

Application of High-Order Stereoscopic Plotting Instruments to Photogeologic Studies

By C. L. PILLMORE

PROCEDURES AND STUDIES IN PHOTOGEOLOGY

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*A discussion of accuracy of
measurement and advantages
of using stereoscopic plotters in
geologic interpretation and mapping*



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PROCEDURES AND STUDIES IN PHOTOGEOLOGY

APPLICATION OF HIGH-ORDER STEREOSCOPIC PLOTTING INSTRUMENTS TO PHOTOGEOLOGIC STUDIES

By C. L. PILLMORE

ABSTRACT

The Kelsh, multiplex, and ER-55 projector-type plotters, all high-order precision stereoscopic plotting instruments, are applicable to many photogeologic studies. The use of these instruments for most geologic mapping projects is justified by their ease of operation and the high quality of results.

The large area per stereoscopic model covered by so-called high-altitude photography (at a scale of approximately 1:60,000 or smaller) in a high-enlargement instrument such as a Kelsh plotter enables geologists to survey large areas rapidly and to map many geologic features reliably. Areas in which detailed geologic mapping is desired may be appropriately studied by use of low-altitude photography (at a scale of approximately 1:20,000 or larger) in one of these instruments. Special geologic studies where numerous stratigraphic thicknesses or altitude measurements are essential, as in isopach or structure-contour studies, may be readily carried out for many areas by using stereoscopic plotting instruments. The use of stereoscopic plotting instruments, particularly when combined with field observations, may result in a more accurate and reliable geologic product than is obtained by use of simple stereoscopic "paper print" plotters, and, under some circumstances, than is obtained from field compilations. The reason for this high accuracy is that the anaglyph (stereoscopic model) may be reoriented, both horizontally and vertically, to a base map. However, reliability of the final product depends upon the base map and the geologist's interpretation of contacts, faults, and other geological features.

INTRODUCTION

Geologic interpretation of aerial photography by means of high-order stereoplottting instruments is a relatively new technique. The two instruments most commonly used to date (1956) are the Kelsh plotter and the multiplex plotter, although the ER-55, a projector developed in recent years by the U. S. Geological Survey, will probably be much used for photogeologic interpretation in the future. These instruments are available for use by Geological Survey geologists; some commercial organizations are beginning to use them for

geologic purposes, but the so-called heavy plotters, such as the stereoplani-graph or the autograph, are rarely available to the geologist because of their high cost.

The Kelsh and multiplex plotters, and the type using ER-55 projectors, utilize the principle of projection of light of complementary colors through glass diapositives of overlapping aerial photographs. The anaglyph, or stereoscopic model, is viewed on a white surface, called a platen, mounted on a tracing table containing a floating light source or pinpoint of light vertically above a plotting pencil. Because the platen can be moved vertically on the tracing table and because the tracing table can be moved horizontally, any point on the stereoscopic model can be located or measured with respect to any other point. Inasmuch as the stereoscopic model is orthographically true, setting the floating dot on the apparent ground surface at various places permits accurate horizontal positioning, and lines or geologic contacts can be plotted orthographically onto a base map. The use of high-order stereoscopic plotting instruments assures accurate compilation of geologic data, provided that interpretation is correct and provided there is sufficient control to orient the model.

Although high-order stereoscopic plotting instruments have been used for many years for topographic mapping purposes, these instruments were first used extensively for geologic interpretation in 1954 by the U. S. Geological Survey. The instrument most widely used thus far for photogeologic purposes is the Klesh plotter because of its high enlargement factor and the high resolution of the stereoscopic model. The enlargement factor is herein defined as the relation between the scale of the stereoscopic model and the scale of the original photography. An instrument using ER-55 projectors also projects a model of high resolution and may become widely used for geologic interpretation and mapping. The multiplex plotter has been used for compilation of geologic field data, but it has not proved to be entirely adequate for detailed photogeologic interpretation.

INSTRUMENTS

One of the main advantages in using high-order stereoscopic plotting instruments for photogeologic study is in working with an oriented three-dimensional true-scale model of the terrain upon which accurate measurements both vertically and horizontally can be made. The detail of the model, as observed on the platen, is related to the scale, focal length, and quality of the original photography, the processing of the diapositives, and the type of instrument being used.

