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Geology from the Air

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Aerial photographs are one of the most important tools of the modern geologist. However, it is only in recent years that aerial photographs have received extensive use in geologic mapping and exploration and that their significance as a source of geologic information has gained wide recognition.

The economic importance of aerial photographs in geologic mapping and exploration has been demonstrated many times in recent years. Noteworthy in this regard was the extensive use of photographs for geologic interpretation of the central Iranian basin, the site of one of the most spectacular oil discoveries of 1956 (*1*). Some years earlier, aerial photographs played a significant part in the discovery of Cerro Bolivar, the iron-ore bonanza of Venezuela (*2*). Today, a number of private Canadian companies are collaborating in mapping part of the Canadian Shield in one of the most extensive geologic mapping programs yet undertaken with aerial photographs (*3*).

Aerial photographs, when properly used in geologic work, add speed, economy, and accuracy to geologic mapping as well as certain geologic information impossible, difficult, or economically infeasible to obtain by routine field-mapping methods. These "assists" to geologic mapping are a result of many factors. Aerial photographs permit views of large areas and hence reveal to the geologist over-all geologic relationships that could not readily be seen otherwise. In addition, the geologist obtains a plan view of the terrain, similar to the planimetric presentation of geologic maps. Photographs may also show the geologic terrane in a way that it cannot be seen by the naked eye, that is, as in infrared, camouflage-detection, or other special photography; hence, geologic information is revealed that might otherwise be obscure.

Furthermore, all features, both natural and cultural, that are clearly expressed on aerial photographs can be easily measured. The accuracy of measurement depends primarily on the scale of the photography. The use of photogrammetric instruments not only permits measurements, which are important in interpretation, but also increases mapping accuracy and to a lesser extent increases the speed and economy of mapping. The degree to which aerial photographs are used varies widely, but to whatever extent photo techniques are employed, they must remain principally an aid, or tool, in geologic mapping and not a substitute for field mapping.

Viewing the Photographs

"Vertical" photographs are most commonly used for geologic study; these are photographs taken with the camera lens pointing vertically down from the airplane. Normally, aerial photographs are taken from positions so spaced that each image within the field of the camera appears on at least two photographs. When two photographic images of the same object, taken from different positions, are combined optically by means of some sort of stereoscopic viewing device, the familiar 3-D effect is seen. The viewing device may be a simple lens stereoscope (Fig. 1), a mirror stereoscope (Fig. 2), or a precision mapping instrument such as the Kelsh plotter (Fig. 3). Aerial photographs, of course, can be studied in two-dimensional "plan view" by using single prints of aerial photographs or groups of prints mosaicked together, but the value of three-dimensional stereoscopic examination of the aerial photographs as compared with the value of examination of the two-dimensional plan view cannot be overemphasized. Whereas conspicuous geologic features are commonly visible on single aerial photographs or mosaics of aerial photographs, the wealth of information shown in a 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, are commonly 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.

The value of the 3-D effect in geologic interpretation is increased by the vertical exaggeration, or relief exaggeration, that commonly occurs in stereoscopic viewing of aerial photographs. This exaggeration results from the wide spacing of camera positions at the time of exposure, as contrasted to the spacing of the human eyes; it is of particular value in interpreting the angle of dip of sloping surfaces, such as sedimentary beds, and thus low dips of 1 to 2 degrees, which may be especially significant in petroleum exploration, may be readily interpreted from the aerial photographs. In addition, minor topographic differences, which may reflect underlying geologic structure, are exaggerated and in turn may be easily recognized. The exaggeration of relief in a stereoscopic model of 1/20,000-scale photographs taken with a 6-inch-length lens is such that a geologist is enabled to differentiate differences in elevation as small as 1 foot.

Kinds of Information

There is hardly any terrane which will not yield some geologic information from a study of aerial photographs. The amount of information naturally varies with the kind of terrane and the climatic environment.

Figure 4, showing a sequence of shales and sandstones in western United States, demonstrates convincingly the usefulness of photogeologic procedures in mapping the distribution of rock types. The clear-cut geologic contacts can be accurately mapped from photographs, thus eliminating much time-consuming effort in the field.

In a different climatic but geologically

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similar area, Arctic Alaska, gently folded and faulted rocks in a potentially oil-bearing region are very poorly exposed (see Fig. 5). Differential resistance to erosion of sedimentary rock units combines with structural attitude to reveal bedding by slight topographic breaks and minor changes in vegetation type. The topographic breaks are exaggerated in stereoscopic view and permit the interpreter to detect information not readily apparent in ground study. Although the rocks do not actually crop out, the structural setting, so important to the petroleum industry, can be easily interpreted.

An extreme example of the value of aerial photographs in interpreting oil structures was a photogeologic study of the Square Lake area in northern Alaska. Fischer (4) reports that field parties have spent entire seasons within and immediately adjacent to the Square Lake area without detecting the Square Lake anticline. No outcrops are present, but small hills in the area are elongate in the same direction as the regional structural trend. Normal to this trend, other hills slope gently in a direction of postulated dip. Also, streams on the postulated dip slope have a slightly less well developed dendritic pattern than those on the opposite slope. There also seems to be a possible correlation between the slopes of the tops of cutbanks 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 study corroborated the photo study, and test drilling in turn confirmed the photo and seismic work. In another similar terrain, photointerpretation based on minor topographic variations and stream patterns indicated a structural axis, later substantiated by seismic work (4). Drilling indicated a huge gas reservoir.

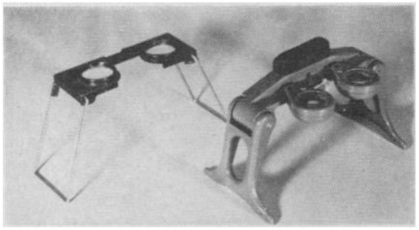

Fig. 1. Simple lens stereoscopes.

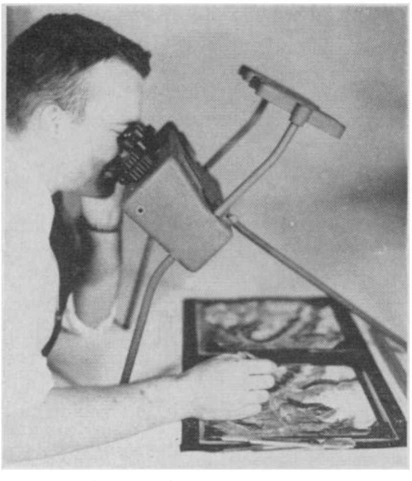

Fig. 2. Mirror stereoscope.

A study of heavily forested terrain of southern Alaska further indicates how aerial photographs and photo procedures may be used in geologic study and mapping. In the Prince William Sound area a detailed study of fracture systems was made, and locations of fractures were plotted with respect to fractures mapped by ground methods and known to be associated with ore deposits, primarily copper. Figure 6 shows how fractures are visible on aerial photographs even within the heavily forested areas. Such fractures are observed only with great difficulty and expenditure of effort by ground traverse. The association of certain fractures with ore deposits in turn suggests areas that might be prime target areas for ore search. Similar studies have been made in British Columbia by a leading mining company, and many square miles have been eliminated as primary target areas prior to any field study. Another leading mining company in eastern United States follows this photointerpretation technique with geophysical surveys of areas of favorable structural setting for ore deposits.

