If no ground control is available and the elevation of the ground is not known, the use of a stop watch to time each exposure while flying on a straight course would furnish a means of determining very closely the distances between exposure stations, and hence the scale, because ordinarily the speed of an airplane is surprisingly constant, and the relation between recorded airspeed and ground speed could be determined by re-flying the course between recognizable points.

As to bearings, in the total absence of any ground indicators such as section lines, the pilot might determine the compass bearing of a line between two recognizable points by pointing the plane along the line between them and reading the plane's compass. Even shadows could be used for determining bearings if time of exposure and approximate latitude were known.

THE MULTIPLEX COMPILATION OF GEOLOGIC MAPS*

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MAPPING in the field on air photos offers the geologist easy, speedy, accurate plotting without instrument work. The lack of uniform scale, true azimuth, and elevations with respect to datum, however, makes impossible the accurate construction of an areal map, profiles, and structure sections, the projection of subsurface geology to the surface (and vice versa), and the calculation of ore reserves. There are no quantitative data until the geology is on a map, or as one geologist succinctly remarked, "No map—no geology." When, for lack of a base map or for convenience, geology is plotted on air photos, the compilation of that information into a map or its transfer to a base map is thus of crucial importance both to the geologist's analysis and to those who would utilize the data he has gathered and analyzed. It is my purpose to outline briefly one method of accomplishing this transfer or compilation.

There are several photo-mapping instruments which are able to solve this problem for the geologist, among them the Mahan, and K.E.K. plotters, the Multiplex Aeroprojector, and more elaborate instruments such as the Stereoplanigraph and Stereoautograph. These instruments use stereoscopic pairs of overlapping aerial photographs oriented so as to produce a true representation of the terrain in the area of overlap. To do so, the light rays that entered the aerial camera may be represented in the instrument by actual light rays or by mechanical levers, but they must be reproduced with their relationship to each other the same as when the photos were taken. This requires close integration in design between the plotting instrument and the taking camera, and each instrument is designed around photography of a specific kind. The specifications of the aerial camera thus are basic, and in mapping operations photography is planned to meet the requirements of the plotting instrument to be used, but when geologists take advantage of available photography their choice of a plotting instrument is immediately somewhat limited by the characteristics of that photography. The Mahan and K.E.K. plotters, for example, are designed primarily for photos taken with cameras of $8\frac{1}{4}$-inch nominal focal length. Some multiplex equipment is available for use with cameras of $8\frac{1}{4}$- and 4-inch focal lengths, but most is designed for cameras of 6-inch and 5.2-inch focal lengths.

The practical mechanics of the design impose other limits on the range of the plotting instrument. In the Mahan and K.E.K. plotters, standard contact

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prints are viewed directly; enlargements, so frequently used by geologists for field mapping, cannot be accommodated. The plotting scale in such instruments also is limited. In the Mahan the plotting scale must be between 0.36 and 1.78 times the photo scale; in the K.E.K., between 0.44 and 1.33 times the photo scale; and in the multiplex all plotting is done at a scale generally about 2.7 times that of the flight negative.

There is still another factor to be considered in selecting the plotting instrument for this job: the base map, if one is available. If the base has been prepared photogrammetrically, the necessary control for the photos has already been obtained, and the map detail corresponds exactly to that shown in the photos. If, however, the map has been prepared by field methods, the topography is somewhat generalized and will not coincide with the stereoscopic picture unless it is a highly detailed survey at a large scale. This would require the geology as mapped on photos to be adjusted to the base map, even after plotting in a stereoscopic instrument, and control points identifiable on both map and photos to be spotted in the field. In these circumstances, other instruments such as the reflecting projector, sketchmaster, multiscope, or duoscope, might prove more practical, in that they allow the base map to be viewed simultaneously with the photo or photos, enabling the necessary adjustments (which must be made by the geologist) to be made as the geology is plotted.

This discussion is restricted to the use of the multiplex aeroprojector. As many geologists are unfamiliar with this apparatus, it seems desirable to start with a few remarks on what it is and how it works.