Smaller stereoscopic plotting instruments, utilizing paper prints of aerial photographs, provide an orthographic solution through a series of metric compromises that is less accurate than that provided by

anaglyphic type instruments, such as the Kelsh plotter. In general, the "paper print" plotters are more difficult to operate than the anaglyphic instruments.

KELSH PLOTTER

The Kelsh plotter, developed by the U. S. Geological Survey, utilizes 9½- by 9½-inch glass diapositives of aerial photographs commonly termed Kelsh plates. Because Kelsh plates are the same scale as the original photography the resolution of the image observed on the platen is excellent. Two projectors are linked to the tracing table so that light rays passing from the projectors through the glass diapositives are restricted to the platen; in the other plotters the entire stereoscopic model is illuminated. The enlargement factor of the Kelsh plotter is about 5 times, making the scale of the stereoscopic model (model scale) 5 times that of the original photography from which the diapositives were made. For example, Kelsh plates made from 1:20,000-scale photographs taken through a 6-inch camera lens would result in a model scale of approximately 1:4,000. The Kelsh plotter can be adjusted to accommodate both 6-inch- and 8¼-inch-lens photography. A description of the Kelsh plotter, of the correct method of placing the glass diapositives in the instrument, and of the orientation procedure for clearing parallax from the stereoscopic model is given by Scher and Thompson (1954).

The high enlargement factor of the Kelsh plotter permits the use of small-scale aerial photography to a great advantage, especially when making reconnaissance studies of large areas. The scale of the photography used in the Kelsh plotter is ideally determined by the geologic problems involved in the area to be studied; that is, in areas that are to be mapped in considerable detail, low-altitude or large-scale photography should be used when available; in areas in which detail is not so important, so-called high-altitude or small-scale photography, if available, should suffice. Recent tests indicate that low-oblique photography can be accommodated in the Kelsh plotter.

MULTIPLEX PLOTTER

The multiplex plotter uses glass diapositives on which the original 9- by 9-inch negative is reduced about 4 times to a size about 1¾ inches square. The enlargement factor of the multiplex is about 2½ times the original photography scale. Therefore, multiplex diapositives made from 1:20,000-scale photography, taken through a 6-inch camera lens, would project to a scale of about 1:8,000. Owing to the great reduction of the image during printing of the diapositives, and owing to the enlargement (approximately 12 times) of this image in projection, the stereoscopic model observed on the platen is usually

slightly fuzzy, and the fine details of the terrain that are important in photogeologic interpretation may be difficult to distinguish. In the Geological Survey the multiplex is being used to advantage especially in compilation of geologic field data onto a base map. A description of the multiplex and the procedure for orienting the diapositives in the instrument is discussed fully by Loud (1952).

ER-55 PLOTTER

The term "ER-55 plotter" is used herein as any stereoscopic plotter using ER-55 projectors. The ER-55 projection assembly consists of ellipsoidal reflector-type projectors which utilize aerial photography reduced to a 4- by 4-inch glass diapositive. This projection assembly produces sufficient light to obtain an excellent image; the enlargement factor of the instrument is 3.4 times, about midway between that of the Kelsh and multiplex. The projectors are also adaptable to low-oblique photography taken along or normal to the flight line (inclination of camera lens axis 20° from vertical). The photogeological aspects of low-oblique photography are at present being evaluated. The use of convergent low-oblique photography in a stereoscopic plotting instrument permits greater accuracy of vertical measurements at any given scale than standard vertical photography. Also, at a given scale a convergent model covers greater area than a vertical model. As the projectors are adaptable to both vertical and low-oblique photography the ER-55 plotter should prove to be very useful to the geologist. ER-55 projectors can be attached to the multiplex or similar-type frame with the use of supporting brackets and a few minor adjustments, depending upon the particular type of frame available.

A discussion of low-oblique photography and of the Twinplex plotter and a short description of the ER-55 projector have been given by Hopkins, Radlinski, and Thompson (1952).