Of more subtle nature, but of considerable economic significance, is the study of patterns, particularly stream patterns, resulting from the adjustment of streams to underlying geologic structure. Even in jungle areas, invaluable data relating to structure may be obtained from aerial photographs by a technique colloquially termed "creekology," the analysis of stream pattern. Figure 7 shows how stream patterns can define a geologic structure, such as an anticline. Note how streams flow away from the suspected elongate domal structure. In other areas soil or vegetation patterns may suggest underlying structure.

It is clear, then, that aerial photographs can be an extremely useful tool in geologic mapping and exploration, but one must realize that the technique has its limitations as well as its advantages. The interpreter can only guess at the composition of rock types; he cannot identify mineral type or absolute ages of rocks, nor can he obtain such information as paleontological data.

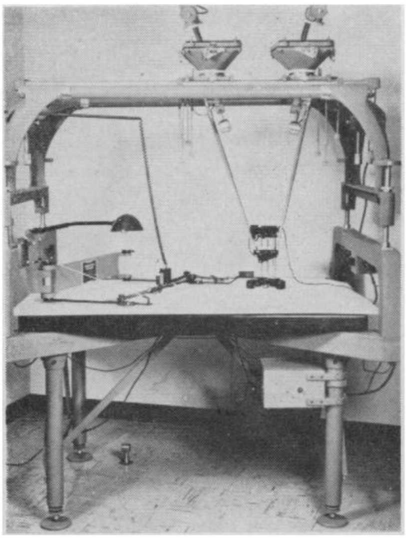

Fig. 3. Kelsh plotter, used for interpreting, measuring and plotting geologic data.

The importance of aerial photographs in geologic study may differ with respect to the geologic terrane being mapped and the objectives to be obtained. In many studies, it would seem logical to make preliminary photogeologic studies just as it is normally a preliminary step to investigate available literature before going into the field. In reconnaissance mapping, especially of remote or inaccessible areas, photogeologic procedures can be used as the principal mapping technique, and preliminary maps can be compiled solely on the basis of photo study. In detailed mapping, photogeologic procedures provide a supplemental mapping technique and assist the detailed field investigation. But, in any event, a look at photographs early in a mapping program is desirable and in certain investigations is necessary to effective follow-up study in the field. Commercial companies are relying more and more on preliminary photo study to delineate potential oil-bearing or mineralized areas in which to concentrate field investigations.

Interpretation—Recognition Elements

Interpretation of aerial photographs is based on recognition elements—characteristics of the photograph that result from the scale selected, the color of the rocks and other elements of the terrain photographed, the kind of film and filters used, the processing of the film, and similar related factors. The most significant recognition elements for geologic interpretation are relative photographic tone, color, texture, pattern, and relation to associated features. Size and shape may also be diagnostic recognition elements in certain geologic problems.

Photographic tone. 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. In areas of good exposures, bedding is characteristically recorded on the aerial photograph by differences of photographic tone. These differences may be abrupt, as illustrated by white-weathering marlstone beds in a sandstone sequence, or they may be subtle, as shown by two successive similarly colored sandstone units. Faults may be indicated by a change in photographic tone as shown on opposite sides of a straight or gently curving line; and alluvial fans, pediments, lava flows, intrusive rocks, and many other geologic features are usually identified, at least in part, by relative differences of tone.

Color. When color aerial photography is available, recognition is greatly facilitated as a result of the ability of the human eye to differentiate about 1000 times as many tints and shades of color as it can tints and shades of gray, characteristics of black-and-white photography. Subtle differences on black-and-white photographs may thus become obvious on color transparencies, as in rock units of only slightly different lithologic composition. The advantages of color aerial photography are generally present even though some color fidelity may be lost in the transparencies. Special color film, in which colors are distorted, as in camouflage-detection film, may be singularly useful in the study of certain areas.

Texture. Texture is the composite appearance of a combination of features too small to be clearly seen individually; thus the scale of the photographs has an important bearing on what is called "texture." For example, a network of fine lines referred to as a texture on high-altitude photographs may well be recognizable as a network of joints on low-altitude photographs. Likewise, a mottled texture on high-altitude photographs, resulting from small amebalike outlines, may be clearly the result of kettle holes that are distinctly discernible on low-altitude photographs. Intrusive igneous rocks commonly have a distinctive texture owing to a crisscrossing of the many joints almost universally present in such rocks.

Pattern. Pattern, or arrangement of geologic or other features, is especially significant in geologic interpretation from aerial photographs. A common use of this recognition element is the analysis of stream pattern, which may be a significant aid in interpreting the underlying geologic terrane. Patterns of joints may suggest certain rock types, or a knowledge of fault patterns of an area may be helpful in locating faults in a similar nearby terrane. Patterns resulting from particular distributions of lines are common, but a single line, or lineation, may be a special illustration of pattern. For example, a lineation may result from an orderly arrangement of stream segments, trees, depressions, or other features. This arrangement may be a continuous alignment of geologic, topographic, or vegetation features, but more commonly it is a discontinuous alignment. Lines are especially representative as expressions of faults, but they may also represent a variety of other geologic phenomena.

Relation to associated features. The relation to associated features is commonly important because a single feature may not be distinctive enough to permit its identification. Thus, for example, identification of depressions in surficial deposits such as kettle holes may be possible because of the presence of associated glacial ice nearby.

Size. The term *size*, used as a general recognition element covering all inter-

Fig. 4. Vertical aerial photograph showing striking delineation of light-colored sandstone in a shale-sandstone sequence.

Fig. 5. Vertical aerial photograph showing traces of bedding accentuated by topographic breaks and changes in type of vegetation.

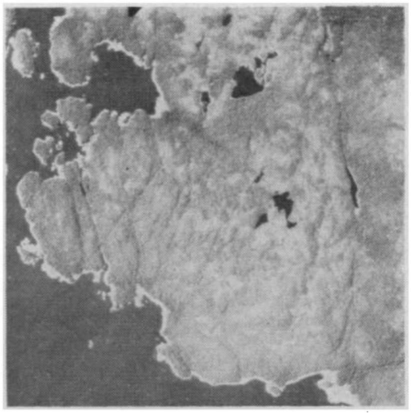

Fig. 6. Vertical aerial photograph showing fractures in heavily forested terrain.

pretation fields, is more appropriately considered in geologic interpretation in relation to thicknesses of strata, amounts of offset along faults, or other finite measurements. These measurements may be directly related to topographic expression. If the thickness of a formation is known, this knowledge may aid in identification, and determining the range in thicknesses may be essential to understanding the regional geology.

Shape. Shape as a recognition element in geologic interpretation is of significance primarily only in its broadest definition, involving relief or topographic expression. In this regard, it may be important for recognizing geologic features in certain areas. For example, the bold cliff face of one formation in contrast to a lesser angle of slope across an underlying formation locally may be of considerable importance in differentiating the rock units. Rectilinear depressions are expressions of faults in many areas. However, in its strictest definition, as a spatial form with respect to a relatively constant contour or periphery, shape is of little importance as a recognition element because nature may reveal the same geologic feature in an infinite number of different shapes.