The multiplex is a stereoscopic mapping instrument for the preparation of topographic (or planimetric) maps from overlappping vertical[1] aerial photographs. This it does by reproducing exactly to scale the conditions existing when the photos were taken. In this reconstruction, the aerial camera is represented by small vertical projectors, one for each exposure station; the negatives are represented by reduced positive prints on glass plates called "diapositives"; and the terrain photographed is reproduced stereoscopically by the overlapping images formed by the projectors from the diapositives. To obtain stereoscopic vision of the projected images it is necessary to see the image from one diapositive with one eye and that from the adjacent overlapping diapositive with the other eye. This is done by projecting one image through a colored filter and viewing it through a glass of the same color with one eye, while the second image is similarly projected and viewed in the complementary color with the other eye. The three-dimensional optical image thus observed from the two superposed projections is called a model.

Each projector can be translated along and rotated about each of its three axes. To form the model, the two rays to any given image point must be made to intersect in space just as they both emanated from the point when the two photos were taken. This is done by adjusting the relative orientation of the two projectors until the parallax-free stereoscopic image is formed. Thus the position of a point in the model is defined by the intersection of the corresponding rays from both projectors. The method may be likened to three-dimensional intersection of points but done at a reduced scale in the office. The multiplex projectors represent the observation points at the ends of the "base line," i.e., the camera stations. When the correctly oriented projectors are separated by a distance $1/n$th of the distance between the camera stations, the intersecting projected rays form a model having a scale of $1/n$.

[1] The multiplex has also been adapted for use with oblique photos such as are obtained in trimetrogon aerial photography.

This method requires all rays to be projected exactly parallel to the direction of the original rays. The projector is a scaled-down version of the taking camera; its critical dimensions are in the ratio of f/F, where f and F are the principal distances of projector and camera respectively, and thus to preserve the angular relationship of the original cone of rays, the original film negative must also be reduced in exactly the same ratio to make the diapositive that forms the projected image. The diapositive is made in a precision reduction printer whose lens also corrects the considerable distortion inherent in the wide-angle camera lenses in general use. The projector lens is free from distortion, so when the undistorted, accurately reduced diapositive is projected, the model-forming light rays have the same angular relationship as the cone of rays that entered the camera lens of when the photo was taken.

Horizontal and vertical control points are required to establish the scale of the model and to level it with respect to the datum plane (usually sea level). The scale is adjusted by varying the "base-line" distance between the projectors, and the model is "horizontalized" by tipping and tilting both projectors as a unit by orienting the bar on which they are supported.

Measurements can be made in the correctly oriented model, as it is true to scale. The measuring is done by means of a white disc or platen $4\frac{1}{4}$ inches in diameter upon which a portion of the model is viewed. As no single horizontal plane contains all of the points in the three-dimensional model, provision for vertical as well as horizontal measurements must be made. The disc can be moved freely over the horizontal plotting surface and vertically raised or lowered in its mount. In the center of the disc is a so-called "floating mark"—a very small hole illuminated by an electric lamp to give the appearance of a pin point of light. This is the reference mark that, as a result of the vertical and horizontal motion of the platen, can be placed "on" any point in the model. Vertically below the floating mark is a pencil that records the orthographic projection of the point in the model with which the floating mark is in contact and plots its position on a suitable medium. The elevation of the point is measured by a scale and vernier that records the vertical movement of the platen. Contours are drawn by locking the platen at the required elevation, bringing the floating mark into contact with the surface of the model, and moving it over the model while keeping the mark in contact with the "ground." Planimetry is drawn by keeping the floating mark in contact with the feature being traced by raising or lowering it as the feature is followed "up hill" and "down."

One great advantage of the multiplex is that several adjacent models in a flight strip may be set up together and adjusted as a group, which permits uncontrolled intervals to be spanned or "bridged" between established control points. The map accuracy requirements limit the length of the bridge. The intersection angle of the two rays that define a point in the model is such that vertical elevations are less definite than horizontal positions, so that "horizontal bridging" is more accurate over longer distances than "vertical bridging." Satisfactory horizontal accuracy can be attained by providing control at intervals of several models along the flight strip, but contouring requires vertical control throughout that bridge. For maps of standard accuracy it is customary to establish three horizontal control points every 7th or 8th model in each strip and at least 4 vertical control points in every model, one near each corner; this is the minimum, under ideal conditions, for a complete topographic map.[2]

[2] Other things being equal, the amount of control required varies directly with the amount of crab and tilt in the photography; as this cannot be anticipated, the control must be planned after the photography has been completed and the overlaps of the photos are known.

