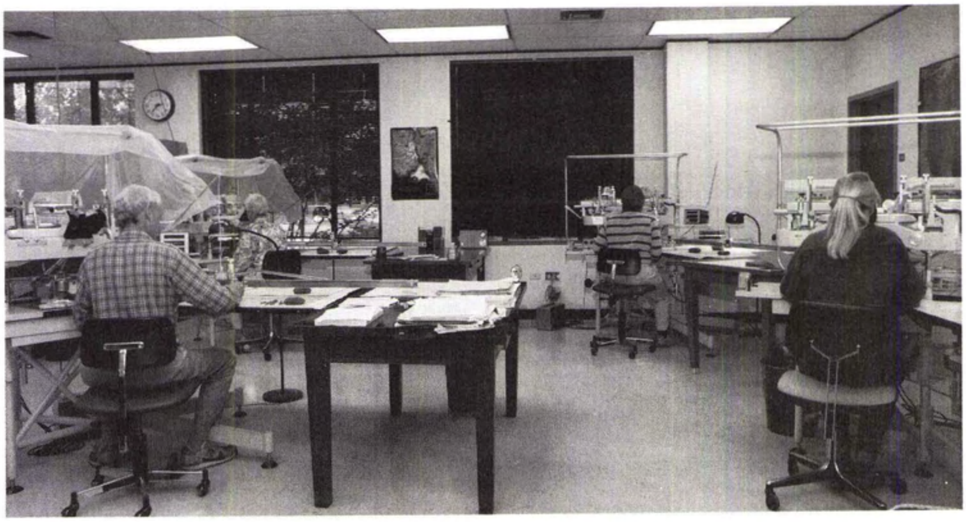

FRONTISPIECE. The Photogrammetric Plotter Laboratory in Denver, Colorado where PG-2 plotters are used for geologic mapping. Model setups are made for geologists by a technician.

Geologic Photogrammetry in the U. S. Geological Survey

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ABSTRACT: Geologic photogrammetry is the application of photogrammetric techniques and instruments to geology. This paper deals primarily with the use of photogrammetry in geologic mapping, the history of geologic photogrammetry in the U.S. Geological Survey, and a brief description of a PG-2-based computer-assisted photogrammetric mapping system for geologic studies.

The 1940s and 50s saw a great increase in photogeology, the use of aerial photographs for geologic mapping. Techniques and equipment developed mainly for topographic mapping were adopted by photogeologists and modified to make certain geologic measurements directly. During the late 1950s, a photogrammetric plotter laboratory was established at the Denver, Colorado, field center of the U.S. Geological Survey, where projector-type photogrametric plotting instruments were made available to geologists for map compilation. Beginning in 1972, the projection-type plotters were phased out and replaced by optical-mechanical Kern PG-2* plotters. Recent changes entail the development of a computer-assisted photogrammetric mapping system for geologic studies.

INTRODUCTION

SINCE THE Second World War, aerial photographs have been used increasingly for making geologic maps by the U.S. Geological Survey (USGS), by commercial mapping firms, and, to some extent, by oil and mining companies. Geologic maps are a means of recording and portraying information about the Earth's surface, such as the distribution and nature of identifiable rock units, surficial material that covers the rocks, and structural features that affect the rocks, such as folds and faults. Geologists can show the relationships of geologic units by mapping the contacts (boundaries) between these units, as they are exposed at the Earth's surface, and by portraying these relationships and the structural features that affect them as various lines and codes on a base map. Geologists prefer to portray their data on topographic base maps so that three-dimensional relationships between geologic units and the topographic surface can be shown, but accurate positioning of geologic data on the topographic maps has long been a problem. Aerial photos have become a popular tool for mapping geology, but geologic data annotated on the photographs must still be traced or transferred to a base map.

Geologic maps have traditionally been prepared by field-surveying techniques, by sketching geologic information onto a topographic or planimetric base, or by plotting or tracing this information on an aerial photograph. Geologic mapping using only a topographic base map still is a common practice, but

*Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 55, No. 8, August 1989, pp. 1185-1189.

0099-1112/89/5508–1185$02.25/0

precision mapping techniques using aerial photographs are widely used. In the USGS, photogrammetric techniques are now used routinely by many scientists for geologic map compilation. Computer support of basic photogrammetric systems now allows the geologist to produce maps in digital format, to make direct geologic measurement, and to do three-dimensional modeling of features within the stereomodel (Dueholm and Pillmore, 1989).