Interpretive Process

The interpretation of geology from aerial photographs involves many of the same mental and physical processes as the interpretation of geology from field observations. If the full value of the photographs is to be utilized, preliminary field reconnaissance combined with cursory study of the aerial photographs must be undertaken prior to detailed interpretation. Detailed interpretation, including measurement of features considered to be geologically significant, is then undertaken; rigorous application of the interpretive process is made in this phase of applying aerial photography to geologic study. Photographs should be used in the field not only for recording locations of observations but for contrasting geologic features with their images on the photographs to provide a basis for further interpretation. Whenever possible, geologic data derived from study of the aerial photographs should be checked and evaluated in the field.

The initial phase of the interpretive process is an observational phase wherein recognition of geologic features or characteristics of the terrain is involved. Recognition of terrain features is commonly based on combined use of fundamental recognition elements such as photographic tone and pattern. Data thus observed are then interpreted with regard to geologic significance, and the geologic history of an area is deduced, insofar as possible, from the distribution and relationships of the features recognized. Many features are expressed on aerial photographs. Sorting those features that are of significance to a particular problem and properly relating these features one to another provides a measure of the ability of the interpreter. In geologic interpretation, this ability depends primarily on the geologist's background training in geology, such as his understanding of structure and natural processes operative on the rocks, and secondarily on his experience in viewing aerial photographs. The geologist may also make use of photogrammetric instruments for making measurements, which in turn become the basis for interpretation of the geologic significance or history of an area.

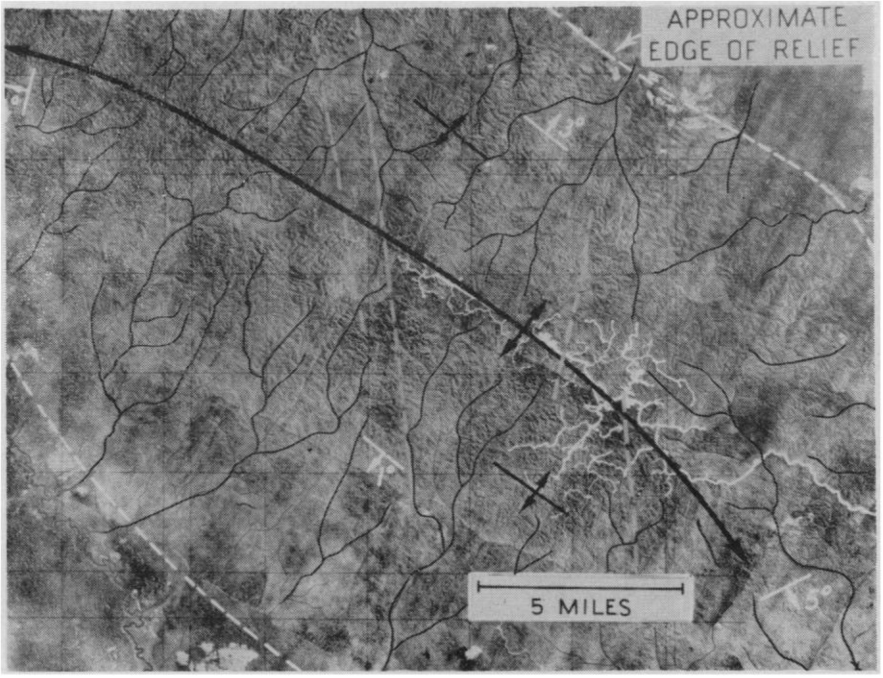

Fig. 7. Anticlinal structure in jungle-covered area, revealed by analysis of drainage pattern [Courtesy D. J. Christensen, Standard Oil Company of California]

Interpretation is a multistep operation, and hence a final comprehensive interpretation of the regional geology may be a synthesis of many lesser but specific interpretations, such as the direction of dip of beds in a sedimentary sequence. On the other hand, the immediate recognition of regional or large-scale geologic features as a result of the over-all aerial view, permitted particularly by small-scale photography, is commonly the basis for interpretation of smaller specific features. For example, a geologist may immediately recognize from the general land form that an area has been glaciated. This basic information would facilitate recognition of specific glacial features, such as kames and morains.

Example of the interpretive process. The interpretation and mapping of the distribution of younger lava flows in an older igneous-metamorphic terrane of southeastern Alaska by W. H. Condon (*5*) provides an excellent example of the interpretive process in geologic study. The area has a maximum relief of slightly more than 2000 feet. Outcrops are masked almost completely by a heavy forest growth, largely coniferous trees. In poorly drained sections, a grassy swamp vegetation or muskeg has developed.

The area is underlain by highly folded and faulted phyllites, schists, and gneisses that have been intruded by granitic and dioritic igneous rocks. Younger basaltic lava flows have been extruded onto the older igneous-metamorphic complex.

Criteria used in photogeologic analysis were derived from photo study of locations where lava flows had been reported in the field. The most important criteria were based for the most part not on actual observation of the bedrock, but

