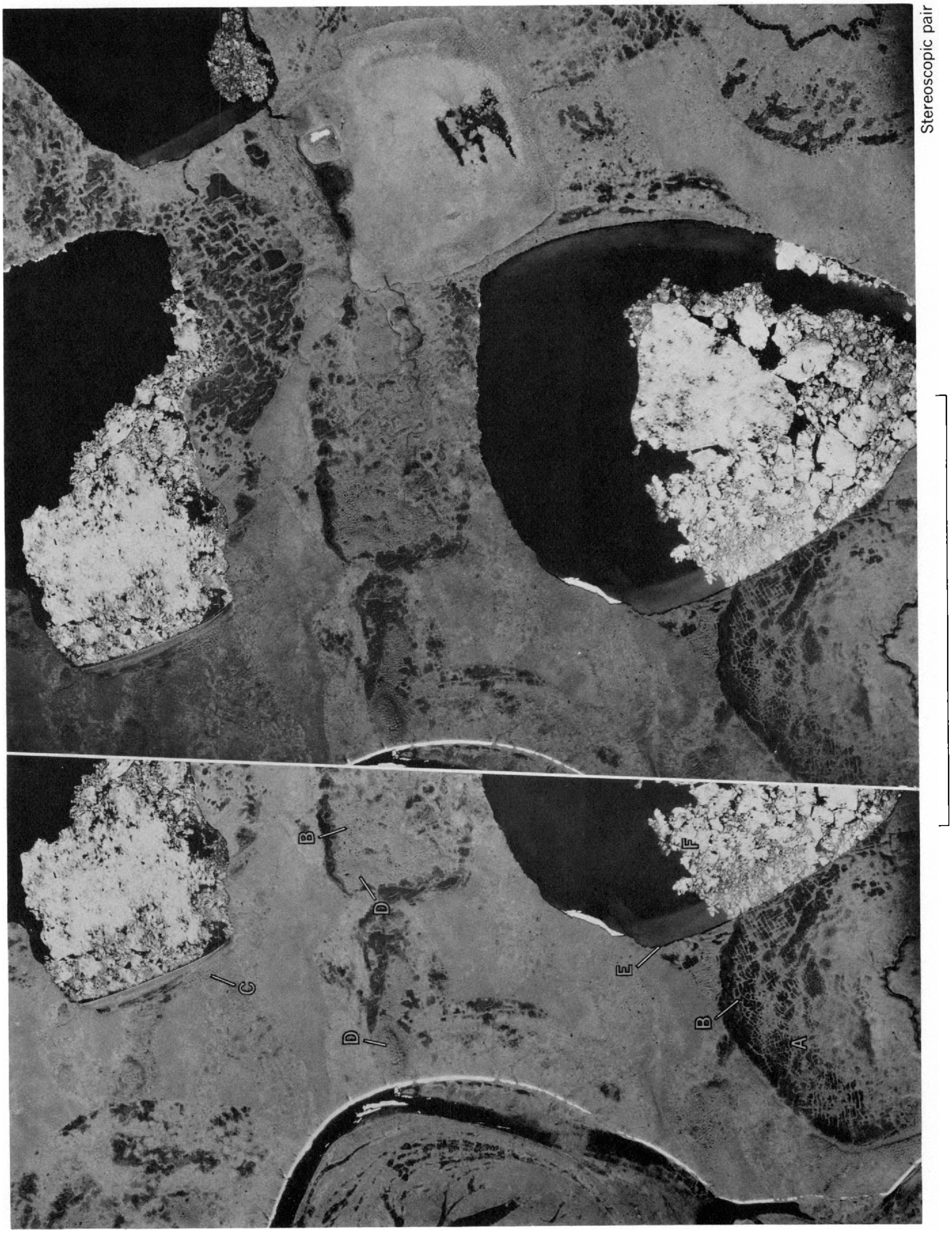
Approximately 1 mile

782-139 O - 65 - 19

FIGURE 110.—WELL-DEVELOPED PINGO IN AREA OF PERMAFROST (NORTHERN ALASKA).

