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PHOTOGEOLOGIC PROCEDURES IN GEOLOGIC INTERPRETATION AND MAPPING

Introduction

In the past few years increasing use has been made of aerial photographs for geologic interpretation and mapping within the U. S. Geological Survey. As a specialized technique in interpretation and mapping, however, photogeologic procedures were extensively used (1947-1953) in the Survey's geologic mapping of Naval Petroleum Reserve No. 4 in northern Alaska and in mapping part of the Colorado Plateau of western United States, principally in Utah (1951-present). Photogeologic work was performed by a specialized group of geologists that was organized as the Photogeology Section in June 1953. This group has more recently made studies of northeastern Utah, southern and southeastern Alaska, and central Alaska. Various photogeologic procedures have been used in these studies; some procedures have been modified, and new ones have been developed. It is primarily the purpose of this paper to discuss these procedures. Photogeologic procedures or techniques used outside the Geological Survey are not discussed herein.

Although "photogeology" is a poorly chosen term and is often poorly defined or not defined at all, it has come into common use in the literature during the last several years.

> Photogeology is here defined as the study and interpretation of photographs, normally aerial, for the purpose of obtaining geologic information; it also normally includes presentation of information from photographs in appropriate form, such as on mosaics, areal geologic maps, or geologic cross sections.

Stereoscopic examination of photographs is usually involved in such study and interpretation, but this is not always necessary. Procedures currently followed in photogeologic work include: 1) annotation of geologic data on photographs, whether these data are interpreted entirely in the office by stereoscopic examination of photographs, or whether they are observed in the field and transferred to photographs as part of the field mapping project; 2) quantitative determination of geologic data from photographs by use of appropriate photogrammetric measuring instruments; 3) limited base-map compilation from photographs; and 4) transfer of geologic data from photographs to base maps. Whether photogeology is employed as a primary mapping method, as in some reconnaissance projects, or whether it is used as a secondary mapping method in conjunction with more detailed field mapping, the procedures practiced are generally the same.

Present day usage of photographs is confined largely to the so-called vertical photography, although there has been and may well be in the future a significant place for oblique aerial photographs as well as terrestrial photographs in geologic work. The procedures described below consequently pertain almost entirely to use with vertical aerial photographs.

Acknowledgments:--The writer wishes to express his appreciation to John C. Reed, Jr., for writing that part of the text dealing with photo-recognition of features associated with glaciers, and to William A. Fischer for describing the multiplex and Kelsh plotters.

Value of stereoscopic viewing and choice of stereoscope

Whereas conspicuous geologic features are commonly visible on single aerial photographs and the casual user of aerial photographs may use single prints, the wealth of information as shown in stereoscopic view is many times greater inasmuch as the stereoscopic model gives a three-dimensional impression of the terrain. Subtle 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. Indeed, vertical exaggeration, or relief exaggeration, is a potent aid in making geologic interpretations from aerial photographs; most stereoscopic models exhibit rather marked vertical exaggeration.

The most important instrument used in photogeologic study is the stereoscope. Choice of the particular stereoscope used may vary widely, but for efficient study in concentrated or prolonged photogeologic interpretation, certain fundamental features should be present in the instrument. Ideally, the stereoscope should be designed to permit comfortable viewing of the photographs without fatiguing the back and neck muscles; it should permit viewing the entire stereoscopic model at one time; it should have a magnifying device so that detailed study may be made of specific features on the photographs; it should be designed to allow freedom of hand movement for annotation; the lens system should be relatively free from distortion to permit estimating quantitative geologic data; and the lines of sight from the eyes to the photographs preferably should be contained in an apparent vertical plane--this permits most interpreters to visualize the horizontal datum of the stereoscopic model more readily and results in more reliable estimates of quantitative data that must be referred to this datum. It would also assist the photogeologist materially in certain studies if the stereoscope assembly were adjustable to correct for the small amounts of tip and tilt that might be present in the photographs. Unfortunately, no one stereoscope meets all the above requirements.

Several makes of stereoscopes exist, but basically there are only three types; these are the lens, the mirror, and the prism types; stereoscopes employing combinations of these basic optical elements are also made. All have certain advantages and disadvantages. Use of the simple lens pocket stereoscope (fig. 1) demands a large overlap of the stereoscopic portion of the two photographs being viewed; it is necessary to "flip" one photograph in order to observe the total area of stereoscopic coverage. Also, it is awkward to annotate photographs under the pocket stereoscope owing to the close spacing of the stereoscope supports; there is little or no freedom of movement of the hand-held pencil or pen. A virtue of the simple lens pocket stereoscope is its

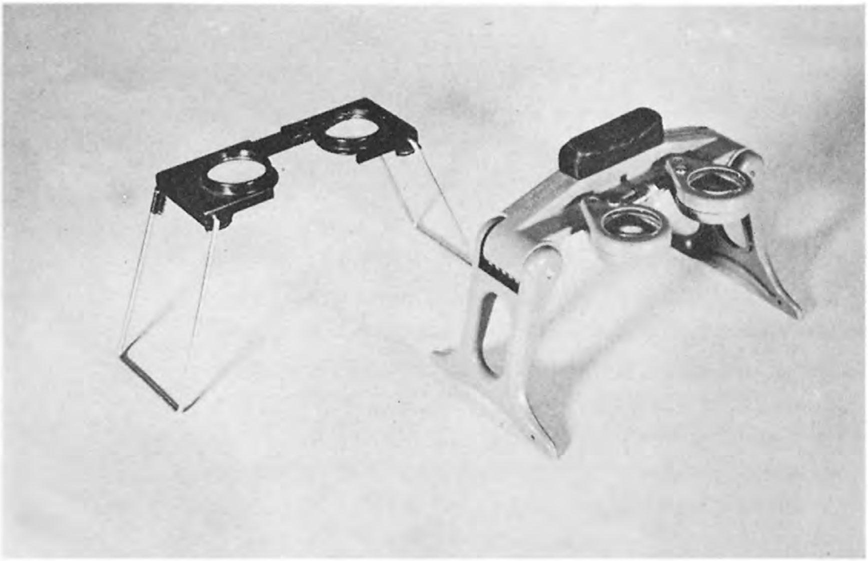

Figure 1.--Pocket stereoscopes commonly used.

magnification, but for estimating quantitative data, such as the strike and dip of a sedimentary bed, the pocket stereoscope must be used with great care because of the pronounced lens distortion. However, for rapid qualitative checking of a geologic feature this instrument is especially helpful and is used frequently in the office in conjunction with the mirror and prism-mirror stereoscopes. The portability of the pocket stereoscope of course recommends it as a field instrument.

Many mirror stereoscopes (fig. 2) are so designed that an observer must look vertically down at the photographs. This is not as comfortable a viewing position for prolonged working as a stereoscope with tilted viewing assembly, but it does fix the line of sight from the eyes to the photographs in a vertical plane, thus permitting easier visualizing of the horizontal datum of the stereoscopic model and consequently more reliable estimating of quantitative data. A special mounting arm allows complete freedom of movement for annotation of the photographs. Mirror stereoscopes of the type shown (fig. 2) permit full separation of the aerial photographs. This allows the entire stereoscopic model to be seen when low-power magnification (normal viewing arrangement) is used; a binocular attachment may be present for detailed work, although a bit awkward to use. With high-power magnification the field of view is considerably reduced; a slight re-positioning of photographs is generally necessary for comfortable stereoscopic viewing when changing from one magnification to the other. The loss of illumination by virtue of the greater number of glass surfaces and distances a light ray has to pass through in the binoculars of the mirror stereoscope is not a serious objection or limitation of its use.

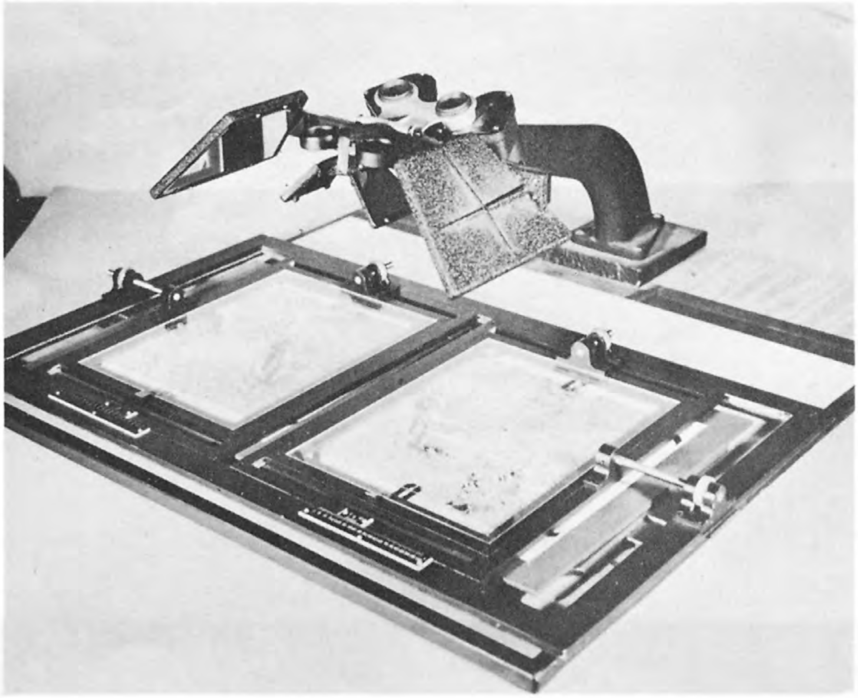

Figure 2.--Mirror stereoscope with binocular attachment.