COMPARISON

One of the major differences between the Kelsh plotter and the multiplex and ER-55 plotters is the freedom of movement of the ER-55 and multiplex projectors. Because of the linkage of the Kelsh projectors to the tracing table and because of the construction of the superstructure that supports the projectors in the plotter, movement of the individual projectors is restricted to the x direction, which parallels the projector line of the instrument. However, in the multiplex and the ER-55 plotters, each individual projector may be moved not only in the x direction but also in the y direction and the z direction. Because of this latitude of movement of projectors, particularly to

compensate for greater scale variation due to high relief, the ER-55 and multiplex plotters may be advantageous for study of high-relief areas. As more than two projectors can be used on a single plotter, depending upon the length of the supporting bar, multiplex and ER-55 plotters are also especially adapted to obtaining control between widely separated control points by bridging (see Loud, 1952).

ACCURACY OF MEASUREMENTS

The accuracy of measurements and spot elevation readings made with high-order stereoscopic plotting instruments in photogeologic studies depends upon the following factors: (1) The inherent accuracy of the instrument; (2) the scale, quality, and focal length of the original photography from which the diapositives were made; (3) the nature of geologic features, such as contacts; and (4) the experience of the operator.

INHERENT ACCURACY

The inherent accuracy of the instruments is an estimation of the minimum error expected under optimum conditions of the other three above-mentioned factors. Under these optimum conditions the Kelsh plotter is estimated to be accurate to within 0.1 millimeter of parallax. The estimated error of the ER-55 plotter is slightly greater than that of the Kelsh plotter. For the multiplex plotter the estimated error is higher mainly because of the lower enlargement factor. Because the stereoscopic model in the multiplex plotter is usually not as sharp as that in the Kelsh plotter or the ER-55, owing to the loss of resolution during reduction in printing and owing to enlargement in projection, the optimum reading is seldom realized. However, the Kelsh and ER-55 plotters usually display excellent images in the stereoscopic model, and optimum readings are commonly obtained when low-altitude photography is used.

FOCAL LENGTH OF LENS AND SCALE AND QUALITY OF PHOTOGRAPHY

The altitude of the airplane and focal length of the lens used in the photography from which diapositives are made are very important factors in estimating the probable error in vertical measurements by use of the different instruments. The scale of photography is directly related to the focal length of the camera and to the height of the camera (altitude of airplane above mean terrain) at the time of exposure; that is, scale = focal length (in feet)/height of camera (in feet).

Most photography for topographic mapping purposes at present is taken with a wide-angle camera lens having a focal length of 6 inches. Some organizations use a lens with an 8 $\frac{1}{4}$ -inch focal length, but Geo-

logical Survey specifications usually require the use of the 6-inch lens. When the 6-inch lens is used the scale of photography taken from 10,000 feet above mean terrain is 1:20,000; photography taken at 30,000 feet above mean terrain is at a scale of 1:60,000. When 1:20,000-scale photography is used in the Kelsh plotter the predicted error is about 2 feet for vertical readings, under optimum conditions. This error is proportionately larger when smaller scale photography is used. The predicted error for the ER-55 and multiplex plotters will be slightly greater primarily because their models are smaller in scale than the Kelsh model.

The quality of each individual negative is one of the factors that determine how close to the predicted accuracy the operator of the instrument can measure. If the film has been underexposed or overexposed, or if the pictures were taken under cloudy or hazy weather conditions, the stereoscopic model observed on the platen may not be sharply defined, and the probable error will increase.

NATURE OF GEOLOGIC FEATURES

The accuracy of readings made on such geologic features as contacts depends upon how well the operator can see these features in the stereoscopic model. The quantitative and qualitative aspects of the stereoscopic model, of course, depend not only on the type of instrument being used but also on the lens focal length and the scale and quality of the photography. If other conditions are optimum and a geologic contact is a sharp tonal or topographic break, then a minimum error should be realized in making vertical measurements with stereoscopic plotting instruments. However, if talus or rock debris, a thin veneer of soil cover, or vegetation cover the contact, then the probable error will increase.