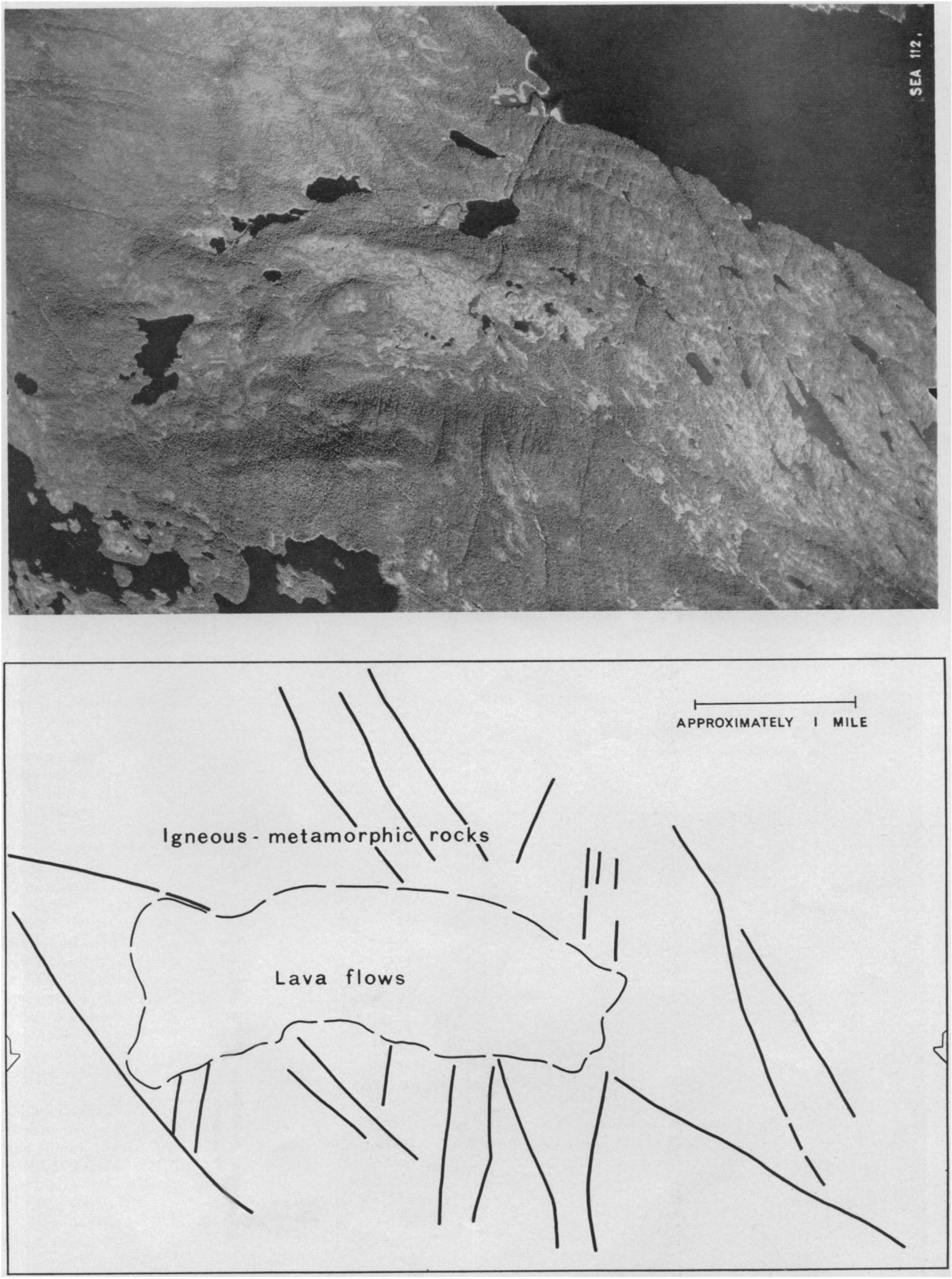

Fig. 8. (Top) Part of vertical aerial photograph showing linear features clearly expressed across ridges of older rocks but not traceable across the area occupied by lava flows. (Bottom) Index showing positions of conspicuous linear features and outline of area occupied by lava flows.

rather on the effects of rock types, structure, and geologic processes on terrain expression. These effects involve vegetation and drainage, which commonly are expressed in significant patterns. Specifically, these patterns involve (i) linear features, (ii) minor streams and abundance of small shallow ponds, (iii) density and type of vegetation, and (iv) vegetation expressed as lobate outlines by denser, darker growth. Further analysis was made for (i) the possible relation of the volcanic rocks to the pattern of probable faults, (ii) terrain forms expected in volcanic rocks, and (iii) the controlling influence of existing topography on the distribution of lava flows.

Linear features of terrain appear as long narrow gullies or troughs of varying depth and are generally well expressed in areas of the older rock complex. In many places they may be seen on aerial photographs to terminate abruptly at the edges of the younger volcanic rocks across which they cannot be traced. The pattern of linear features is most probably the expression of faults, although at least locally the possibility of joints, bedding, schistosity, or, perhaps, glacial gouging, the gross effect of which cannot be overlooked completely. Any of these possible alternate interpretations, however, would serve similarly to date the volcanic rocks with respect to the older metamorphic-igneous complex. Figure 8 shows linear features clearly expressed across ridges of older rocks but not traceable across the intervening valley, interpreted as occupied by lavas.

Drainage characteristics and stream patterns have developed in response to the rock type, structure, and slope of terrain surfaces, and to the degree of fracturing of the bedrock. In adjusting to terrane, streams on the complexly fractured older rocks tend to be channelized to the system of linear features and to form a pattern of parallel drainage. In contrast, streams that developed on the slightly sloping surfaces of the volcanic flows, or on the steeper sides of volcanic

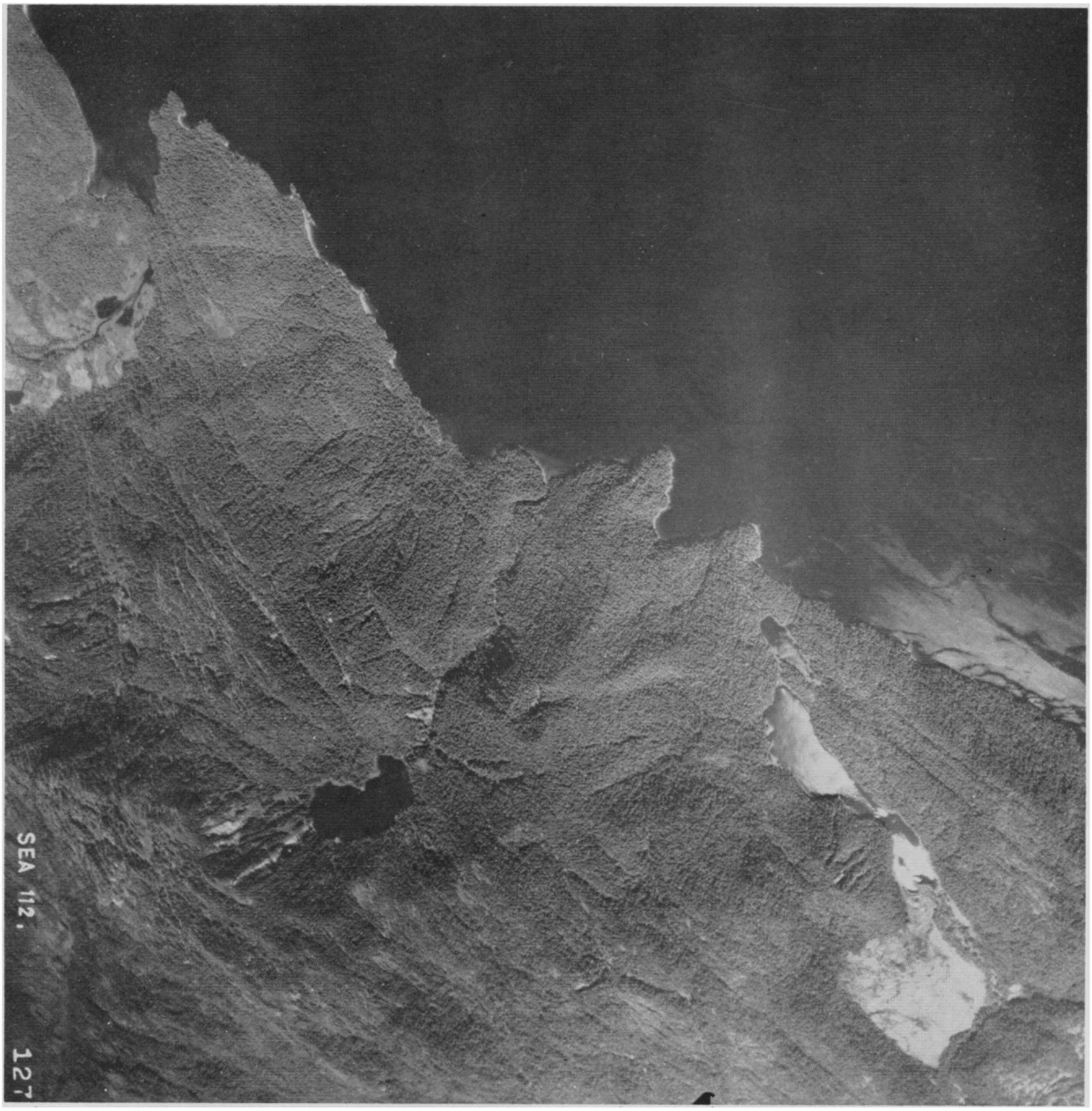

Fig. 9*A*. Part of vertical aerial photograph showing parallel drainage pattern of older rock sequence and radial-dendritic pattern on slopes of volcanic cone.

cones, show an irregular, somewhat dendritic or radial dendritic pattern of drainage not controlled by a fracture system. Furthermore, upon the nearly flat, poorly drained, muskeg-covered surfaces of the volcanic flows there is an abundance of small, shallow, swampy ponds not characteristic of the generally better drained surfaces of the older rock complex. Figure 9*A* shows the contrast of parallel drainage pattern of the older rock complex to the somewhat radial-dendritic stream pattern on the slopes of a probable volcanic cone, and Fig. 9*B* is an index to Fig. 9*A*.