The cost of the necessary ground control depends largely upon the number of models to be worked. The cost of plotting depends directly on the same factor, other things being equal. The cost of multiplex mapping, therefore, is nearly a direct function of the number of models to be worked, dependent in turn upon the number of photos involved. Lower costs are most easily attained by reducing the number of photos required to cover a given area. Economy thus leads to smaller-scale photography taken from higher altitudes with wide-angle lenses of shorter focal length. Such photography, furthermore, improves the vertical accuracy, strengthens stereoscopic perception, and improves the orientation between projectors—all because the ratio of the air base to the flight altitude is increased, which results in stronger angles of intersection of the corresponding rays from the projectors.

If geology plotted on a set of air photos is to be transferred to a map by means of the multiplex, it is necessary to put the geologic data onto diapositives for use in the multiplex projectors. When that is done, a stereoscopic model showing the geology can be scaled to the map, and the contacts and faults can be traced with the floating mark just like any planimetric feature that registered on the photos. As the multiplex system requires the diapositives to be accurate reductions of the flight negatives in a precise predetermined ratio, the most important consideration is to obtain diapositives bearing the geologic data that fulfill this requirement as closely as possible. Every precaution that can be taken toward this end is worthwhile.

The precision reduction printer in which the diapositives are made takes only flight negatives and diapositive plates, hence the contact prints or enlargements on which the geology has been plotted must be photographed onto film negatives the same size as the flight negatives before the final reduction to diapositives can be made. This necessary return to the scale of the flight negatives[3] is really the crux of the whole operation. As the geology diapositives are made from contact prints or enlargements they are dependent upon those prints for quality of image and accuracy. Not only the geology, but also the image detail of the photos must show with all possible clarity on the new negative. The definition of the prints should be the best in order to obtain sharp, clear stereoscopic models, and the prints should be made on low-shrink paper and air dried, in order to reduce scale changes and minimize the rotational effect of differential shrinkage. These prints should not be trimmed, as the fiducial marks are required by the optical system, and the entire picture area of the flight negative should be retained. One other simple step should be taken if possible: the dimensions of the original flight negative should be measured and recorded, then the new negative bearing the geologic data can be made exactly the same size.

The plot of the geology submitted for multiplex transfer has special requirements: it has to be photographed, and the geology must be clearly and unequivocally legible in the model to an operator who may have little or no understanding of it. The contacts must register clearly when photographed by reflected light. The definition of the lines is heightened by maintaining contrast with the background. Black ink is very satisfactory in gray to white areas, but white ink should be used in areas that are slightly dark to black. White ink has been used exclusively with satisfactory results on photos that were quite dense. Fine lines such as made with crow quill and Hunt 104 pens are too narrow to

[3] The reduction could be made in one step in a printer of suitable design using a lens similar to the present printer lens in that it corrects the distortion of the camera lens; the demand for this work has not produced such a printer.

photograph well and be legible in the model. A fine black line especially is lost amid the photo detail; this is less true of white. A width of about 1/32 inch is generally satisfactory, provided strong contrast is maintained, otherwise a wider line should be used. A line even 1/32 inch wide is too wide for general map work and certainly much wider than should be used for contacts on field sheets. In areas of "fine-grained" geology where contacts are numerous and differentiated rock masses are small, the use of a wide line may require omitting some of the detail for the sake of easy legibility in the model and to avoid undue exaggeration of the size of the units. A dike, for example, might be shown by a single line, or only one of its contacts plotted. This will serve to locate the feature on the map; it then must be completed later by sketching. Dip and strike symbols should be omitted; they can be plotted more accurately on the map by the geologist and only complicate the task of the photogrammetrist. Likewise, formation symbols should be kept to the bare minimum essential for the geologists to identify the rock units delimited. Because such simplification may be required and because photos used in the field may become dirty or torn and are subject to scale changes, it is recommended that the geology plot submitted for multiplex transfer be made on a special set of prints on low-shrink paper. Then, too, the multiplex operator will need to have at hand a set of prints with the geology on them for reference and study. He can use this special set without tying up the geologist's field sheets.