[Approximate scale 1 : 20,000. Photographs by U.S. Navy]

Partly drained lake basin, *A*, a particularly favorable area for development of permafrost, is conspicuous. Note old beach lines, *B*, shown by narrow bands of contrasting photographic tones and along which polygonal ground has developed. Low-center polygons having dark-toned centers and light-toned marginal ridges are abundant, as at *C*. High-center polygons with light-toned centers and dark-toned marginal trenches, are also conspicuous in many places, as at *D*. Pingo, *E*, with a single crest crack here, is almost always diagnostic of underlying permafrost conditions. Also note pingolike forms, *F*, covered with polygonally patterned ground.



Stereoscopic pair

FIGURE 111.—AREA OF PERMAFROST (NORTHERN ALASKA).

[Approximate scale 1 : 20,000. Photographs by U.S. Navy]

Low, wet but drained lake basins, as at *A*, are favorable areas for the development of permafrost. Low-center polygons, *B*, shown as dark-toned depressed centers and light-toned raised edges are common. High-center polygons, *C*, exhibiting high, light-toned centers, and dark-toned marginal trenches, are also present. Pingolike forms, *D*, also covered with polygonally patterned ground, are highly indicative of permanently frozen ground conditions. The serrated shoreline, *E*, of some lakes is typical of the thawing of polygonal ground and further suggests the presence of permafrost. Note floating ice, *F*; bottom of lake may be seen at edge of ice, and in places depth of water may be measured from the aerial photographs.