EXPERIENCE OF OPERATOR

The experience of the operator concerns not only his experience with photogrammetry and practice with stereoplottting instruments, but also his geologic knowledge of the area with which he is working. The geologist with no experience in photogrammetry and no practice in using stereoscopic plotters may accurately position a geologic contact horizontally, but he may incorrectly position this contact vertically at a point 10 or 15 feet above or below the ground surface. An operator with photogrammetric experience may make accurate readings on the ground surface, but he may not be able to identify the geologic unit that this ground surface represents.

Experience has proved that an individual with normal or corrected vision can readily learn to clear parallax from stereoscopic models,

level them, and scale them to a base map using a pantograph. With little practice he can make reliable measurements with use of the floating dot and can plot geologic features expressed in the stereoscopic model.

IMPORTANCE OF SCALE

The scale of the original photography determines the scale of the stereoscopic model, depending on which stereoscopic plotter is used. As stated previously the model scale and the instrument affect both the clarity of the image observed on the platen and the reliability of readings made with the tracing table. Commonly the geologist must use photography that is already available. Many times this photography was not designed for geologic interpretation; however, the enlarged scale of such photography in the Kelsh or ER-55 plotters is usually acceptable for most geologic-mapping studies. In areas that are to be mapped in great detail, the geologist may find it desirable to obtain new photography at a scale large enough to permit him to distinguish very minor features in the stereoscopic model. In areas of reconnaissance study it may be desirable to obtain new photography of small scale. The use of a variable-ratio pantograph linked mechanically to the tracing table of any of the instruments described enables the geologist to plot the data observed on the tracing table directly and accurately on base maps of different scales.

HIGH-ALTITUDE PHOTOGRAPHY

One of the most recent and promising developments in photogeology within the Geological Survey is the application of photography taken at altitudes as high as 35,000 feet, termed high-altitude photography (scale of 1:60,000 to 1:70,000, and commonly about 1:63,360 or 1 inch to a mile), for use by the Army Map Service in the 1:250,000-scale topographic compilation of the United States. In the Kelsh plotter, this photography effects a model scale of about 1:12,000, and the estimated error in measuring vertical distances is 5 to 6 feet under optimum conditions. Because this photography is of small scale, some of the minor details of the terrain are difficult to distinguish in the stereoscopic model, but in areas suited to photogeologic study this loss of detail is not generally a deterrent in interpretation and mapping. High-altitude photography is especially useful for small-scale reconnaissance mapping because of the rapidity with which the operator can cover a large area. One stereoscopic model from high-altitude photography covers approximately 10 times the area covered by the stereoscopic model from low-altitude photography (1:20,000 scale). Because the original photography scale is increased less with the multiplex than with the Kelsh plotter, high-altitude photography

may not be as suited to geologic interpretation when used in the multiplex. Also, resolution in the multiplex stereoscopic model is less than that in the Kelsh stereoscopic model. In fact, geologic detail visible in a 1:12,000-scale Kelsh stereoscopic model from original 1:60,000-scale photography commonly may be more easily delineated than the same detail visible in a 1:12,000-scale multiplex stereoscopic model from original 1:30,000-scale photography. It may also be significant that this multiplex model covers only one-quarter the area represented by the Kelsh model.

High-altitude photography may be used in the ER-55 plotter, but the model will not be as large scale as the model obtained in the Kelsh plotter.

IMPORTANCE OF BASE MAP

The model scale of stereoplottedting instruments is calculated from a base-map scale or from control points identified in the stereoscopic model. The accuracy of most measurements, both horizontal and vertical, depends on how accurately the scale of the model has been determined. Among the best available base maps for use with one of the high-order stereoscopic plotters are topographic maps compiled on stereoplottedting instruments by the U. S. Geological Survey. The geologist should obtain an exact-scale copy of the base map printed on some stable material such as Mylar or metalmount paper, because the accuracy with which he can map geology by using stereoscopic plotting instruments is greater than the amount of error realized by the expansion or contraction of most less stable materials.