A relatively new prism-mirror stereoscope of foreign make is shown in figure 3. Its tilted viewing assembly permits easy operation without undue strain of the back and neck muscles, but this very arrangement so designed for comfortable viewing causes the image plane to appear tilted and thus for most interpreters the instrument is difficult to use in making quantitative estimates of geologic data that must be referred to the horizontal datum of the stereoscopic model. One unique feature of this stereoscope is the positioning of the photographs a considerable distance away from the observer. This permits two stereoscopes to be arranged "back to back" so that two individuals may view the same stereoscopic model simultaneously. The largest field of view includes approximately one half the stereoscopic model. Scanning of the stereoscopic model is accomplished by movement of prisms in the optical system, rather than by physical movement of the photographs; once the photographs are properly oriented they need not be reoriented or moved during study of that stereoscopic model. A simple knob adjustment permits rapid change of magnification from 1.5x to 4.5x; no shifting of photographs is necessary when changing from one magnification to the other. Design of the supporting legs does not permit complete freedom for annotation, but this is not a serious objection. The instrument is not easily portable, and is thus primarily used in the office.

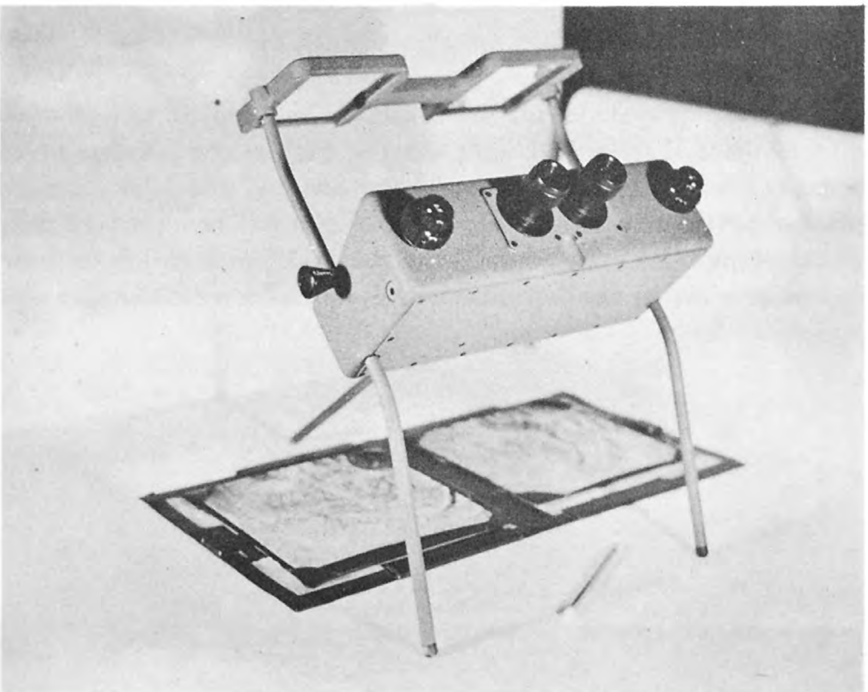

Figure 3.--Stereoscope with tilted viewing assembly.

Orientation of photographs for stereoscopic viewing

Proper orientation of photographs for stereoscopic viewing is necessary in any work where quantitative measurements or reliable estimates of structural data are involved. A three-dimensional impression of the terrain can often be obtained in haphazard arrangement of photographs under the stereoscope owing to the ability of the human eye to compensate small areas for misorientation of the photo-pair, but such misorientation may cause significant errors, especially in the quantitative evaluation of low-dipping planar structures. Also, as mentioned previously, the field of view preferably should appear to be horizontal for estimating quantitative geologic data inasmuch as planar and linear structures in the stereoscopic model are generally referred mentally by most interpreters to the horizontal plane of, say, the desk top. Proper orientation of photographs is also to be encouraged to avoid eye strain.

Regardless of the type of stereoscope used, proper orientation of photographs demands that they be alined along the flight line. This involves alining the principal points and transferred principal points, and can be accomplished in a number of ways. (The principal point is located at the intersection of lines drawn between opposite fiducial marks located on the four sides of the photographs. It is transferred to the other photograph of the stereo-pair by stereoscopic inspection.) One photograph is fastened to the table by a straight pin through the principal point, allowing for rotation of the print around this axis. The second photograph is fastened to the table in the same manner, the distance of separation of the photographs ranging from about 2 inches if a pocket stereoscope is used to more than 10 inches if a mirror or prism-mirror stereoscope is used. With the two photographs free to rotate around the respective pins, a straight edge is laid against the two pins. Each photograph is then rotated until the transferred principal points also lie along the straight edge (equivalent to the line of flight) (fig. 4). This places all four points--two principal points and two transferred

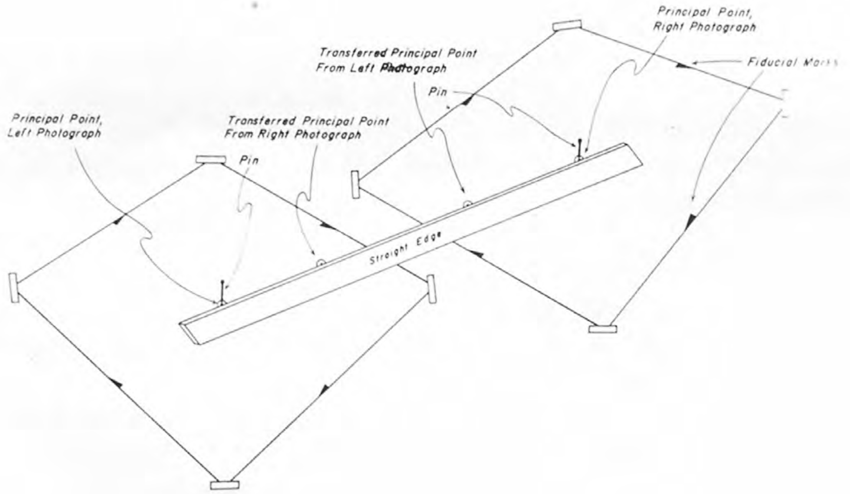

Figure 4.--Diagram showing correct orientation of photographs for stereoscopic viewing.

principal points--along the same line, and the photographs are then taped down in their correct positions for stereoscopic viewing. In placing the stereoscope into position for viewing, care should be taken that the stereoscope axis--the horizontal line through the centers of the eye lenses--is parallel to the line connecting the principal and transferred principal points of the photo-pair. Although the discussion of proper orientation technique appears to be long, orientation procedure takes but a short time and is essential in work where quantitative measurements or reliable estimates are to be made_/.

Correct orientation may also be made in the following somewhat simpler manner: A thread or fine string is stretched in the plane of the photographs parallel to the stereoscope axis (the horizontal line through the centers of the eye lenses) and attached to the table with thumb tacks. Each photograph, with its principal and transferred principal points marked, is then slipped underneath the thread or string. The principal points and transferred principal points are merely lined up under the string, taking care to separate the prints for comfortable viewing, and photographs are taped to the table. In practice some photogeologists have the thread and photo-holding assembly on a separate movable cardboard mount. This allows movement of the stereoscopic model when the Ryker stereoscope, which is most conveniently mounted in a fixed position, is used.

Annotation on aerial photographs

The importance of careful annotation of geologic and related data ranks high among photogeologic procedures. Just as photo-interpretation is limited by the quality of the photographs, so too are results of many compilations from photographs limited by the quality of the annotations. Much has been said and written regarding the use of transparent overlays for annotating, but several disadvantages have been pointed out by Desjardins_/ who prefers to annotate directly on the photographs. The common practice of placing photographs directly in the so-called paper print plotters, which are used frequently for transferring detail in map compilation, is also a compelling factor for annotating directly on the photographs.

Annotations may be made in several ways. Grease pencils, semi-grease pencils, or colored lead pencils have been used for marking photographs, but these are not too satisfactory. Most grease pencils make lines that are too wide (consider that .01 inch on a 1:20,000 scale photograph represents about 16½ feet on the ground); exact positioning of fine detail is difficult. Colored lead pencils do not "take" well to most print surfaces and furthermore tend to damage the photograph surface because of pressure exerted to make even a poorly legible mark. Ink is the best medium for annotating. Various types of inks have been used and two types, tempera and india, have been found to be satisfactory, although there are distinct advantages and disadvantages with each. Tempera, which comes in a wide variety of colors, shows up clearly on the face of a photograph and is easily erased with a water-damp cloth or cotton. Its brightness recommends it on photographs to be used in various projector-type machines for transfer purposes. However, tempera dries rapidly, gums up the pen point, and makes wider lines than are desirable for some purposes. If a person is proficient in

_/ Nowicki (1952), Manual of Photogrammetry, p. 529-533.