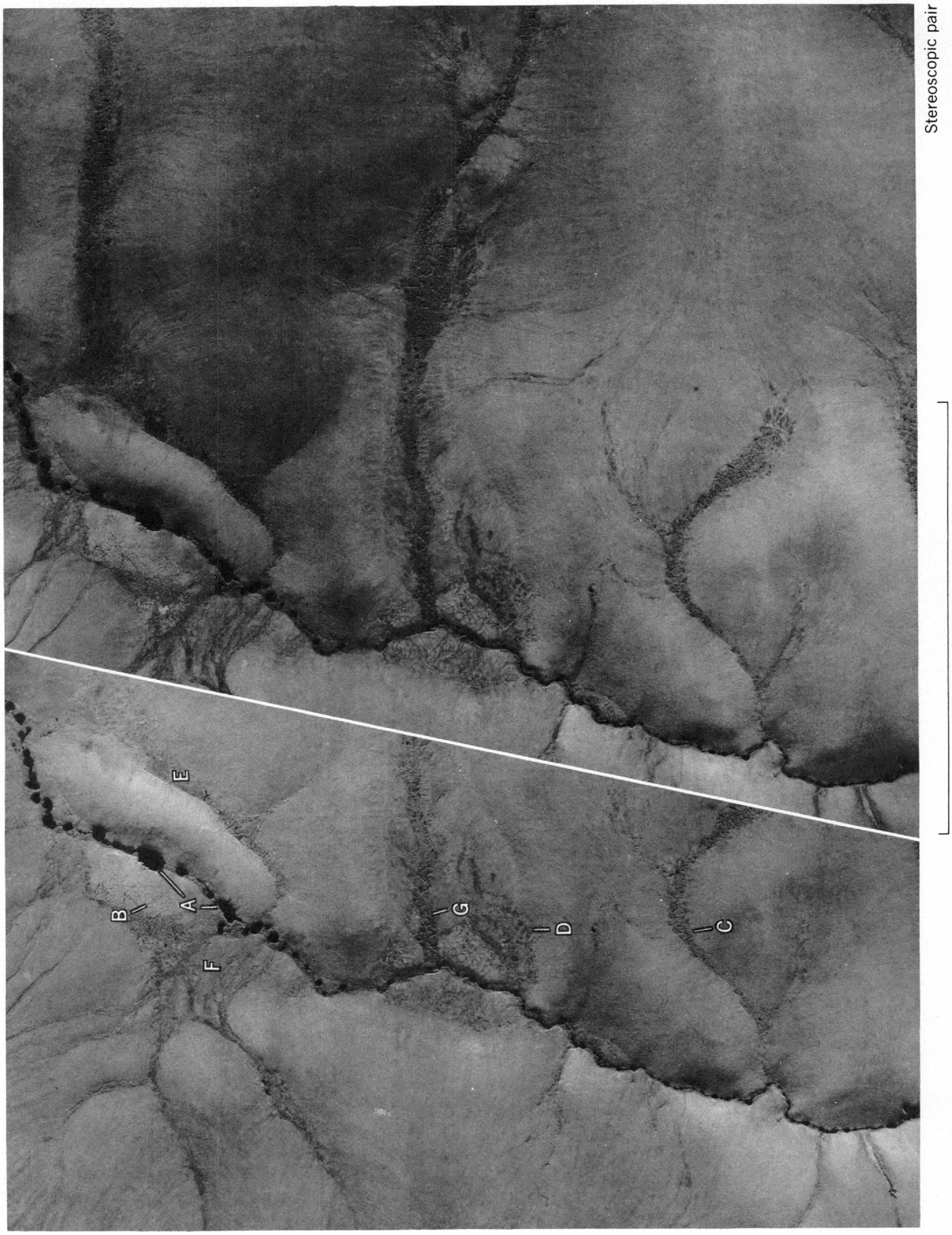
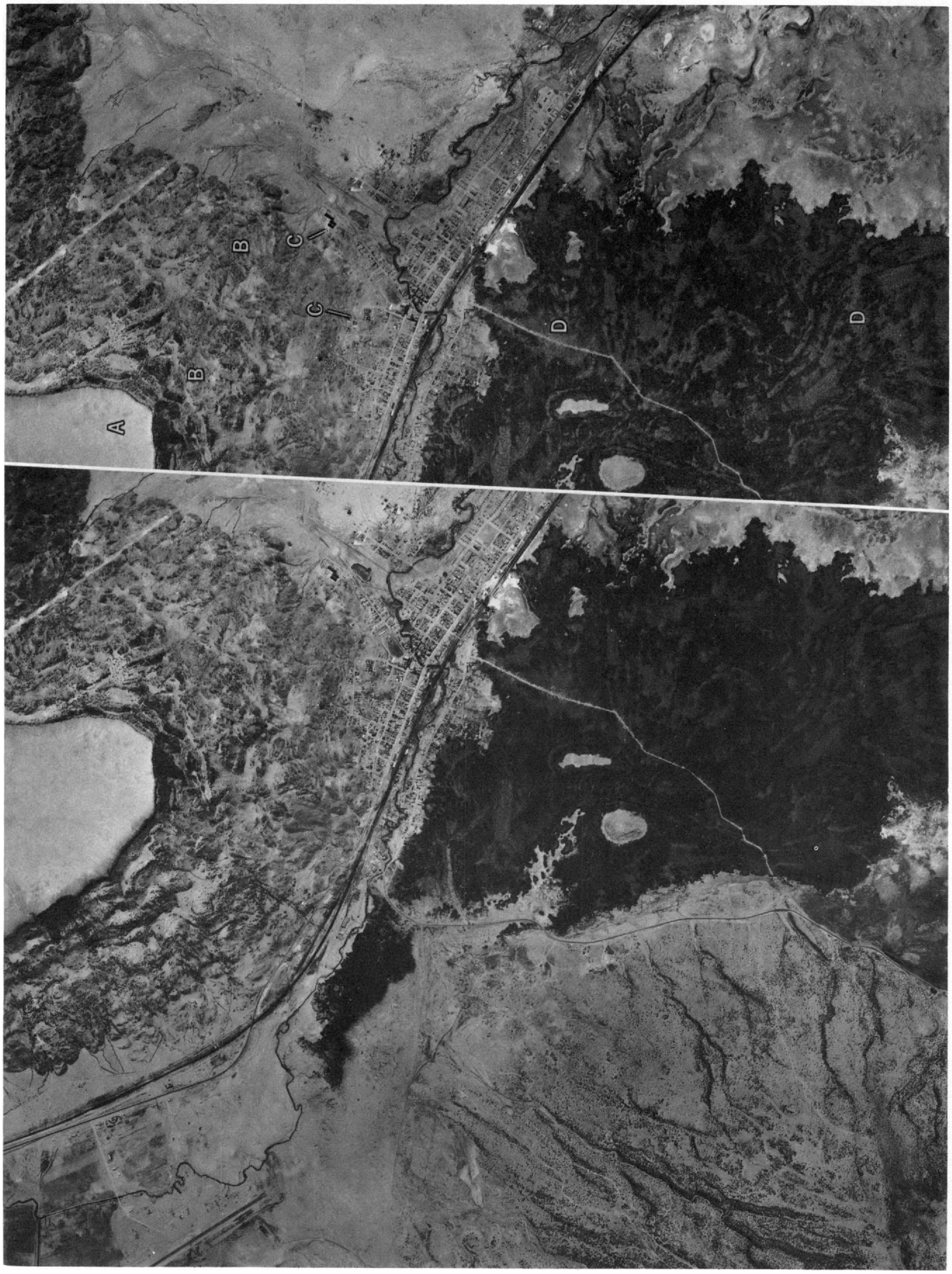