The density and type of vegetation, and thus the pattern, seem to be greatly influenced by the drainage conditions of the surface. Where drainage is good, as on the steeper slopes of volcanic cones and the generally well drained igneous-metamorphic terrane, the surface is heavily timbered with coniferous trees. Where drainage is poor, as on the nearly flat surfaces of the volcanic flows, a swampy muskeg with a sparse and patchy tree cover has developed. On these nearly flat lava surfaces a patchy vegetation pattern results from the contrast between the lighter-toned, low, grassy swamp vegetation and the taller brush and trees, which tend to be concentrated only along stream courses.

Lobate patterns of vegetation formed by dense growths of coniferous trees contrast sharply in height and in photographic tone with the low, light-toned swamp vegetation. These patterns are interpreted as marking the raised edges and fronts of the most recent lava flows, and they are particularly useful in indicating direction of flow. The development of such patterns is believed to be caused by better drainage along the raised edges of the flows in contrast to poorer drainage within the muskeg-covered central areas.

A comparison of the distribution of rocks interpreted as volcanic with the pattern of linear features in the older rocks is believed to be significant. Volcanic rocks were probably extruded along or very close to continuous and prominent linear features, interpreted as faults,

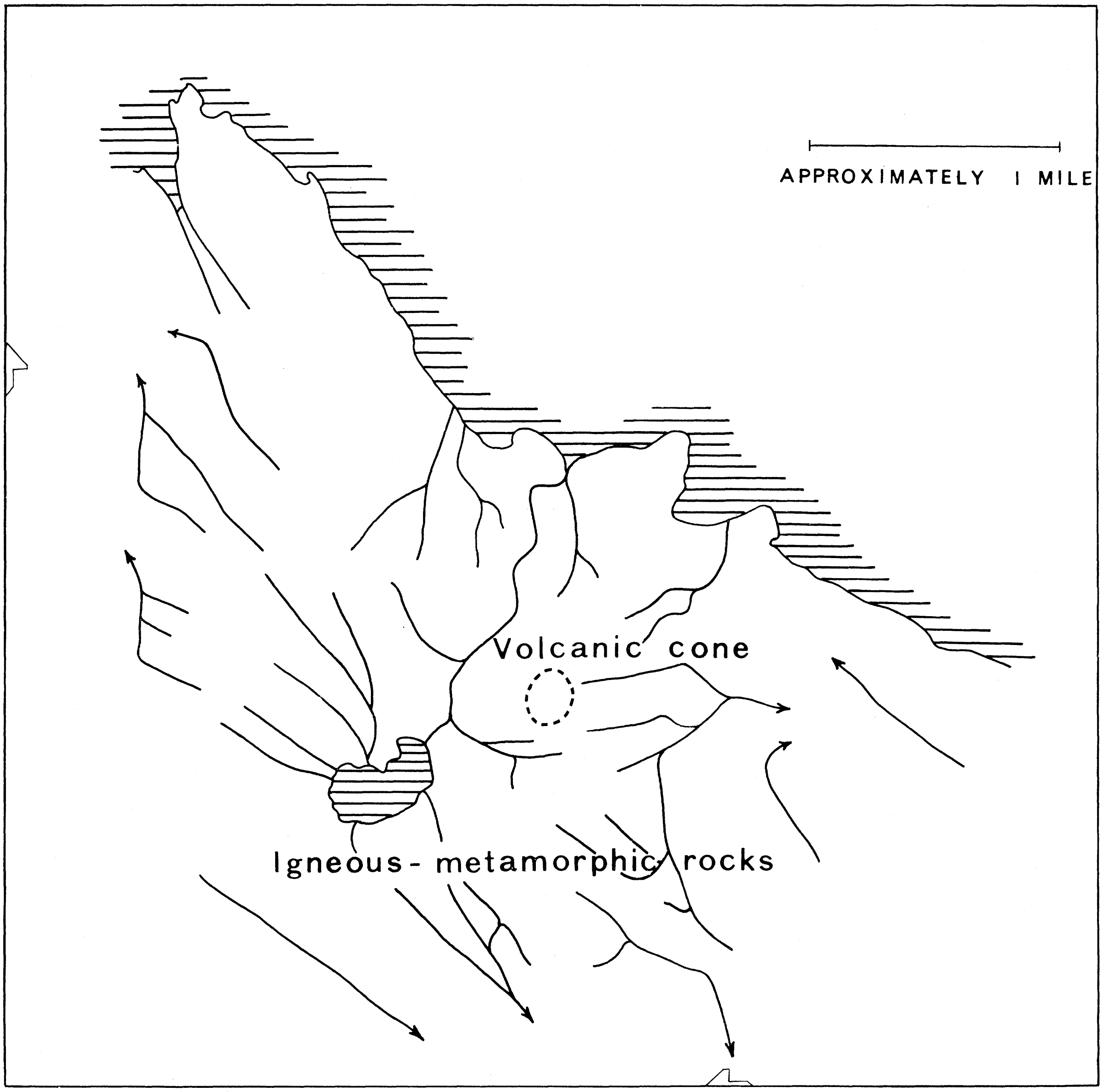

Fig. 9*B*. Index overlay to Fig. 9*A* showing contrasting stream patterns.

trending north-northeastward to northward. Along the extension of one major fault a second area of volcanic rocks was interpreted from aerial photographs. The presence of these rocks was verified in the field.

A further analysis of terrain was made for topographic features to be expected in volcanic rocks, such as remnants of cones and volcanic necks or plugs. Two sizable crescentic features were observed, one definitely a remnant breached cone, and the second probably also a breached cone.

A final consideration was made for the controlling influence of the existing topography on the distribution of the volcanic flows during the time they were being poured out on the earth's surface. Field workers in southeastern Alaska have postulated that the topography has not been greatly changed in either form or relief since the last general glaciation. It has been stated also, with some reservations, that the young volcanic rocks within this area are of late- or post-glacial Quaternary age. As seen on aerial photographs, lava flows not disturbed by glacial erosion exist on ridge slopes and occupy the bottoms of U-shaped valleys, presumably glaciated valleys. Their undisturbed appearance is anomalous within glaciated valleys, unless they were not subjected to the last general glaciation. Thus a post-glacial age is strongly suggested.