_/ Desjardins, L., (1950), Bull. Am. Assoc. Pet. Geol., vol. 34, p. 2288.

using a crowquill or other fine-point pen, india ink can be controlled better than tempera and makes finer lines if applied properly. The need for fine lines is very aptly put by Desjardins who says/ :

> In the first place, these fine lines are appropriate for the order of magnitude of many of the features noted, and for the desirable habit of drawing precisely upon the outcrops or other features. This extreme care with the positions of the lines is insurance against jumping of beds, and it keeps the eyes alert for small important details. In the second place, the finer the line, the less it covers up. Thicker lines or misplaced lines are a sure way to cover up and prevent recognition of small features. In the third place a fine line located with precision gives the eyes a valuable geometric tool. If the line follows an outcrop, for instance, the eyes are provided something they can grasp visibly standing out in the three-dimensional picture to facilitate its spatial projection and discovery elsewhere in the surrounding topography.

Although india ink will give the desired fine lines, some colors erase with difficulty, even in the solvent ammonia, and some colors, especially red, cannot be erased completely. However, if fine lines are essential to a particular study and a variety of colors is not needed, black india ink is to be highly recommended for annotating purposes.

Recognition of geologic features on photographs

Inasmuch as recognition of geologic features on photographs is basic to carrying out many of the procedures described herein, a discussion of recognition criteria seems appropriate. It is generally true that the larger the photograph scale the more detail that can be seen, but the photographic expression of strictly geologic features may also differ considerably depending on the geologic environment, weathering conditions, topography, etc. Reference is made herein only to areas with which personnel of the Photogeology Section are familiar. These areas include the following types of terranes and environments: 1) tundra-covered sedimentary terrane of northern Alaska, 2) glaciated but sparsely vegetated terrane of interior Alaska, 3) heavily vegetated igneous-metamorphic terrane of southern and southeastern Alaska, and 4) sparsely vegetated sedimentary terrane of the Colorado Plateau and Uinta Basin of Utah. The more important geologic features identifiable on aerial photographs of these areas will be discussed only in reference to these four types of terranes and environments. All photographs studied have a scale of 1:20,000 or smaller. Geologic features within one or more of these areas that have been recognized on and mapped from aerial photographs include: bedding, faults, unconformities, joints, cleavage, terraces, alluvial fans, pediments, lava flows, glacial features such as outwash and moraines, and intrusive

/ Desjardins, L., (1950), Bull. Am. Assoc. Pet. Geol., vol. 34, p. 2290 rocks such as volcanic plugs, bosses, stocks, and dikes. It is important to remember that basically such geologic features, as seen on photographs, are recognizable because of photograph tone differences, textural differences, and/or patterns. Particularly are straight lines of significance in the formation of photograph patterns.

Bedding:--Recognition of bedding or other features that reflect bedding is, of course, fundamental in any structural and stratigraphic study of sedimentary terrane. In some of the tundra-covered areas of northern Alaska, where outcrops are scarce, bedding may be easily interpreted from indirect evidence of aerial photographs. The surface expression of more resistant beds results primarily in a break in topography and change in vegetation. In areas of low dips a topographic steepening of the slope across the stratigraphic interval of the resistant bed is common, and an associated vegetation change imparting a darker photograph tone to the steepened slope may also be characteristic although in some areas the steepened slope may show a lighter photograph tone owing to a lack of vegetation. The topographic steepening is particularly apparent in study of the photographs owing to relief exaggeration inherent in most stereoscopic models; in most areas the vegetation change is more easily seen in the aerial view than it is directly on the ground. Although these bedding expressions, conveniently called structure traces, generally are not continuous, it is frequently possible to correlate individual beds over many miles. Determining the bedding attitude by visual estimate or by actual measurement with photogrammetric measuring devices is relatively simple, and the associated folded structures can be readily defined.

In areas such as the sparsely vegetated Colorado Plateau and Uinta Basin of Utah, outcrops are abundant and bedding in the sedimentary rocks can be observed directly. For the most part photograph tone together with differences in topographic expression are the bases for delineation of beds as seen on aerial photographs, although topographic expression or photograph tone alone is of considerable help locally. Different beds may also exhibit different textures as seen in aerial view. The continuous rock exposures over wide areas favor rapid correlations of stratigraphic units by photogeologic methods. However, in some areas dip slopes are thinly mantled with windblown sand or residual soils, but a topographic expression of the beds is generally visible, thus permitting correlations and structural determinations.

Bedding in metamorphic rocks may be much more difficult or impossible to recognize from photographs because of physical changes in the beds, including the superposition of metamorphic structures. Where rock exposures are good, differences in photograph tone offer the best clue to recognition of bedding, although vegetation may favor a certain bed and reflect the attitude and position of the bed. Topographic expression, such as the geologic "grain" of an area, may also suggest bedding, but in glaciated areas this evidence must be used with caution.

Faults:--One of the greatest advantages in study of aerial photographs is that of delineating high-angle faults or suspected high-angle faults. This advantage is a direct result of the aerial view, allowing a greater area and the gross features within it to be seen at one time. For the most part individual high-angle faults show on aerial photographs as straight lines or gently curving lines, and this characteristic is probably the most important clue that a fault may exist. The linear character of fault expression is commonly conspicuous on aerial photographs, whereas it is inconspicuous on the ground. Although the burden of proof of faulting rests with other criteria, any linear feature should be examined with care. Lines indicative of faults may be expressed as alinements of vegetation, straight segments of stream courses, conspicuous changes in photograph tone, topographic expression, or any combination of these; where bedrock is well exposed the actual physical break may be seen. In some places a lineament 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 of strike as well as abnormal stratigraphic position with respect to beds on the other side. In sedimentary terrane, offsets on opposite sides of such a lineament are generally easily detected, owing to the vertical exaggeration inherent in most stereoscopic models.

In semi-arid environments such as the Colorado Plateau and Uinta Basin of Utah, all the above criteria for faults may be observed. In heavily vegetated areas such as southeastern and southern Alaska, topographic expression, particularly long, narrow, troughlike depressions, is the dominant criterion for suspected faults although in areas above timberline other expressions of faulting may be visible. It should be pointed out that, even though many of the criteria of suspected faults exist, until an area is field-checked, faulting should be considered proven only where an offset of beds or rock types can be demonstrated.

Suspected faults should be examined carefully, for other features may be expressed, at least in part, on an aerial photograph in the same manner as faults. For example, the limits of old river flood plains may show as short straight line segments or as gently curving lines, and the difference in altitude of associated terraces could be mistaken for offsetting of nearly horizontal strata. In some areas jointing in one direction within a formation may be particularly prominent. The relative frequency of subparallel lineations and the lack of recognizable offset of associated rock types typify the appearance of joints on aerial photographs. In a few places where an apparent offset is present owing to the occurrence of an erosion scarp along a joint plane, the scarp line may easily be erroneously interpreted as a fault trace. Erosion scarps are very similar to some fault traces as seen on an aerial photograph. Where a sedimentary formation has been channeled, and a rock type of different lithologic character now occupies this channel, a distinct lineation between the channel-fill and the original sedimentary rock, now truncated, may be mistaken for a fault in some areas. Owing to weathering and erosion an apparent offset of the original bed may be visible, but careful analysis of the terrane will generally eliminate misinterpretation. Lines between two distinct types of vegetation, although possibly reflecting the presence of faults, may well be due to differences in underlying rock types in normal sequence, and/or to the moisture content of the soil, or even to man-made features such as fences and irrigation ditches. In some areas the simple erosion of dipping strata may result in an alinement of topographically higher points that suggests a fault. The need for extreme 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.

Unconformities:--Of several types of major unconformities, it is doubtful that any other than angular unconformities might be recognized readily or suspected on vertical aerial photographs, although local channeling in the top of a formation may be conspicuous. Bedding is the significant feature to be observed. On photographs of northern Alaska terrane a discordance of bedding may be inferred from the structure traces, described above; in the well-exposed rocks of the Colorado Plateau discordance of bedding at a contact line may actually be observed. But discordance alone does not prove the presence of an unconformity, since a discordance of bedding may be due to thrust faulting, or locally due to crossbedding. The areal distribution of rocks or structures as seen after plotting geologic data over a large area may also suggest the presence of an unconformity, but without some ground observations it is debatable whether many angular unconformities between consolidated sediments could be demonstrated convincingly from a study of vertical aerial photographs. Strong evidence for such an unconformity would be the presence of a line, across a wide area, separating bedding parallel to that line from bedding that had a discordant relation to that line. On a local scale, the separation of unconsolidated, nearly horizontal, river gravels from the truncated, underlying strata is a good example of such an unconformity.

Joints:--Joints are recognizable on aerial photographs without much difficulty, and in the well-exposed sedimentary rocks of Utah even the closely spaced fine lines as seen on photographs are rather obvious representations of joints, although these fine lines would not represent close-spaced joints as defined by the field geologist. Not infrequently vegetation may grow along joints and thus show as straight lines on the photographs. A good clue to the presence of joints is the general abundance of short lineations on a photograph and a more or less constant trend of these lineations within a given area of a few square miles extent. In some areas joints have been widened through weathering and erosion processes, and appear as especially conspicuous linear features. The similarity of these joints to faults is superficially striking, but other criteria of faulting are lacking.