Stereoscopic pair
Approximately 1 mile
E
B
A
F
G
D
C

FIGURE 112.—CONSPICUOUS BEADED DRAINAGE IN AREA OF PERMAFROST (NORTHERN ALASKA).

[Approximate scale 1 : 20,000. Photographs by U.S. Navy]

Beaded drainage along main stream, shown as rounded pools of water connected by deeply incised watercourses, typically forms in areas underlain by permafrost. Note steep banks of pools, as at *A*, which have resulted from thawing of frozen ground and subsequent caving. Interpretation of permafrost conditions is supported by presence of high-center and low-center polygons. High-center polygons, *B*, generally are shown by relatively light-toned centers and dark-toned rims, although locally, as at *C*, the reverse tonal contrasts may be present. Low-center polygons with relatively dark-toned depressed centers and light-toned raised rims are shown at *D*. The wetter areas, as in the partly abandoned drainage channel, *E*, or upper reaches of minor drainageways, are especially susceptible to formation of polygons. Area *F*, probably a small alluvial fan area, shows well-developed drainage. The angular pattern may indicate incipient polygon formation in contrast to the angular pattern of drainage, *G*, which is typical of areas where melting of ice wedges in polygonal ground is taking place.



Stereoscopic pair

Approximately 1 mile

FIGURE 113.—LANDSLIDE AREA IN VOLCANIC AND SEDIMENTARY TERRAIN (NEW MEXICO).

[Approximate scale 1 : 37,000. Photographs by U.S. Geological Survey]

Resistant flat-lying basaltic lava, *A*, caps mesa underlain by weakly resistant mudstone, shale, siltstone, and sandstone, a geologic environment particularly susceptible to the occurrence of landslides. Landslides, *B*, below lava cap are characterized by hummocky topography and local lobate form suggestive of flowage. Note buildings, *C*, constructed on toe of slide areas. Recent lava flows are indicated by the dark photographic tone and irregular surfaces, *D*. The lobate character typical of flows can also be seen.

Stereoscopic pair

Approximately 1 mile

FIGURE 114.—DAMSITE AREA (SOUTHEASTERN ALASKA).

[Approximate scale 1 : 40,000. Photographs by U.S. Navy]

Conspicuous faults, indicated by linear topographic depressions *A*, *B*, *C*, and *D*, are present. The outlet of the lake itself appears to flow along a fault marked by the rectilinear depression *E*; this fault is probably the most significant geologic structure in the area because a dam would have to straddle it. Highly fractured rocks comprise metamorphic types and intrusive quartz diorite.