Photogrammetry

Photogrammetric measurements. The important task of interpretation cannot always be accomplished by mere observation of photographs. It may be necessary to plot geologic data and to measure geologic features by photogrammetric methods in order to arrive at a sound interpretive conclusion. Photogrammetry is the science of obtaining reliable measurements by means of photography. Photogrammetric instruments used in conjunction with the three-dimensional stereoscopic model formed by overlapping aerial photographs thus provide a tool of significant use to the geologist. It is commonly possible to make necessary measurements to compile isopach and structure-contour maps of well-exposed areas without going into the area of study, although to assure best results a thorough field check of all work should be made. Isopach maps are those that show lines of equal thickness of parts of a rock formation—information that is vital in many commercial studies such as the search for petroleum and for some ore deposits. Structure-contour maps are maps that show lines of equal elevation on the top of a formation and help delineate geologic structures that may be important to the petroleum industry.

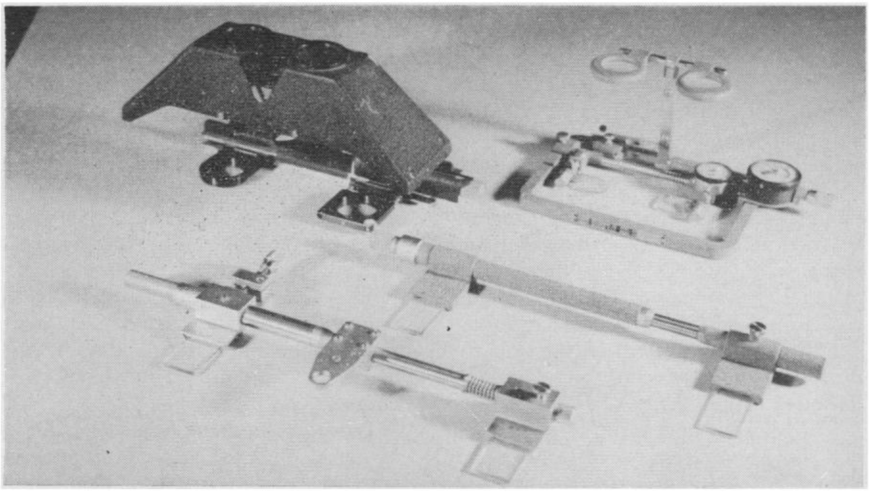

Fig. 10. Stereometers—instruments used to measure heights or altitudes from overlapping aerial photographs.

Example of the use of photogrammetry. An isopach-mapping project in Monument Valley, Arizona, illustrates the photogrammetric value of aerial photography in geologic study (*6*). In Monument Valley favorable sites for uranium minerals occur in paleostream scours or channels in the top of the Moenkopi formation. In these channels the overlying Shinarump member of the Chinle formation has thickened and provides loci of deposition of uranium minerals. The Shinarump member is particularly resistant to erosion and normally forms broad benches or the capping unit of buttes and mesas, a relation that aids in its identification on aerial photographs. By measuring a stratigraphic interval below the Shinarump member with a suitable photogrammetric instrument, it has been possible to show local thinning of the underlying rock units and inferred thickening, or channel formation, in the overlying Shinarump member. The isopach intervals—local thicknesses of the Moenkopi formation and underlying Hoskinnini tongue of the Cutler formation—were measured with a Kelsh plotter by using photography of approximately 1/20,000 scale. The Moenkopi formation and Hoskinnini tongue of the Cutler formation were measured as a unit because the base of the Hoskinnini tongue provided a more reliable structural datum, and was more readily identifiable on aerial photographs. Numerous altitude measurements were made at the base of the Hoskinnini tongue and at the top of the Moenkopi formation. Corrections were made for tilting of the rock units, and true local thicknesses were computed, which then served as a basis for isopach compilation—that is, connecting all points of equal unit thickness.

The resulting maps showed several lines, or contours, that closed in an elongate pattern, indicating the presence of a channel, possibly uranium-bearing, in the overlying Shinarump member of the Chinle formation. It is significant that the map was compiled entirely from aerial photographs; no ground control was used. The channels delineated by photogrammetric methods agreed closely with those located by field study. Although details of the afore-mentioned study have necessarily been omitted, the results demonstrate the significance of photogrammetric procedures in geologic interpretation.

Types of Instruments. The instruments used in making measurements for geologic purposes are varied; the choice of instrument depends not only on the geologic objectives sought but also on a complex set of factors, including photography available, accuracy desired, time available, reliability of ground control, character of topography, and character of vegetation and cover. Measurement of differences in elevation can be made with the simple stereometer or parallax bar from paper prints (Fig. 10). These measurements are thus made economically, but some reliability of results must be sacrificed, for no correction can normally be made for tilt that may be inherent in the photography. Corrections for tilt can be made if precision instruments (see Fig. 3) are used, and thus correct thicknesses of rock units and correct altitudes can be obtained. Local accuracy of 2 feet in elevation readings may be possible with the common 1/20,000-scale photography, but accuracy throughout the entire stereoscopic model will be less than this.

As the scale of photography decreases, so does the reliability of measurements. Hence scale of photography is important in considering objectives to be attained, particularly if only one type of instrument, such as a parallax bar, is available for use in measuring. Greater over-all accuracy may be obtained from a given scale of photography with precision photogrammetric equipment (see Fig. 3) than with simpler instruments.

The procedures described may be considered as routine in using aerial photographs in geologic study; that is, interpretation is accompanied by collection of metric data which in turn may be of further use in final interpretation.

New Techniques

In addition to these routine procedures, many new avenues of study are being tested. The new procedures involve experimentation with photographic systems, high-altitude photography, color aerial photography, new photogrammetric applications, and orthophotography (*7, 8*).

Photographic systems. Based on the premise that aerial photographic tone or color of an object should be predictable for any particular film-and-filter combination if certain factors are known, a photographic system may be devised to accomplish a specific objective, such as differentiating certain rock units. The wavelength and intensity of light reflected from a surface are the main requirements in devising a photographic system. Spectrophotometer analyses are made of the reflective spectra of rocks in question, and resulting spectral curves are used as a basis for devising a film emulsion that will differentiate the reflected light of each sample, thus recording a different photographic tone for each rock photographed.

High-altitude photography. High-altitude photographs taken from approximately 30,000 feet above mean terrain have been used recently with much success in geologic mapping and measurement. The three-dimensional view provided by this photography may provide the geologist with a single stereoscopic view of as much as 50 square miles. This is a much larger ground area than was heretofore covered by a single stereoscopic model. This view of a larger area enables the geologist to begin his study with a broader understanding of the relations of the general geologic features.

The advantages of extensive areal coverage in a single stereoscopic model are realized even further in the technique of using twin low oblique photographs, in which the overlap area of photographs taken at 30,000 feet flying height can cover more than 100 square miles (*9*). Experience indicates that in many areas, regardless of the complexity of the geology, a fundamental orderly arrangement of geologic structures can be discerned on photographs, provided that the scale is small enough. Because of the large area covered per stereoscopic model with high-altitude photographs, precision photogrammetric equipment may be used economically in some photogeologic mapping, depending on the geologic terrane and metric requirements of the job. If camera lenses of the same focal length are used, reliability of measurement varies inversely with the altitude of the aircraft taking the photograph.