In many igneous intrusions the joint pattern is not as uniform as it is in sedimentary rocks. Joints striking at wide angles to the strike of dominant joint planes are common; this results in a crisscross pattern somewhat distinctive of intrusive rocks in many areas.

Cleavage:--Although cleavage is almost universally present in metamorphic rocks, especially in those that were originally shale or other thin-bedded sediments, it is difficult to differentiate on aerial photographs of small scale. On 1:40,000-scale photographs of some Alaska areas flow-cleavage parallel to bedding can only be differentiated locally; fracture cleavage known to be conspicuous in outcrops cannot be seen in the stereoscopic model. The grain of a metamorphic terrane as reflected in the aerial view by distinctive stream and vegetation patterns might well represent pronounced flow-cleavage, but proof of this would lie in ground observations.

Terraces:--Within areas studied to date (1955) many terraces have been mapped. These are terraces formed almost entirely in alluvium; the so-called rock terraces formed in alternately resistant and weak horizontal strata are not considered here. In some places the terraces have typical terrace form--that is, a nearly flat surface bounded by a steeper ascending slope on one side and by a steeper descending slope on the opposite side; in other places they occur as flat-topped mesalike forms. Generally, terraces are easily recognized from photographs, except where erosion has dissected and strongly modified the original form. Commonly the relatively flat terrace surface extends over some distance and is, of course, at some distance above the present associated stream, the apparent altitude above the stream being exaggerated in the stereoscopic model. In many areas terraces at approximately the same altitude are present on opposite sides of a valley. Where two or more terraces occur at successively higher altitudes the limits of any one terrace level usually conform to a gently sweeping curve that marks the width of the old river flood plain when the terrace material was deposited. Where terraces occur as isolated mesalike forms the accordance of their surfaces is characteristic. As terraces here considered are mostly in unconsolidated deposits a mottled photograph tone distinct from that of surrounding rock outcrops may be present. Where dipping strata underlie the terraces, truncation of the beds may be very apparent owing to the vertical exaggeration of any dipping structure in the stereoscopic model. At first glance the separation of two terraces at different altitudes by a line that represents the old flood plain limits may be mistaken as offset of nearly horizontal beds along a fault, but consideration of the geologic environment together with closer inspection of photographs will generally show this to be a misinterpretation. In some areas talus or vegetation has obscured beds that are present below the terrace deposits. Here the accordance of levels, extent of the suspected original flood plain as judged by the positions of accordant erosional remnants, and general nature of sedimentary strata in the immediate vicinity together would support an interpretation of terraces.

Alluvial fans or cones:--Recently-formed alluvial fans or cones are best distinguished on photographs by their form, together with their occurrence at the mouths of canyons where such canyons enter broad open valleys or lowlands. The cone-shaped structure is accentuated by the vertical exaggeration in most stereoscopic models, and in aerial view the more or less triangular outline of isolated undissected cones may be conspicuous. Although alluvial fans in some areas are covered with vegetation, it may be different from that on surrounding steeper slopes and thus serve as a distinguishing feature. In semi-arid regions where vegetation is commonly sparse or absent, especially on recently-formed fans, a photograph tone distinct from that of surrounding rocks may be apparent.

Where rejuvenation of streams has taken place erosion and dissection makes recognition of alluvial fans more difficult. The elevated position of fan remnants are suggestive of river terraces, but the relative irregularity of these surfaces in contrast with known river terraces, their common restriction to one side of a valley, and the general convexity of the reconstructed surface when the altitudes of individual fan remnants are considered, plus the occurrence of these remnants in places where steep-gradient streams could have entered old lowlands or wide valleys, serve to identify these as probable old alluvial fans. Where dissection of fans has been extreme it may not be possible to distinguish them on photographs from old terrace remnants, except where fan remnants are at different altitudes that cannot be reconciled with any reconstructed terrace level or levels.

Pediments:--In parts of the Colorado Plateau pediments are a characteristic feature of the terrain. They occur as high-level surfaces in places several hundred feet above the master streams of an area. Commonly a pediment is a rather extensive, gently dipping surface generally covered by vegetation that imparts a very dark photograph tone to it. Because of the extensive nature of some pediments, they may be best observed on small-scale photographs, 1:40,000 or smaller. Discordance between a suspected pediment surface and underlying sedimentary strata is good evidence that this surface is actually a pediment, although care must be exercised in interpretation, as this criterion also holds for lava flows. Where several remnants of a pediment surface occur a general accordance of these surfaces may be evident. Care should be taken that such surfaces are not confused with extensive sedimentary dip slopes that are common in many areas. Normally the presence of a veneer of gravel and debris that mantles most pediment surfaces must be verified by field checking.

Lava flows:--Whereas there are a number of different criteria for recognizing lava flows from aerial photographs, certain criteria are to be emphasized and sought, depending on the geographic location and type of terrane being studied. The structural relation of flows to associated rocks is also important; where flows have been strongly tilted, folded, or deformed, recognition may be extremely difficult or impossible. Only those relatively undeformed flows, mainly Tertiary and younger, are readily identified from aerial photographs without some knowledge from ground surveys. The following discussion is in reference primarily to undeformed flows.

In the Colorado Plateau, where rock exposures are excellent, a diagnostic criterion of recent basalt flows is their unconformable relation to underlying sedimentary beds. The flows are commonly near-horizontal in attitude and thus may appear to truncate a sequence of dipping beds of differing lithologic character. Where the underlying beds are also nearly horizontal the following criteria may be helpful. The surface of a flow may be rather irregular in contrast to the surfaces of sedimentary strata, and where several flows have piled up, present topography may show several terracelike forms with irregular surfaces. A very dark photograph tone is characteristic in many places, but tone alone is not necessarily a definitive feature. Lobate patterns of vegetation and topography, especially at the terminations of suspected flows, are rather diagnostic, and association with volcanic cones makes misinterpretation of flows virtually impossible.

Locally, flow channels may be visible. Caution should be exercised, however, in interpreting lava flows in areas where high-level pediments may be present, for on photographs pediments may resemble lava flows, at least in part.

In the heavily vegetated igneous-metamorphic terrane of southeastern Alaska flows are difficult to recognize solely from photo study. In most areas ground observations are needed in interpretation; certain criteria may be observed on aerial photographs, however, that suggest the presence of flows. In contrast to the rugged topography of the older deformed metamorphic-igneous rocks, a generally low-dipping surface associated with a lobate pattern of vegetation and topography is rather strong evidence for a flow surface. Locally where relief is high, structures in older rocks, particularly faults, may be traced as far as the edge of a suspected lava flow and may be picked up at the opposite side of such a flow. Unfortunately, vegetative cover, although it may be characteristic of certain sedimentary rocks, does not appear to be at all distinctive with respect to flows in the areas studied to date. Photograph tone is not diagnostic, owing to a paucity of rock exposures in areas of heavy vegetation cover.

Intrusive rocks:--A few mafic intrusions in the Colorado Plateau, primarily volcanic necks, have been studied. The darker color of these bodies as seen on aerial photographs commonly contrasts strongly with the surrounding strata which have a lighter photograph tone. Most of these volcanic necks stand up in bold relief, have vertical walls, but have rounded top surfaces so characteristic of weathered surfaces of many igneous rocks.

Other small igneous plugs may be recognized by associated dikes that connect with them. The mafic dikes of the Colorado Plateau stand out on photographs because of their dark color with respect to surrounding rocks and because of a pronounced rectilinear surface expression. However, because of the 1:20,000 scale of most of the photography available, dikes less than 10 feet wide are generally very difficult to observe. In some places dikes may be more resistant to weathering and stand topographically higher than the enclosing rock, or if less resistant they may appear to occupy straight line depressions in the country rock. Such differences in relief are exaggerated in most stereoscopic models and hence are generally easily recognized.

In southern and southeastern Alaska igneous bodies are difficult to recognize unless they are well exposed above timberline. Here the surface expression of many bosses and stocks, whether silicic or mafic, is rather distinctive owing to their coarse-textured appearance on photographs. This coarse texture results from the crisscross pattern of the numerous joints almost universally present in such rocks. In many areas the surface of igneous bodies is weathered into subdued, rounded forms. However, alpine glaciation has left some igneous bodies as jagged, rugged masses, but even in these the coarse texture is apparent on the photographs. In a few places mafic dikes within lighter-colored rocks have been recognized, but for the most part dikes are very difficult to distinguish on photographs of southern and southeastern Alaska terrane.

Features associated with glaciers:--Because of their characteristic topographic expression many glacial features lend themselves particularly well to photogeologic interpretation, and many areas in Alaska have been mapped by photogeologic methods alone or in conjunction with field studies. Recently, glacial deposits in the Mt. McKinley quadrangle in interior Alaska have been mapped almost entirely by photogeologic methods and it is to the Mt. McKinley area that the comments below refer.