The quality of the base map is important because geologic features should be plotted as accurately as possible with relation to topographic and planimetric details. If a good base is not available, a base map can be constructed by photogrammetric methods by using ground control points within the map area. Many 1:250,000-scale topographic maps compiled for the Army Map Service from high-altitude photography are available and can be used to advantage in areas that are not covered by recent large-scale topographic maps. Many topographic details are lost in these maps because of their small scale, but there is generally sufficient control shown to approximately orient stereoscopic models from high-altitude photography in the Kelsh or ER-55 plotters.

ECONOMIC ASPECTS

The most important advantage of photogeologic mapping by means of high-order stereoscopic plotting instruments is the high order of accuracy obtained at low cost, provided there is access to an acceptable base map or sufficient control available to construct a base map. The main factor influencing the cost in a geologic mapping

problem is the time in man-hours necessary to complete the job. As mentioned before, 1 model obtained from high-altitude photography and used in either the Kelsh or ER-55 plotters covers an area approximately equivalent to about 10 models from low-altitude photography, or about $\frac{1}{2}$ of a $7\frac{1}{2}$ -minute quadrangle. Even with a minimum of control, data for special studies such as structure-contour maps, isopach maps, fence diagrams, control for isometric drawings, and detailed structural overlays, are readily available from spot-elevation readings and horizontal and vertical measurements made with the tracing table. In addition simple geology in well-exposed areas can be interpreted and mapped accurately with a minimum of field checking. The geologist can then spend his field season working out the more complicated areas, collecting samples, and measuring detailed sections necessary for stratigraphic studies. Because vertical control is readily available from the stereoscopic model valuable field time need not be used to obtain this control for special studies. Stereoscopic plotters are also useful in compiling geologic data that have been annotated on photographs as part of a field mapping project.

If diapositives of high-altitude photographs are used, it is suggested that low-altitude paper prints of the area also be purchased if available. These prints are an aid to field checking and are often very useful for detailed interpretation in areas which, for one reason or another, are not well defined in the stereoscopic model.

For areas in which very detailed interpretations are desired, diapositives made from low-altitude photography should be used. If rock exposures are numerous and continuous and the geology is not complex, a large part of the field work necessary to map distribution of formations can be eliminated.

Kelsh and multiplex diapositives can be purchased from many of the larger private flying companies, and ER-55 diapositives should become available in the future. Diapositives made from Geological Survey film and from Army Map Service so-called high-altitude film on file with the Geological Survey may also be purchased for any of the plotters from photograph sales offices within the Geological Survey.

ADVANTAGES IN GEOLOGIC STUDIES

The main advantage in the use of high-order stereoscopic plotting instruments such as the Kelsh or ER-55 plotter in the identification and interpretation of geologic features is that the geologist works with a large-scale optically corrected model of high resolution, and geologic features observed in this model may be plotted or measured rapidly and accurately, or both. Because more than

one geologist can view the stereoscopic model at the same time, consultation with experienced personnel may help to solve interpretation and identification problems.

If a geologist has access to literature or field data on a particular area, he may be able to identify the units of measured stratigraphic sections with a stereoscopic plotter by studying the relations of formations as to photographic tone, topographic expression, thickness, texture, and, sometimes, bedrock-controlled vegetation. Thicknesses of sedimentary units may be important in determining depositional environments and are therefore paid close attention by most geologists. If contacts are observable in the stereoscopic model, then numerous thickness measurements may readily be obtained by using a stereoscopic plotter. If thicknesses or attitudes are known to be constant, the geologist may be able to position covered contacts on the basis of thickness or attitude measurements.

The use of the floating dot as a spatial reference mark within the stereoscopic model is of particular significance. With proper use of the tracing table in uniformly dipping strata, the geologist can project contacts for hundreds of feet to intersect covered slopes.

Stereoscopic plotters may be particularly useful in obtaining structural data. Detailed structure studies with stereoscopic plotters usually have been confined to areas of relatively simple structure with numerous rock outcrops; however, in some areas structure studies have been made on the basis of vegetation patterns observable in aerial photographs but indistinguishable or distinguished with difficulty on the ground. The success in obtaining reliable structural data is a direct result of the ability to make accurate vertical measurements by use of stereoscopic plotters. Areas of more complicated structure with good rock exposures are also suitable for study with stereoscopic plotters, but they should be studied in conjunction with a correspondingly greater amount of field work.