Color aerial photography. Recent experimental color aerial photography has demonstrated significant uses in geologic interpretation not possible with available black-and-white photography. In Death Valley, California, it has been possible to differentiate lava flows of similar color but of different ages and to differentiate certain lake sediments from lava flows, all of which appear similar on black-and-white photographs. Many of the stratigraphic units in this area have characteristic colors. When the units are in normal stratigraphic sequence, the characteristic colors are likewise arranged in a normal sequence. Interruptions in the normal sequence of colors have suggested thrust faults, later verified by field check, that were not interpreted from black-and-white photographs.

Perhaps of greater significance is the ability to differentiate some zones of alteration on color aerial photographs; these zones of alteration may be significant in mineral exploration. In a study of the Tonopah and Goldfield areas in Nevada, it was found that early stages of rock alteration could be distinguished by color and were characteristic of certain rock types. Intense alteration, however, although readily identified on color photographs, tended to produce the same color regardless of the original composition of the rock. Such intensely altered zones may well be significant with regard to ore deposition, however. With regard to color photography, it is interesting to note that the Canadians plan to "fly" the Sudbury, Blind River, and Bancroft districts with color film to determine whether clues to mineralized areas can be picked up which may guide in the search for new districts (*3*).

Color aerial photography in geologic study has received only limited use, presumably because of its relatively high cost compared with the cost of black-and-white photography. The high cost is ascribed by many to technical limitations of color film, such as the limited latitude in photographic conditions, the need for lenses of long focal length, and the requirement of low altitudes of flight. However, many of these limitations have been overcome in recent developments, and color aerial photography may be expected to become more competitive with black-and-white photography for purposes of interpretation. And, in any event, an evaluation of cost should logically be made in terms of results of use, as in an exploration program, and not solely in terms of the cost of black-and-white photography.

New photogrammetric applications. The introduction of projection-type stereoscopic plotters, such as the Kelsh, multiplex, and ER-55 plotters, has facilitated geologic mapping and study, for the geologist uses these instruments to combine interpretation, measurement, and plotting in a mutually supporting operation. These instruments increase the accuracy and soundness of interpretation (i) by presenting the terrane in proper orientation so that features are in correct relation one to another, (ii) by allowing features to be plotted orthographically during the process of interpretation so that their relationship to features previously interpreted from adjacent stereoscopic models can be continuously studied, and (iii) by allowing measurements to be made quickly and easily so that measurement becomes a closely integrated tool of interpretation. With stereoscopic plotting instruments, isopach or structure-contour maps of some areas may be made primarily or entirely by photogrammetric means; the isopach map of part of Monument Valley, which has been described, is an example of the usefulness of photogrammetry in geologic mapping. The accuracy of stereoscopic instruments is considered particularly significant with respect to plotting features that are visible on aerial photographs but that are difficult to locate on the ground. Correct plotting of positions of features aids in their subsequent location and study in the field.

Several new instruments have recently been devised to aid in geologic interpretation. One of these is a tilting platen, or viewing surface, used with projection-type stereoplotting instruments. The surface of the tilting platen can be made to coincide with a sloping surface in the stereoscopic model, and the angle of tilt can be directly measured with a clinometer or other measuring device. A profile plotter also has been constructed; it not only permits an accurate profile of the terrain to be drawn in any orientation of the stereoscopic model but also permits exaggeration of this profile, as desired, at the time of plotting. Another instrument is being made to measure directly the thickness of inclined rock formations shown in stereoscopic view.

It is expected that projection-type stereoplotting instruments will be useful in geophysical studies in determining the altitudes of gravity stations and measuring the mass of the topography surrounding gravity stations for terrain correction. Statistical methods used in conjunction with the plotting instruments may eliminate many of the laborious computations of terrain corrections from topographic maps.

Some stereoplotting instruments can be equipped with coordinate-measuring devices so that any point or object on the photograph may be located quickly in a three-dimensional grid system. Thus the photograph becomes an ideal starting point for translating positions into a form usable in electronic computers. Furthermore, these instruments allow a model to be deliberately inclined; in this way regional dips may be introduced or removed, and the model may be studied and measured in any desired hypothetical orientation. Stereoplotting instruments provide quantitative information easily and thus allow closer integration of photogeologic interpretation with an over-all exploration program. In some areas the photographs may be the prime source of metric data.

Orthophotography. Orthophotography is photography that has the position and scale qualities of a map plus the abundant imagery of photographs. Conventional vertical aerial photographs are perspective views, and, in this form, all images are displaced radially from the center of the photograph. This displacement of relative position of features makes it difficult to transfer data accurately from a photograph to a map.

Figure 11 (top) is a direct copy of a part of a perspective aerial photograph; it shows the straight path of a power line as it is distorted by normal relief displacement. Figure 11 (bottom) is an orthophotograph made with a device, the orthophotoscope (*10*), that removes relief displacement; note that the power line is straight. An orthophotograph is in itself an excellent planimetric map; data may be transferred directly from the orthophotograph to a topographic or planimetric map. Orthophotographs also provide a means for rapidly determining altitudes in the field by reading vertical angles with an alidade, or similar instrument, and scaling the horizontal distances directly from the orthophotograph.

Historical Summary

Flying advances in World War I were influential in stimulating aerial photography for commercial use during the 1920's. Since that time aerial photographs have been used increasingly in geologic study. One of the first important uses of aerial photographs for geologic study was in compiling mosaics, which were used for general interpretation purposes, as planning maps, and as general base maps for plotting geology. Interpretations were generally made by viewing the over-all mosaic rather than by stereoscopic inspection of photo pairs.

Subsequently stereoscopic study of photographs was undertaken in a rather extensive way, by use of simple viewing devices. Among the first important geologic interpretation studies from aerial photographs was a reconnaissance study of 35,000 square miles in New Guinea, begun in 1935 by the Dutch (*11,* pp. 110–117). Although the final maps were compiled by simple methods, and although positioning errors were present, the results met the requirements of reconnaissance study and demonstrated convincingly for the first time the potential of aerial photographs in a petroleum exploration program, from the standpoint both of information obtained from the photographs and of the great saving in time and money in completing the job.

Yet, no extensive use of photographs was made by the petroleum industry as a whole prior to World War II. It was only after World War II, and as a result of techniques and interests developed during the war, that the use of aerial photographs began to rise spectacularly in commercial studies. Primarily the petroleum companies began extensive use of photogeologic maps, but the mining industry also indicated an increasing interest in photogeologic procedures.