An alternative method of making the geology diapositives is to trace the geology from each print onto a sheet of transparent acetate, making a sort of geology template for each photo used. This acetate, reduced photographically if enlargements are used, is then combined with the aerial negative in the reduction printer and the diapositive made by printing both together.

In preparing the low-shrink prints or the acetate tracings, only alternate exposures in each flight should be used, and the overlap in the geology should be just enough to eliminate all gaps. In spite of very careful work, geology plotted on two overlapping photos may fail to coincide exactly and appear at different elevations in the model, which is confusing to the operator. By using nearly the entire area of each alternate exposure, overlap is kept to a minimum; the models are formed by pairing a geology diapositive with the adjacent standard diapositives.

The geologist is best served by having the multiplex plotting of the geologic data done directly on a copy of the map. It is possible, however, to plot the geology on a transparent overlay and to transfer to the map later by tracing or by combining the two sheets in a contact printer. The compilation should preferably be done in pencil to facilitate editing by the geologist, which is required to see that the contacts lie on the proper sides of roads and creeks, for example, and that all the data have been transferred. Because of slight inaccuracies in making the geology diapositive and lack of extreme care or understanding on the part of the operator, such minor errors may occur.

This procedure has much to recommend it, but is practical only if the base map has been made in the multiplex by the time the geology has been mapped. (The geology can of course be transferred during the drawing of the base, doing all in one operation.) The necessary ground control would thus have been obtained by the map makers. Where conditions of vegetation and relief make accurate locations on photos possible, transfer by multiplex preserves this accuracy, and instrument work in the field by the geologist is eliminated. If necessary, geologic mapping can be done in advance of the preparation of a base map, for the geology can be easily and accurately transferred to the base at any time.

It is theoretically possible to set up multiplex models on the control afforded by existing topographic maps, but unless the map has been made from air photos it does not seem practicable. The geology must fit the base, cannot be any more accurate and should be no less accurate, hence any discrepancies must be eliminated by adjusting the geology to the base as drawn (unless the base is to be revised). When contours are sketched in the field the topography differs in detail from the actual shapes shown in the stereoscopic model formed from photos; if the geology is mapped on photos it must be adjusted to the base by inspection, and this can be done only by the geologist. If a base map is available the geology should usually be plotted directly on it in the field.

There is a further application of the multiplex that is worth considering when no base map exists. In such cases any map at all is a major help to the geologist, and standard accuracy may perhaps be sacrificed. The capacity of the multiplex to bridge between widely spaced control points has already been mentioned. This permits fair horizontal accuracy with few control points. Established primary triangulation stations, if accurately marked on the photos in the field, may afford enough control for a planimetric map. At least 3 or 4 stations are necessary in the area to be mapped. The geologist might be able to establish his own triangulation net to control such a map without undue expense. Accuracy with such minimum control improves when more than one strip of photos is used, but it is not practical to attempt to adjust more than 6 strips as a unit. Very satisfactory horizontal accuracy could be attained with one control point at each end of each flight strip. Contouring, as we have seen, is more of a problem; with two established elevations at each end of a strip of 7 or 8 models the contours in the middle of the strip would be of questionable accuracy. The expense of plotting with less than adequate control is great because of the time spent adjusting the models and distributing the errors. With control requirements fulfilled accurately and completely, the multiplex produces a first-class map. Even though this is not always possible, geologists could still make wider use of the capacity of the multiplex to do a creditable job with minimal control.

To summarize, the steps in the transfer of geology from photos to base map by means of the multiplex are outlined below.

1. Geology is mapped on contact prints or enlargements; specifications of aerial camera are known.

2. Geology is compiled on a set of low-shrink contact prints or enlargements, with some simplification, or

2a. The geology is traced on transparent acetate overlays carefully registered to the prints. Alternate exposures are used in both cases.

3. Low-shrink prints are photographed, reducing if enlargements were used, on to film negatives the exact size of the original aerial negative, or

3a. The transparent acetate tracings are reduced if necessary to the size of the original aerial negative.

4. Diapositives are made in the reduction printer from (3) or by superposing (3a) on the original film negative and printing both together.

5. Base map copy or transparent overlay is prepared at required scale.

6. Geology is plotted in pencil from the models set up in the multiplex.

7. Geologic map is inspected, edited, and completed (cf. 2) by the geologist, and inked.