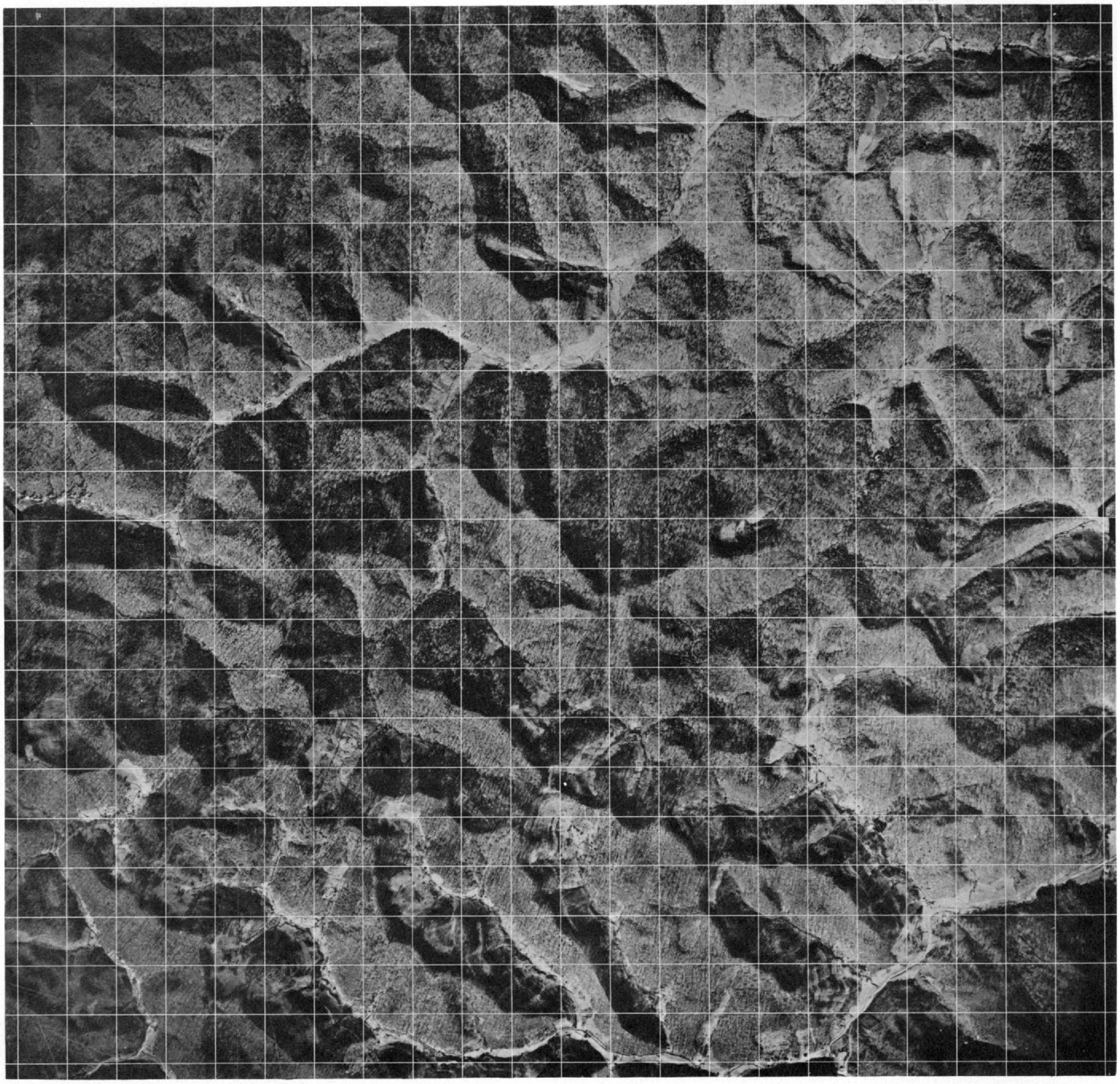


FIGURE 115.—GRIDDED PHOTOGRAPH.