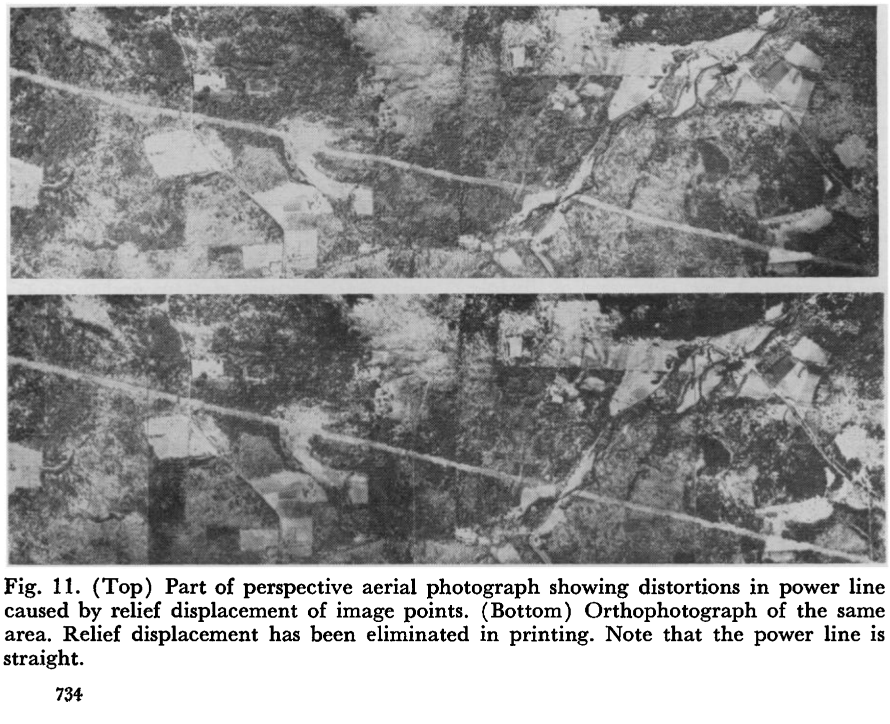

Fig. 11. (Top) Part of perspective aerial photograph showing distortions in power line caused by relief displacement of image points. (Bottom) Orthophotograph of the same area. Relief displacement has been eliminated in printing. Note that the power line is straight.

Noteworthy since 1945 has been the increased use of photogrammetric instruments in compiling geologic data interpreted from aerial photographs. Although the advantages and limitations of many photogrammetric instruments have only recently received wide attention, the desirability of reliable compilation of photogeologic information has long been recognized, and the Dutch study of New Guinea in 1935 was followed by a test of the A-6 precision stereoplotting instrument for photogeologic purposes (*11,* pp. 115–116); plotting with stereoplotting instruments was found to have many advantages. But use of instruments lagged until after World War II. Within the past few years, however, stereoplotting instruments, such as the Kelsh and multiplex, have come into increasing use, both for interpreting and for plotting geologic data.

In a general way it may be said that use of aerial photographs in geologic study in the United States has evolved through the following stages: (i) emphasis on uncontrolled mosaics and use of single views for interpretation and plotting; (ii) use of stereoscopic pairs of prints for interpretation together with simple procedures for plotting these data; (iii) use of stereoscopic pairs of prints for interpretation together with rectification of positioning these data with simple instruments such as the radial planimetric plotter; and (iv) use of stereoscopic pairs of diapositive glass plates in precision photogrammetric instruments for interpretation and plotting. In addition, with increased use of aerial photographs in recent years, new instruments have been devised especially for geologic study, and new avenues of research are actively being pursued in interpretation studies.

The recent use of precision photogrammetric instruments in photogeologic study presages a closer integration of photogeologic and field studies. Because of the reliability of geologic measurements and positioning with precision stereoplotting equipment, a greater amount of photogeologic data may be expected to be incorporated in the geologic maps of the future (*12*).

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Sexual Differentiation in Hydra

Control by Carbon Dioxide Tension

W. F. Loomis

The chemical nature of the stimuli that control cellular differentiation may be approached with advantage in *Hydra,* for it has been shown that these animals do not differentiate sexually in response to an internal stimulus that is part of their life cycle but rather in response to an external stimulus that is controlled by the environmental conditions under which they are cultured. Although previous attempts to define the responsible variable have been unsuccessful, factors such as crowding, stagnation, nutrition, and temperature have been shown to affect the process. A few years ago we reported that *Hydra* differentiate sexually when cultured under crowded conditions such that their oxygen tension was reduced to about 70 percent saturation with air (*1*). Quantitative study of this phenomenon was carried out with the aid of a new and rapid method for determining dissolved oxygen (*2*).

Effect of Surface/Volume Ratio

In the experiment shown in Table 1, four otherwise identical cultures of *Hydra* were grown in differently shaped containers so that the depth of the four cultures and their surface/volume ratios varied progressively. Each culture consisted of 25 *Hydra littoralis* in 25 milliliters of 70-milligram-per-liter $CaCl_2$ and 100 milligram-per-liter $NaHCO_3$. The animals were grown in a beaker and three sizes of petri dishes with internal diameters of 4.8, 6, 9, and 15 centimeters, respectively. Each culture was fed for 30 minutes daily with an excess of brine shrimp larvae (*3*), following which it was rinsed with clean culture solution to remove all uningested brine shrimp and left at 25°C until the following day. A constant degree of crowding was maintained by the daily removal of all newly detached buds.

The results of this experiment demonstrated that, although sexual differentiation and reduced oxygen tension were parallel phenomena, they did not develop proportionally. It appeared likely, therefore, that some other volatile factor, besides oxygen, was the inducing variable. This conclusion was confirmed by the finding that artificial reduction of the oxygen tension did not induce sexual differentiation in *Hydra.*

Subsequent experiments demonstrated that *Hydra* differentiate sexually in response to an unidentified gas given off by the animals themselves (*4*). The rate at which this gas was secreted was found to depend on both temperature and nutrition, being especially high during periods of active digestion. Its rate of accumulation was found to vary with the depth of the water as well as with the degree of crowding and stagnation within the culture. The gas was highly volatile, for brief aeration prevented sexual differentiation from occurring in cultures that otherwise would turn sexual. Its solubility coefficient was of the order of 1, for the gas could be transmitted to the air phase and back into clean water in sufficient quantity so that it still induced sexual differentiation (Table 2).

Air Bridge Experiment

In the air-bridge experiment (Table 2), the sex-inducing gas present in the culture water of crowded *Hydra* was transferred to an air phase and back into clean water by the following technique. Twenty milliliters of "used" culture water, obtained each afternoon from the two cultures described below, were drawn into a 25-milliliter syringe and shaken with 5 cubic centimeters of air for 30 seconds. The air phase alone was then transferred to another syringe, where it was shaken with 10 milliliters of clean water. This treated sample of clean water was given to one culture, while a similar sample of untreated clean culture water was given to the control. A constant degree of crowding was maintained by the daily removal of all newly detached buds. In this experiment, each culture consisted of 10 *Hydra littoralis* in 10 milliliters of 100-milligram-per-liter $CaCl_2$, 125 milligram-per-liter $NaHCO_3$, and 12 milligram-per-liter disodium ethylenediaminetetraacetate (Versene) brought to *p*H 8.0 with NaOH. Both cultures were contained in 15-milliliter beakers and fed and cleaned daily as described in the preceding section. In addition, both cultures received a second afternoon rinse about 5 hours after their daily feeding, at which time the "air-bridge" vessel received the treated water, while the control vessel did not.

Since this experiment indicated that an active gas was present in samples of air equilibrated with "used" culture water, a concentrated sample of this gas was prepared and subjected to analysis by infrared spectrophotometry, mass spectrography (*5*), and gas-liquid partition chromatography. It was found that, within the limits of these instruments, no gases were present other than carbon dioxide, oxygen, nitrogen, and argon, the carbon dioxide concentration being increased and the oxygen concentration decreased relative to their concentrations

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The author is director of the Loomis Laboratory, Greenwich, Conn. This work was described in part before the Symposium on Cell Division and Differentiation held by the American Chemical Society at Atlantic City, N.J., 17 Sept. 1956.