Moraines of two advances correlative with Wisconsin advances, and moraines of at least two advances of pre-Wisconsin age have been mapped from aerial photographs. In addition many minor moraines associated with relatively recent advances have been recognized. Wisconsin and post-Wisconsin moraines are easily distinguished by their hummocky, lake-dotted topography, poorly integrated drainage, and lobate shapes. The youngest moraines are characterized by sharp, irregular topography, steep frontal slopes, numerous amoeba-shaped lakes, abundant erratics, lack of integrated drainage, and absence of vegetation. In the older moraines the topography has become more rounded, many of the lakes have been drained as the master streams cut into their basins, the remaining lakes have assumed more rounded outlines, erratics are less conspicuous, and a carpet of vegetation mantles the topography.

The pre-Wisconsin moraines are recognized only by their very much subdued topography, still lake-pitted but without conspicuous erratics. They lack the lobate shape that is characteristic of younger moraines; the boundaries of these moraines as now exposed are determined by stream dissection or by extent of more recent eolian or alluvial deposits and not by the original extent of the ice. Some care is necessary to distinguish the morainal topography of the older moraines from recent thermokarst topography developed in areas of permafrost.

Glacial outwash is best recognized by its relationship to a terminal moraine. It generally bears subparallel channel scars that head in notches in the terminal moraine or in side glacial channels. It is commonly pitted by groups of small circular kettles arranged along the dry channels and grades downstream into normal alluvial deposits. Sand dunes deposited by strong winds blowing over unvegetated outwash during cold glacial climates cover large areas beyond the limits of moraine or outwash. Black spruce growing on these dunes contrasts sharply with the muskeg-type vegetation in the interdune areas, emphasizing the sinuous dune-pattern as seen on aerial photographs. Care should be taken that these sinuous patterns are not confused with traces of folded resistant beds in a vegetated metamorphic terrane.

Glacial valleys commonly bear traces of well-defined kame terraces, terraces of ice-dammed lakes, and bedrock channels cut by side glacial streams. Where side glacial streams have carved bedrock channels around the snout of a retreating ice lobe the scars may appear on the valley walls as a series of traces plunging down valley at angles of 10° to 15°. On aerial photographs these scars may easily be confused with traces of bedding planes that dip downstream.

Features of existing glaciers such as crevasse systems, moraines, kames, and ice-dammed lakes, are easily recognized and mapped on aerial photographs. By tracing well-developed medial moraines to their source on aerial photographs, it is frequently possible during later field study to check rock types at many scattered points within a glacier basin merely by examining the multiple medial moraines near the terminus of the trunk glacier. Rapid field checking of photogeologic interpretations of bedrock geology is thus facilitated.

Determination of quantitative data from photographs

An integral part of most photogeologic studies is the quantitative determination of geologic data by use of appropriate photogrammetric instruments. These instruments are measuring devices that afford reliable objective data concerning structural attitudes, stratigraphic thicknesses, and relative altitude differences. Such measuring devices aid in photogeologic interpretation of an area in much the same way as the Brunton compass or plane table and alidade do in field interpretation. The procedures involved in making these quantitative measurements are varied and depend on the particular photogrammetric instruments used.

Several different simple instruments have been or are currently being used for determining relative altitudes of points in a stereoscopic model. These include the Fairchild stereocomparagraph and other simple stereometers. All are based on the "floating dot" principle, where two dots, one seen with each eye, are fused stereoscopically into a single dot that appears to float in space. The apparent height of the single fused dot 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, cliff, etc.) 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, the so-called parallax difference is obtained, and this is directly related to the height of the object.

A height-finding instrument commonly used is the stereocomparagraph (fig. 5) mounted on a parallel motion arm. Only the stereoscope and measuring device are needed; other accessories of the instrument can be eliminated for height-finding purposes. The measuring device, or parallax bar, is attached to a drum-type scale reading directly to hundredths of millimeters or thousandths of inches. In practice the horizontal separation of individual dots is measured to the closest hundredth of millimeter or thousandth of inch. In order to obtain the object's height in feet the resulting parallax difference must then be multiplied by a conversion factor determined by the flying height of the plane at the time of exposure of the photo pair and by the air base of that photo pair.

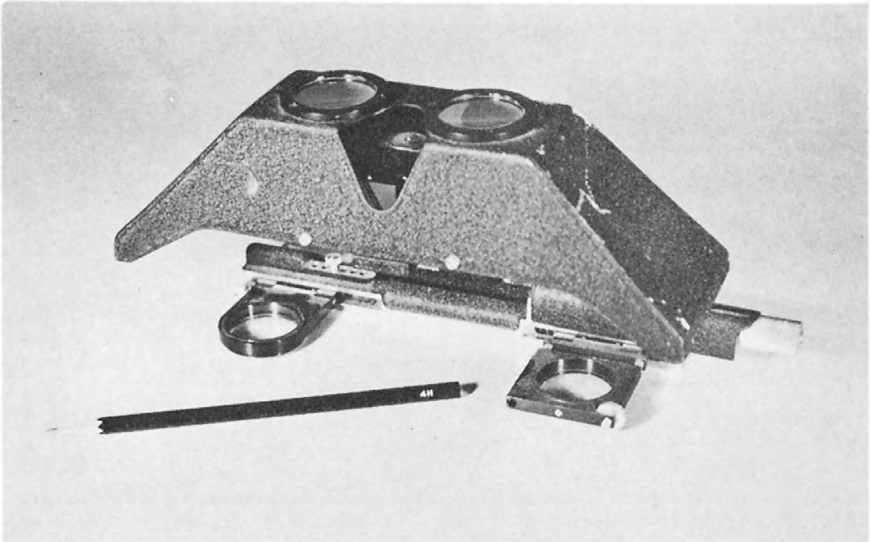

Figure 5.--Stereocomparagraph

Computing relative altitudes using other stereometers follows the same general procedure as with the stereocomparagraph. Some of these stereometers have no mechanism for attaching the instrument to a parallel motion arm, but this is not a serious deterrent to their use as proper orientation is achieved optically. Parallax may be read on a drum-type scale or dial-type scale, depending on the instrument used (figs. 6, 7, and 8).

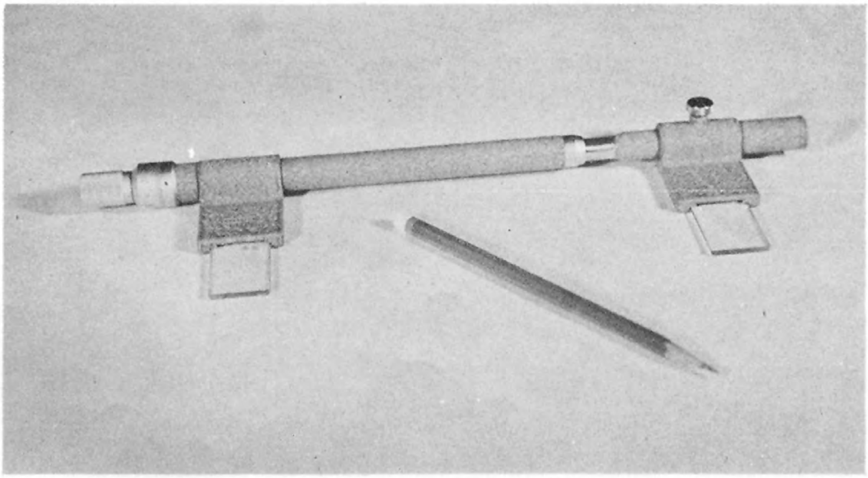

Figure 6.--Stereometer with drum reading scale

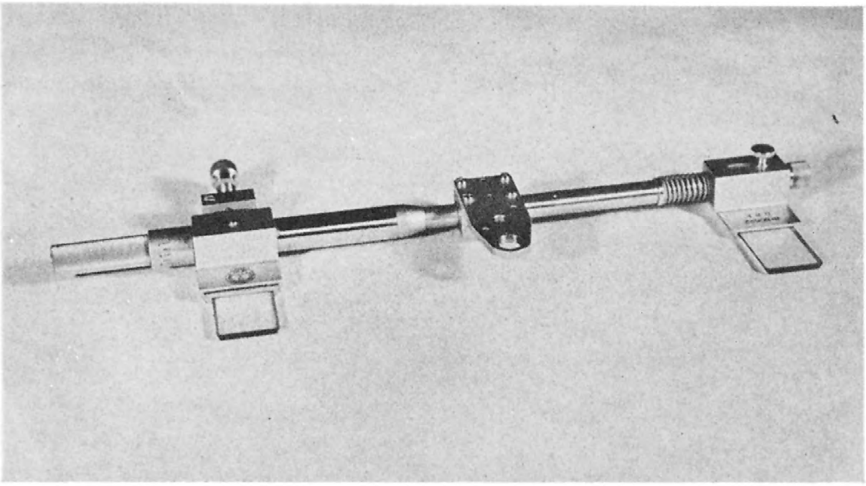

Figure 7.--Stereometer with drum reading scale and parallel motion arm attachment.