The floating-dot principle of stereoscopic plotting instruments allows rapid, accurate measurement of altitudes. These measurements can be used to compute strike and dip by means of the standard three-point method, and to construct structure contours, provided recognizable geologic horizons are persistent throughout the area. By use of a tiltable surface with an attached clinometer on the tracing table, reliable strike and dip measurements can be made without mathematical calculations by alining this surface to a dipping sedimentary unit in the stereoscopic model.

Faults with as little as 18 inches of vertical displacement may be identified in some stereoscopic models, depending on the nature of the faulted strata, the kind of fault, and the resolution and scale of the model. Usually, faults are expressed as linear elements (linear

features) which aid the geologist in interpretation in areas of vegetation or surficial cover, as well as in areas of exposed rock. The geologist mapping on stereoscopic plotting instruments may find it easier to visualize faulted areas and to project stratigraphic units than is possible in the field.

APPLICATION TO SPECIFIC GEOLOGIC STUDIES

Stereoscopic plotting instruments can be used to produce isopach and structure-contour maps and other special maps entailing high-order accuracy. The Kelsh and ER-55 plotters are better suited to many special problems because of their high enlargement factors and the highly resolved models obtained from most of the common photography; however, the multiplex plotter is also suited to these studies if large-scale photography is available, or if the geologic requirements will permit use of small-scale photography.

ISOPACH MAPS

One of the most important advantages of isopach mapping by means of high-order stereoscopic plotters is that a very large number of readings can be taken, and many thicknesses computed, in a relatively short time. If the geologic contacts under consideration are sharp and distinct in the stereoscopic model, if dips are gentle and structure is not complicated, and if the operator has stereoscopic-plotter experience, the majority of measurements will be as accurate as, or sometimes even more accurate than, those obtained in the field. However, easily recognizable rock units are not necessarily essential to successful isopach mapping by stereoscopic plotting instruments. Topographic, vegetational, or other criteria that will permit interpretation of geologic contacts may well be adequate to allow compilation of isopach maps.

Several factors may limit accuracy in isopach mapping by use of high-order stereoscopic plotters. Geologic contacts upon which readings are taken should preferably be sharp and distinct; talus, soil, and vegetational cover should be at a minimum. Ideally a tonal break between formations is preferred over contacts expressed by changes in topographic expression or changes in vegetation.

Good base-map control is important for detailed work but not absolutely necessary if accuracy requirements are not too high. Spot field checking during compilation of the project will enable the geologist to evaluate the accuracy of both thickness measurements and identification of geologic contacts. If optimum conditions prevail throughout the project area, and low-altitude photography is used in either the Kelsh or ER-55 plotters, the geologist can predict an error as low as 2 to 5 feet per 100 feet for most measurements.

STRUCTURE-COUTOUR STUDIES

Similar principles and limitations apply to structure-contour studies as to isopach mapping by use of stereoscopic plotting instruments. Resolution of detail in the stereoscopic model is also important in structure-contour studies, and it may be advantageous to use the Kelsh plotter or ER-55 plotter. However, because the limiting error need not be too small in many studies of this kind, the multiplex plotter may be substituted when low-altitude photography is used. The surface to be contoured should preferably be clearly visible in the stereoscopic model and relatively free from cover, although vegetated areas of sparse rock outcrops have been successfully structure contoured from aerial photography.

SPECIAL COMPILEATION PROJECTS

Stereoscopic plotting instruments offer the geologist many desirable features that are especially applicable to special compilation projects. Some lineations are mappable from the Kelsh plotter stereoscopic model that are indistinguishable or difficult to distinguish in paper prints. Examples of these features are those expressed by alinement of tall trees in a dense forest, minute lines in darker grassland vegetation, and parallel elements thought to be foliation trends of metamorphic rocks. Most of these linear elements probably are controlled by bedrock. It is interesting to note that most of these features cannot be recognized easily in the field owing to a dense vegetational cover, and hence the accurate map positioning afforded by stereoplottting instruments facilitates the location of such features on the ground.

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