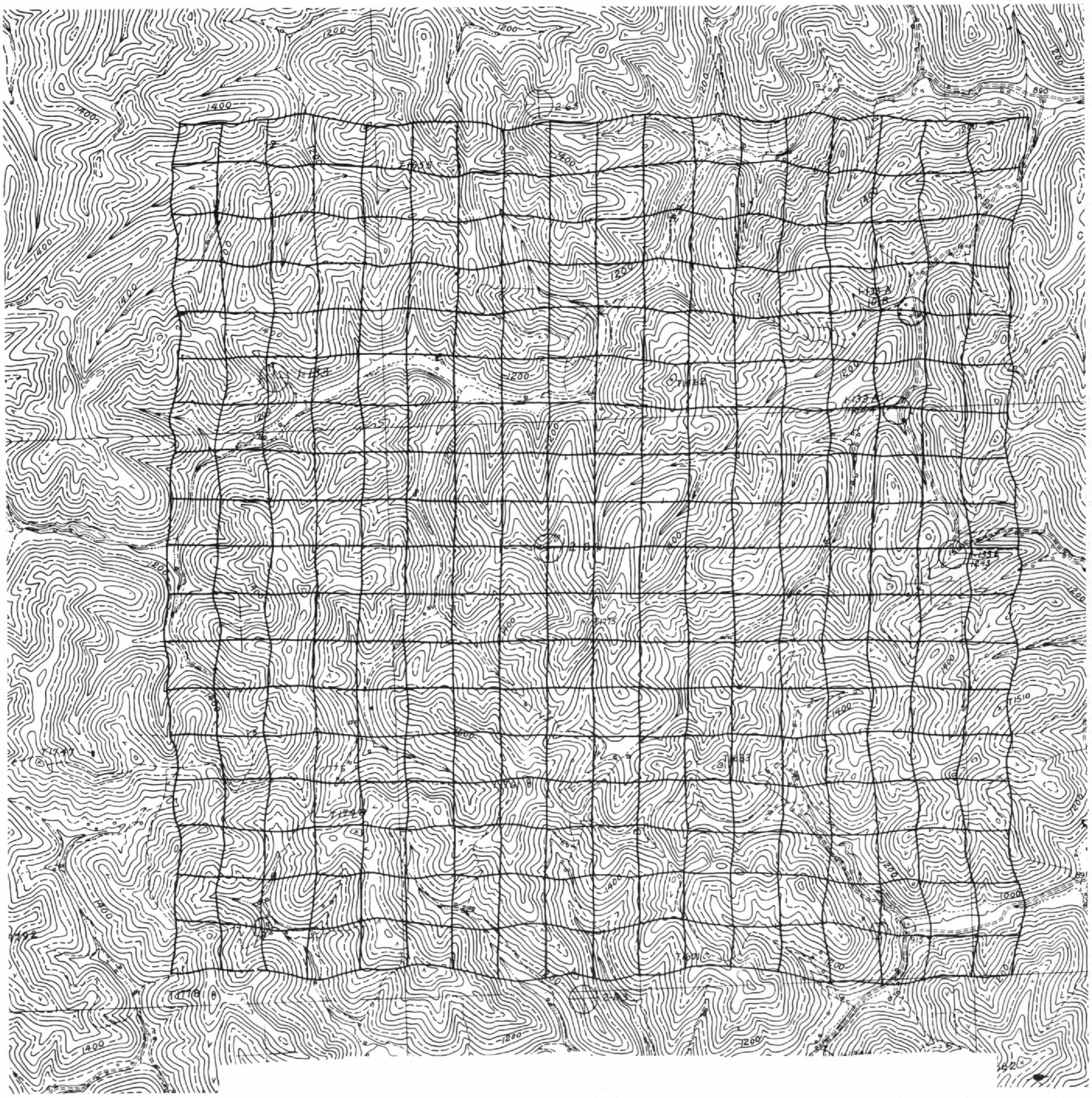


FIGURE 116.—GRIDDED BASE MAP OF AREA SHOWN IN FIGURE 115.

SOURCE AND IDENTIFYING DATA OF AERIAL PHOTOGRAPHS

The following table gives all data needed to identify the aerial photographs and also the agencies from which the aerial photographs may be purchased. Note that the agency holding the negatives is not necessarily the one that originally acquired the photographs.