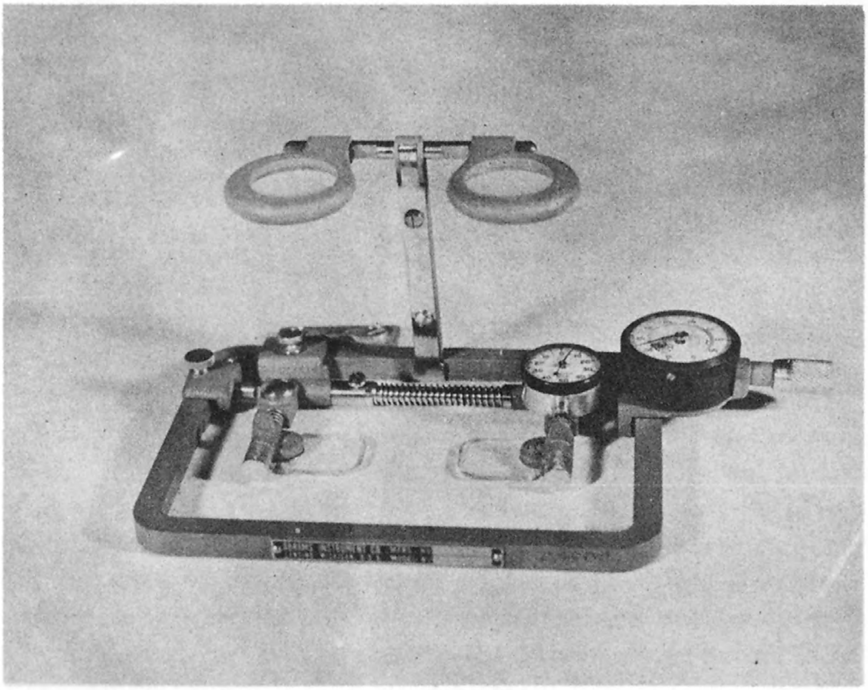

Figure 8.--Height-finder with dial reading scale.

Another height-finding instrument, of particular use to the field geologist because of its portability and design for use with the pocket stereoscope is shown in figure 9. This new parallax ladder is also advantageous for field use as it is designed to read relative heights directly in feet. Like the above-mentioned instruments, it is based on the floating dot principle. The instrument consists of two rows of dots on separate lucite arms, and a device for introducing factors of photo base and flying height of the plane. Introducing

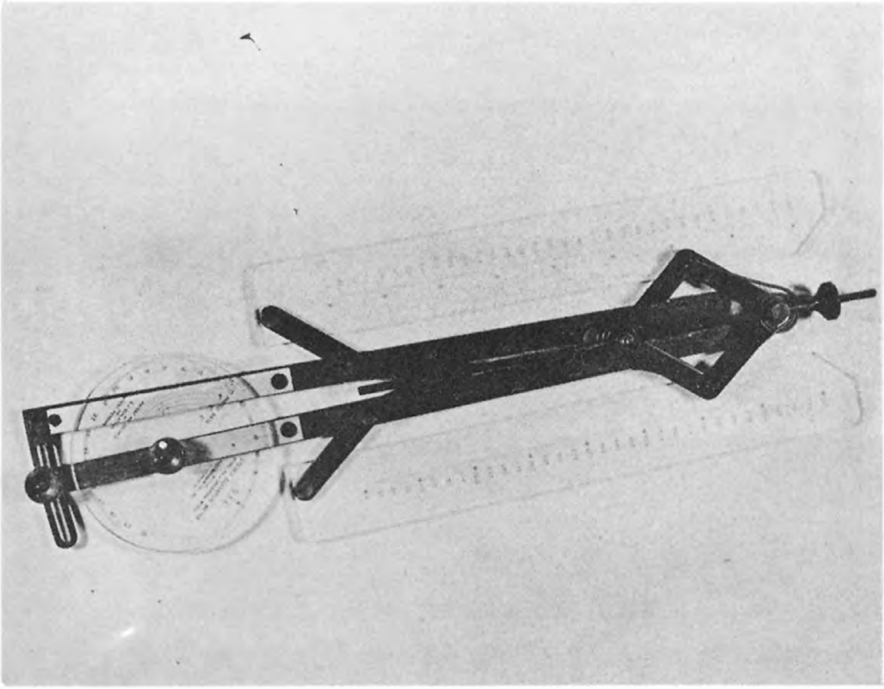

Figure 9.--Direct-reading parallax ladder.

the photo base and flying height gives a slight divergence to the arms on which the dots are scribed. Thus, a series of pairs of dots each with different horizontal separations exist. The difference in separation of any two pairs of dots for different flying heights and photo bases has been pre-determined and set to represent 5 feet of relative elevation. The instrument, oriented at right angles to the flight line, is used by sliding it over the stereoscopic model until a pair of dots--seen stereoscopically as a single dot in space--appears to fall on the base of the object whose height is to be determined. A relative reading in feet is then made directly from the instrument. The elevation meter is then moved until a different pair of dots--seen stereoscopically as a single dot in space--appears to fall on the top of the object whose height is to be determined.

Again the relative reading in feet is made directly from the instrument. The difference of these two relative readings is the height of the object in question. The instrument has also been designed for use with mirror stereoscopes.

An instrument designed strictly for slope determinations has recently become available. The instrument consists of two transparent disks with concentric circles of specific diameters scribed thereon (fig. 10). These disks are mounted in a frame so as to be movable horizontally in a fashion similar to the dots of the stereocomparagraph or

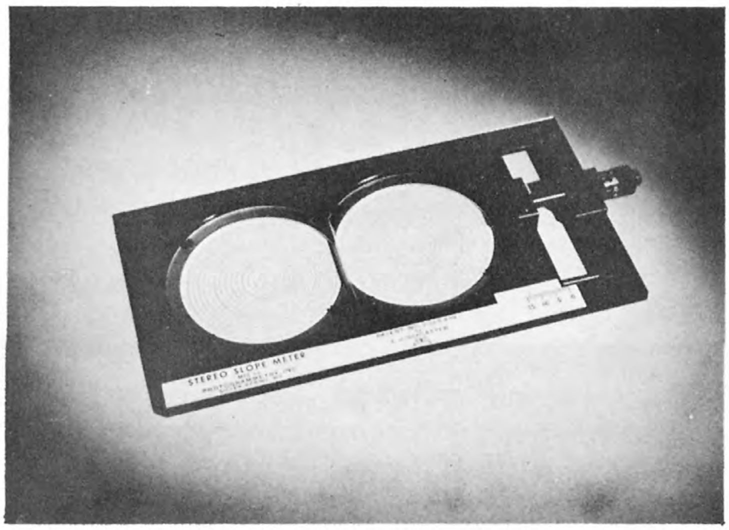

Photo by Photogrammetry, Inc.

Figure 10.--Slope-measuring instrument

stereometer. In stereoscopic view the two sets of concentric circles appear as a dome. The circles have been so spaced as to produce a surface divided into zones having definite pre-determined slopes with respect to a horizontal plane. By proper horizontal spacing of the two disks, the resulting dome 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.

An instrument that promises to be of particular use to geologists using aerial photographs is the Super Duper Dipper (fig. 11), now being tested and evaluated.

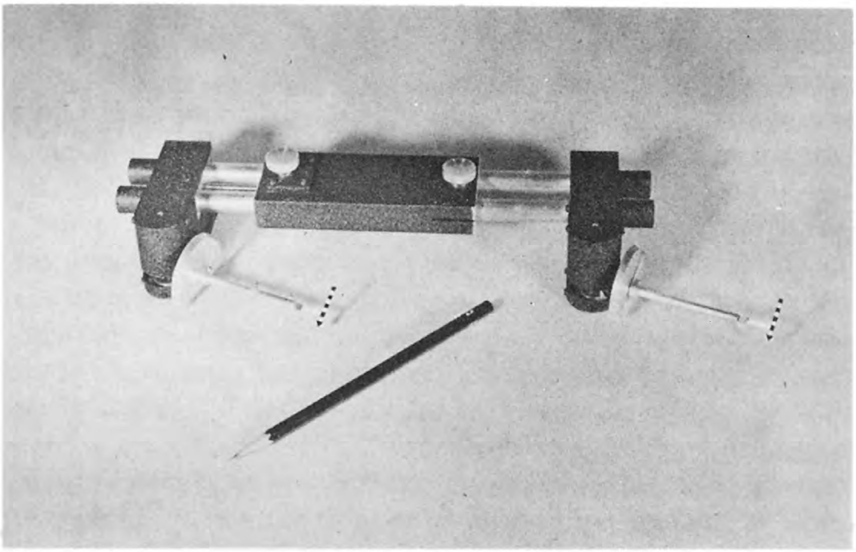

Figure 11.--Super Duper Dipper

The instrument is designed specifically for determining strikes and dips of planar structures. The instrument differs somewhat in operation from the stereometer-type instruments for slope determinations. It uses two small targets that may be fused stereoscopically into a single target. Like the fused dot in the stereometer-type instrument, the fused target is raised or lowered with respect to the stereoscopic model by varying the horizontal separation between individual targets. However, the dip is determined by actual physical tilting of the target in space. Because of the vertical exaggeration inherent in most stereoscopic models, the dip determined is an exaggerated dip that must be reduced to a true dip. This is done by applying to the exaggerated dip a factor determined from a supplementary slope chart. The Super Duper Dipper has the particular advantage of allowing strikes and dips of planar structures to be determined rapidly.