NEED FOR PHOTOGRAMMETRY IN GEOLOGY

Aerial photographs can be used most effectively for geologic mapping through utilization of overlapping photographs and observation of three-dimensional stereoscopic models, thereby giving the advantage of inherent image detail for interpretation and accurate delineation of geologic features (Ray, 1960). Lines depicting the geology can be drawn directly on the photographs or on transparent overlays using only a stereoscope. Such details must then be transferred to a base map, and much of the accuracy gained by careful annotation can be lost by imprecise line transfer. Excessive radial displacement of photographic images caused by relief and distortions caused by tip or tilt of an aerial camera must be corrected in the transfer process. This correction can be attempted visually, by careful and skillful terrain interpretation and free-hand sketching, or made instrumentally, using photogrammetric correction devices. In areas of gentle topography, where distortions caused by relief are small, most geologic observations mapped on aerial photographs of good metric quality can be compiled accurately onto a base map by tracing or by use of a simple optical projector to make necessary adjustments for scale differences; where tip or tilt presents problems, a simple tilt-correction device such as a Sketchmaster can be used (Loving *et al.*, 1980). However, rocks are usually found best exposed in areas of rugged high relief, where radial distortion in photographs is significant and correction by photogrammetric methods is advisable.

GEOLOGIC PHOTOGRAMMETRY IN THE U.S. GEOLOGICAL SURVEY

During the 1940s and early 1950s, use of aerial photographs for geologic interpretation and mapping greatly increased. Various photogeologic techniques and procedures were devised for use of aerial photographs, many of which are still used today (Ray, 1956, 1960; ASP *Manual of Interpretation*, 1960). In areas where no adequate topographic base maps were available, radial-line templets or plots (sometimes referred to as "spider nets") helped to control planimetric base maps (Slama *et al.*, 1980); these plots were followed by stereotemplet control bases. The stereotemplet control bases were made on projection-type plotting instruments from small-scale photographs and consisted of control points for the large-scale photographs used for planimetric geologic map compilation. The control point bases made from stereotemplets provided more accurate control than radial-line plots (Scher, 1955; Slama *et al.*, 1980). Kail Radial Planimetric Plotters were used for compiling hundreds of photogeologic maps of the Colorado Plateau on these stereotemplet base nets during the 1950s. (For a description of the use of Kail Plotters, see Ray (1956).) These types of plotters remove radial distortion from the projected image, but they do not remove tip and tilt distortions and cannot be used for making the various measurements required for calculating strike and dip and other geologic map information, such as structure and isopach contour data. However, these measurements were made routinely from paper prints of aerial photos, using stereometer-type instruments (Hemphill, 1958).

USE OF PROJECTION-TYPE PLOTTING INSTRUMENTS

During the mid 1950s, anaglyphic projection-type photogrammetric plotters such as the Kelsh, Multiplex, and ER-55 were tested and adopted for use by photogeologists in the USGS (Pillmore, 1959; Ray, 1960). On anaglyphic plotters, filtered light of complementary colors (red and blue) is projected through glass or film transparencies to the viewing surface (platen) of the plotter (Figure 1). A stereoscopic effect is achieved by viewing the projected image through spectacles of the same colors (Loving *et al.*, 1980). At first, experienced photogrammetrists set up stereoscopic models in the machines for geologists and made various readings and measurements as directed; however, photogeologists soon learned the procedures for setting up and orienting models and they began taking measurements unassisted. During the 1960s several of these plotters, mainly Kelshes and ER-55 or Balplex plotters, were acquired for geologic mapping, and the USGS Photogrammetric Plotter Laboratory was established in the Central Region Field Center at Denver, Colorado, where assistance and training in geologic use of these plotters were available.

During the early operation of this joint-use facility, each geologist was trained in the basics of photogrammetry and in how to clear parallax and to orient and level stereoscopic models to their base maps. Though most learned these procedures quite readily, the inefficiency of training each geologist to be a photogrammetrist was soon realized, and photogrammetric technicians were employed to set models for geologists desiring to use the plotters. The procedures for mapping geology on a photogrammetric plotter are quite simple once the parallax has been cleared and the stereoscopic model has been oriented and scaled to the base map. With little training and guidance, the geologist can begin tracing contacts and compiling his map. The basic methods for information transfer from photographs to the base map are quite similar for nearly all photogrammetric instruments. By moving a tracing carriage (Figure 1) around in