Figure	Identifying photographic data					Negatives held by [1]—
	Project code	Roll	Exposures	Focal length of lens, in inches	Area	
39	DKK	3	16–17	8. 25	"DKK" Gunnison area, Colorado	E
40	BAR	309	071–072	6	Alaska	A
41	DSA	2K	19–20	8. 25	Kane County, Utah	D
42	GS–WI	12	146–147	6	Utah	A
43	DIG	1F	127–128	8. 25	San Juan County, Utah	D
44	GS–RR	3	147–148	6	Arizona	A
45	AFTRC/3415TTW/ 49–10/M–1.		697VV–698VV	12	Golden, Colorado	B
46	GS–VJV	3	150–151	6	Colorado	A
47						N
48	71	60	8395–8396	6	South Carolina	A
49	138	3	489–490	5. 2	Texas	A
50	DRK	21	3–4	8. 25	"DRK" Addition to Humboldt River, Nevada.	E
51	GS–COL	3	56–57	6	California	A
52	GS–JF	6	11–12	6	Wyoming	A
53	DLG	7G	97–98	8. 25	Elmore County, Idaho	D
54	71	26	3514–3515	6	North Carolina	A
55*A*	73	4	117–118	6	Maine	A
B	GSM	3	31–32	5. 2	do	A
56	Mission 649		0120–0121	6	Alaska	A
57	Mission 648		0161–0162	6	do	A
58	113	16	1746–1747	6	South Dakota	A
59	GS–WI	10	102–103	6	Utah	A
60	126	18	1723–1724	6	do	A
61	CUU	8G	141–142	8. 25	Stephens County, Texas	D
62	GS–RO	1	125–126	6	Utah	A
63	GS–WI	36	68–69	6	do	A
64	GS–AZ	2	119–120	5. 2	Virginia	A
65	AQV	1D	55–56	8. 25	Northampton County, Pennsylvania	C
66	113	21	2600–2601	6	South Dakota	A
67	SEA	92	019–020	6	Alaska	A
68	138	10	1919–1920	5. 2	Texas	A
69	CNP	1C	11–12	8. 25	Gooding County, Idaho	D
70	GS–VE	5	26–27	6	South Dakota	A
71	GS–CMA	32	88–89	5. 2	Wyoming	A
72	SEA	29	028–029	6	Alaska	A
73	71	50	7084–7085	6	North Carolina	A
74	71	7	820–821	6	do	A
75	GSY	1	145–146	5. 2	Alabama	A
76	SEA	112	181–182	6	Alaska	A
77	ZF	2G	174–175	8. 25	Wabaunsee County, Kansas	D
78	CUU	8G	152–153	8. 25	Stephens County, Texas	D
79	BAR	44	61–62	6	Alaska	A
80	131	11	1711–1712–1713	6	Wyoming	A
81	BPM	11	63–64	6	Muddy River area, Utah	E
82	GS–PB	1	50–51	6	New Hampshire	A
83	GS–WI	5	156–157	6	Utah	A
84	GS–RR	17	43–44	6	do	A
85	SEA	112	077–078	6	Alaska	A
86	131	7	1187–1188	6	Wyoming	A
87	120	70	10110–10111	6	New Mexico	A
88	DRW	1K	94–95	8. 25	Duchesne County, Utah	D
89						N
90	GS–RO	4	167–168	6	Utah	A
91	GS–RR	2	64–65	6	do	A
92	GS–RR	17	64–65	6	do	A
93						N
94	138	5	867–868	6	Texas	A
95	138	5	867–868	6	do	A
96					Wainwright, area index quadrangle D–19, Alaska.	A
97	BAR	44	139–140	6	Alaska	A
98	DRK	21	197–198	8. 25	"DRK" Addition to Humboldt River, Nevada.	E

See footnote at end of table.

SOURCE AND IDENTIFYING DATA OF AERIAL PHOTOGRAPHS—Continued

Figure	Identifying photographic data					Negatives held by [1]—
	Project code	Roll	Exposures	Focal length of lens, in inches	Area	
99	SEA	133	019–020	6	Alaska	A
100	SEA	106	125–126	6	do	A
101	109	43	5283–5284	6	Oregon	A
102	GS–VE	5	112–113	6	South Dakota	A
103	GS–QQ	1	89–90	6	California	A
104	DRW	1K	47–48	8.25	Duchesne County, Utah	D
105*A*	BKP	4G	14–15	8.25	Pottawattamie County, Iowa	C
B	BNQ	172	15–16	8.25	Valley County, Nebraska	C
C	BNQ	96	30–31	8.25	Valley County, Nebraska	C
106	128	5	751–752	6	Nebraska	A
107	GS–DY	5	40–41	5.2	Iowa	A
108	CMU	3R	139–140	8.25	Burlington County, New Jersey	C
109	BAR	72	087–088	6	Alaska	A
110	BAR	72	098–099	6	do	A
111	BAR	72	093–094	6	do	A
112	BAR	92	010–011	6	do	A
113	GS–VID	1	46–47	6	New Mexico	A
114	SEA	114	008–009	6	Alaska	A

[1] Code is as follows:
A—U.S. Geological Survey, Map Information Office, Washington, D.C. 20402.
B—Chief, News Photo Branch, Department of Defense, Directorate of Information Services, Washington, D.C. 20301.
C—Eastern Laboratory, Agricultural Stabilization and Conservation Service, U.S. Department of Agriculture, 45 South French Broad Avenue, Ashville, North Carolina 28801.
D—Western Laboratory, Agricultural Stabilization and Conservation Service, U.S. Department of Agriculture, 2505 Parleys Way, Salt Lake City, Utah 84109.
E—Soil Conservation Service, Cartographic Division, Federal Center Building, Hyattsville, Maryland 20781.
N—Negatives not available.

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