Base map compilation

Where no base maps exist planimetric bases may be compiled using control derived from radial-or stereo-templet laydowns. In brief a radial- or stereo-templet laydown is a triangulation net established from aerial photographs. The map positions of selected points on the photographs are determined by this aerial triangulation network. These points then serve as control for transfer of planimetric data from the photographs to the base. Although the base-map compilation is primarily an office technique, horizontal control based on field survey is necessary for checking accuracy and for determining the scale. Completion of the base map requires transfer of planimetric data, primarily streams and culture, to the point-control manuscript. The transfer of planimetric data is usually accomplished at the same time as transfer of geologic data from photographs to the base manuscript. These transfer procedures are described below.

Transfer of geologic data from photographs to base maps

Reflecting projectors:--Transfer instruments of this type involve direct projection of a single photograph to the base map or base control. In practice the photograph is projected so that control points on the photograph coincide insofar as possible with the control points on the base manuscript, and planimetric detail is then sketched directly. All photograph control points and base manuscript control points will rarely coincide, however, because of ground relief which results in radial displacement on all single aerial photographs. This is especially true if relief of the area being studied is high. Therefore, this transfer technique works best on photographs of areas of low relief. Adjustments in scale of different parts of a photograph may be made to compensate for excessive relief displacement, but map accuracy is generally lost under these conditions. If fairly dense stream control already exists on a base map, it may be feasible, provided relief of the area is low, to transfer data by direct projection based on this control, and thus obtain more reliable positioning of geologic data than by point control alone. Errors due to tilt inherent in aerial photographs cannot be corrected with most direct-projection instruments. However, in present commercial photography, the small amounts of tilt do not pose serious positioning errors of planimetric detail, especially if the map is only semi-detailed or is of reconnaissance nature.

Sketchmaster:--The sketchmaster is a device making use of the camera lucida principle in transferring data from the photographs to the base map. Both vertical and oblique sketchmasters exist, but most geologic interpretation and annotation is done on vertical aerial photographs, and use for this type instrument would be confined largely to the vertical sketchmaster (fig. 12). In brief, the sketchmaster allows the operator to view a single photograph superposed on the base map. Adjustments for scale changes 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 the direct reflecting projector large amounts of radial displacement due to relief exaggeration cannot be effectively removed.

Multiscope:--The multiscope is a combination of mirror stereoscope and camera lucida (fig. 13). Photographs are mounted on moveable photograph plates that permit small adjustments for tilt. The viewing assembly is constructed to allow the insertion of one or two semi-transparent mirrors in the eyepiece, so that in operation either a single photo-image or the stereoscopic model may be seen superposed on the map base. Although the stereoscopic model may be seen at all times, use of only one semi-transparent mirror permits the eye to see only one photo-image superposed on the map base; the resulting plot is similar to that from the sketchmaster--no errors due to relief displacement

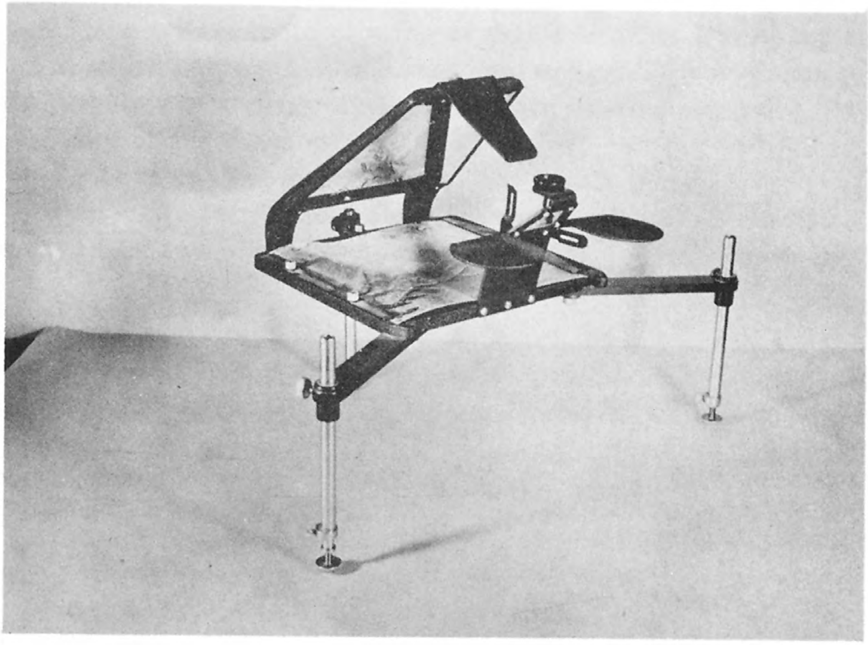

Figure 12.--Vertical sketchmaster

Photograph by Northeastern Engineering Co., Inc

Figure 13.--Multiscope

are removed. If, however, two semi-transparent 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 various special lenses in the viewing assembly together with varying manually the distance of the viewing assembly above the map base.

Radial planimetric plotter:--The radial planimetric plotter consists of a mirror stereoscope mounted over two photograph tables (fig. 14). A transparent plastic arm with a

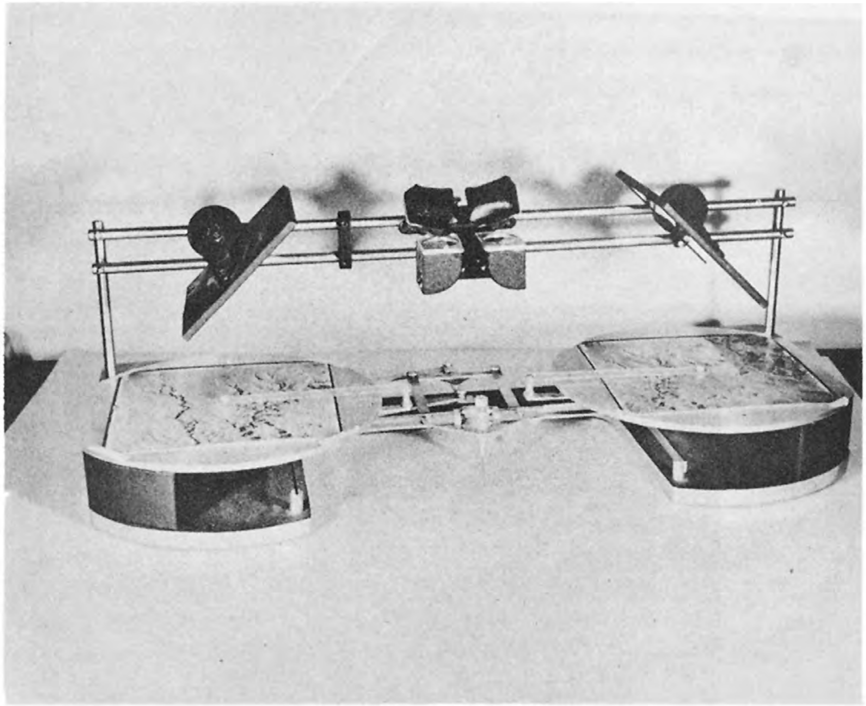

Figure 14.--Radial planimetric plotter

centrally scribed line extends from and pivots around the center of each table. These arms are linked to a pantograph attachment. In operation, a pair of vertical photographs are oriented on the photograph tables for proper stereoscopic viewing, and control points on the photographs are oriented to control points on the base manuscript. As the plastic arms radiate from different centers they cross each other and form the so-called plotting cross. 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 an object on each photograph represent, or very nearly represent, azimuth lines from known points on the base manuscript, the intersection of these two arms will represent the true map position of that object. Thus, the displacement of an object on a photograph resulting from high relief of the terrain is effectively removed; this is one of the chief advantages in using the radial planimetric plotter. Unfortunately, the radial lines do not intersect along the principal line between photographs, and the photograph tables must be shifted to their alternate centers before the central area of a stereoscopic model can be delineated. However, the radial planimetric plotter is easily set up and takes no great skill in operation. It is highly recommended for transfer of data from photographs to base maps especially where semi-detailed maps are concerned. This instrument does not permit removal of tilt that may be present in the photograph, and thus generally cannot be used in precision large-scale mapping.

The KEK plotter:--The KEK plotter consists of a stereoscope, two photograph tables, floating-dot assembly, and drawing attachment (fig. 15). Its operation is based on the floating-dot principle and it may therefore be more difficult for some persons to use than the radial planimetric plotter. The plotting cross of the radial planimetric plotter

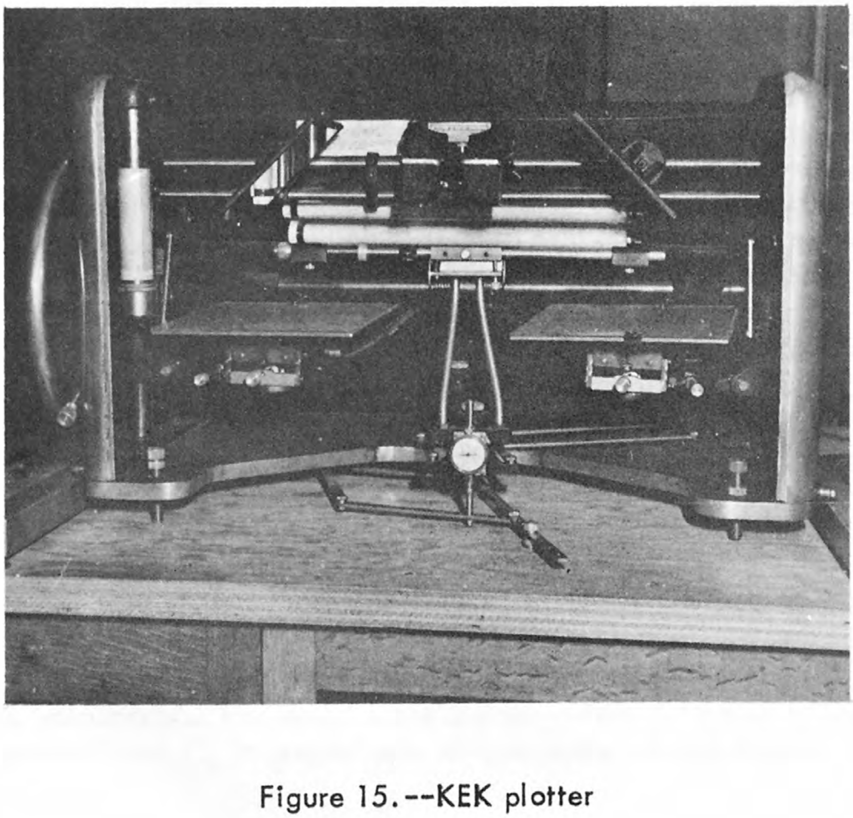

Figure 15.--KEK plotter

is replaced in the KEK 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 movement of the photograph plates. Because the photograph plates may be tilted to approximately correct for tilt that may be present in the photographs, the instrument is a more precise instrument than the radial planimetric plotter. It also permits contouring. However, for many geologic map compilations, the somewhat less accurate, but simpler radial planimetric plotter is preferred.

Wernstedt-Mahan-type plotter:--The Wernstedt-Mahan-type 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 Wernstedt-Mahan-type plotter is adjustable, permitting very nearly the recovery of the perspective of photographs from photography ranging in focal length from approximately $8\frac{1}{4}$ inches to 12 inches.

Multiplex:--The multiplex (fig. 16) is a precision stereoplotting instrument in which photographic images on 2" x 2" glass plate diapositives are projected directly to a viewing surface beneath the projectors. The anaglyph principle is used to create the third dimension, two or more photograph images being projected through colored filters, alternately red and blue. The stereoscopic model is viewed through glasses similar in color to the filters used in the projectors, that is, red over one eye and blue over the other. In multiplex projection all features of the terrain are optically recreated in the stereoscopic model in essentially true relationship. The model is usually viewed on a small white-surfaced table called a platen, which may be raised and lowered so that a small illuminated 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 parallax or, on some instruments, to a scale reading heights directly in feet. Features are traced orthographically on the base map by a pencil located directly beneath the illuminated dot on the platen. 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.

In geologic work the multiplex has many advantages over simpler photogrammetric instruments. The model scale approximately 2.5x that of the original photography generally results in greater ease of interpretation and measuring of geologic data

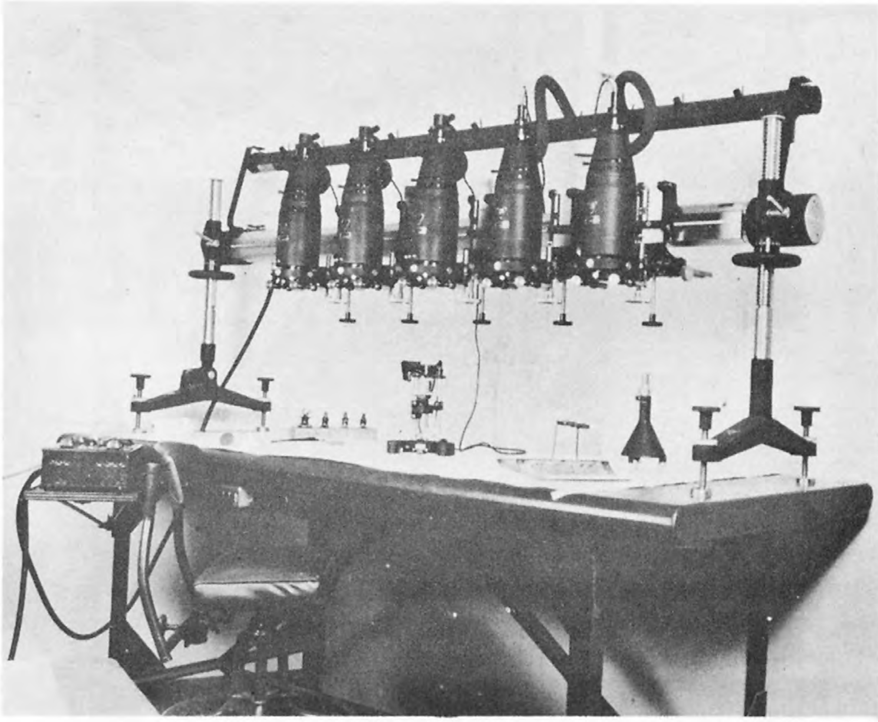

Figure 16.--Multiplex

as well as closer positioning of detail on the map. Where field control is available any tip or tilt inherent in the photography can be removed so that true orthographic positioning of detail is obtained. The multiplex is especially advantageous in that interpretation, measuring, and plotting of geologic data can be carried out in one continuous operation.

Kelsh plotter:--The Kelsh plotter (fig. 17), like the multiplex, projects an image from glass plate diapositives to a viewing surface below the projectors; measuring and plotting are done with attachments to a small moveable carriage mounting a platen on which the stereoscopic model is viewed. As in the multiplex the anaglyph principle is used to create the third dimension.

The Kelsh plotter differs from the multiplex in using 9" x 9" glass plate diapositives on which the photograph image is the same scale as the original photography. The projected model scale is approximately 5x that of the original photography, or about 2x the scale of the multiplex model. Only that part of the Kelsh model appearing on the platen

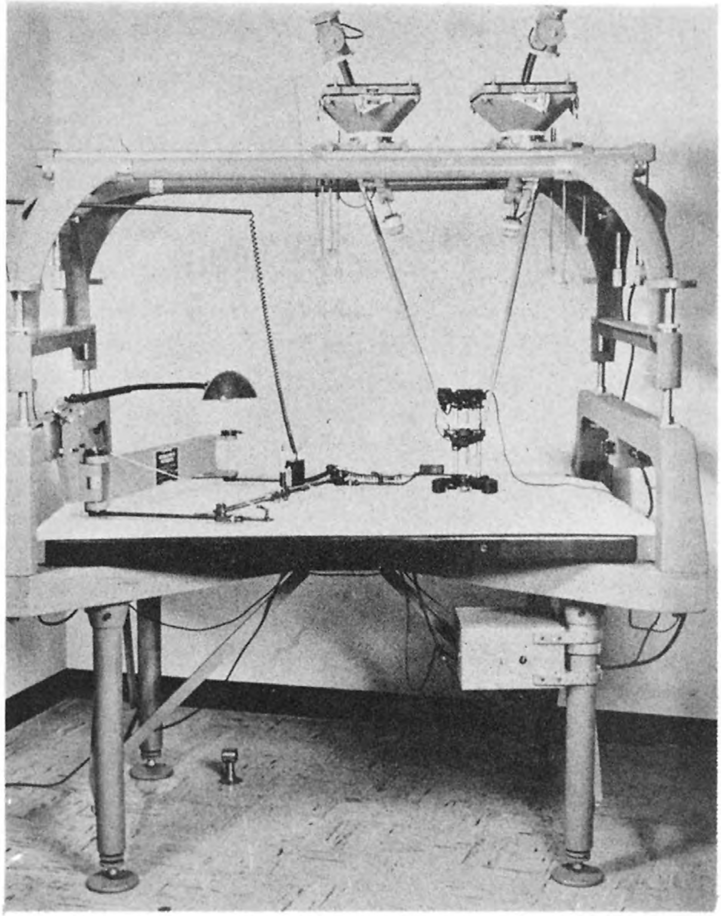

Figure 17.--Kelsh plotter

is illuminated; this results in a greater concentration of light and a more brightly illuminated model. However, this light concentration prevents viewing of the entire model at any one time.

Because of the 5x enlargement of the original photography scale plus the use of diapositives the same size and scale as the original photographs, thus preserving a high degree of resolution in the projected model, high-altitude photography at scales of 1:60,000 to 1:70,000 can be used in the Kelsh plotter in routine photogeologic compilation where 1:20,000 scale photographs are normally employed with simpler photogrammetric instruments. This may reduce by as much as 90 percent the number of stereoscopic models that would normally be oriented for interpretation and plotting using 1:20,000 scale photographs. In detailed studies the use of 1:20,000 scale photography, enlarged to 1:4,000 in the Kelsh plotter, gives the interpreter a great advantage in interpreting geologic data as well as positioning such data on the base map. As with the multiplex, interpreting, measuring, and plotting geologic data can be carried out in one continuous operation with the Kelsh plotter.

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