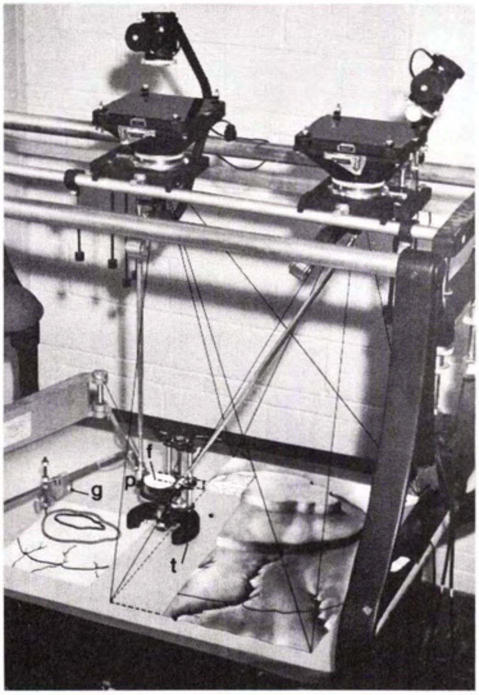


FIG. 1. Photograph of a projection-type Kelsh plotter. The graphic representation of a stereoscopic model depicts how the floating dot (f) on the platen (p) of the tracing carraige (t) can be used to make thickness measurements of strata and to follow geologic contacts and plot them on a base map through the use of a pantograph (g).

the stereomodel and keeping the floating reference mark (an illuminated dot) on the apparent ground surface, images that portray geologic contacts and other features can be traced and mapped (Figure 1). A pencil mounted on a pantograph (attached to the tracing carriage directly beneath the floating dot) records the movements of the dot on a base map at the required scale. The position of the floating dot in vertical space is controlled by a gear or thumb wheel. When the wheel is moved, the dot appears to float above, at, or below the apparent ground surface. For accurate mapping and transfer of data, the dot must be maintained on the apparent ground surface at all times as contacts are followed in the model. A dial or an optional digital readout displays the vertical movement of the dot and readily allows accurate measurement of altitudes that can be used to calculate strike and dip of strata (by solving a 3-point problem), to measure stratigraphic thicknesses, and to make structure contour maps. Geologic information transfer using these plotters is easy where rocks are clearly exposed and contacts are visible in the stereomodel; however, transfer using the projection-type plotters is problematic where detailed mapping has been done on paper prints of the air photos, because a satisfactory method has not been developed for making distortion-free transparencies or glass plates from annotated paper prints. Transfer of field-mapped contacts from paper prints to the model was done by careful visual inspection and transfer using only a stereoscope. This process was impeded by the low light intensity (illumination) required surrounding the plotters.

The ER-55 and Multiplex plotters allowed more than one stereomodel to be set up at one time (Figure 2). Steven Oriel, one of the USGS's most enthusiastic users of the stereoplotters, used this multiple-model technique on the ER-55 in his mapping in the thrust belt of southeastern Idaho. He considered the ability to trace faults and contacts back and forth through two to three models at a time a definite asset to his mapping in the Preston 1° by 2° quadrangle, which was compiled largely on the ER-55 (Oriel, 1980).

Accessory Instruments

To facilitate geologic interpretation and measurement, various accessory instruments were devised for use on the projection-type plotters, namely, the profile plotter and the universal tracing table. The profile plotter consisted simply of a spring-loaded pencil mounted on the viewing surface (platen) of the tracing table. As the tracing carriage moves along the line of profile, the pencil plots the movement of the floating dot on a vertical plotting board. A trackway guides the tracing carriage along the line of profile. An adaptation of this profiling device was a pantograph arrangement for the pencil designed to produce 2×, 3×, and 5× exaggeration of the vertical movement of the platen as it is moved along the trackway of the plotting board (Figure 3). The profiling devices were used at the USGS on any of the plotters and were employed to make geologic cross sections and to help correlate beds across stereomodels.

The Universal Tracing Table (UTT) is a device that could be used on Multiplex and ER-55 plotters. Its use was restricted on the Kelsh plotter because of the guide rods on the tracing carriage. The UTT (Figure 4) directly measures dip and strike and thickness of inclined strata. The UTT consists of a Bausch & Lomb Multiplex tracing table modified to feature a rotatable platen-support arm (Figure 4a) and a platen that consisted of a white disk with two rows of floating dots at right angles to each other (Figure 4b). The platen of the tracing table is freely rotated and tilted in the stereomodel so that the cross of dots rests on a geologic surface and the attitude (dip and strike) of that surface is read directly from graduations on the drum of the support arm. The plane of the tilted platen is then manually moved parallel to the strike to help correlate geologic horizons (beds) to show where a particular horizon might intersect other parts of the model. In addition, a drivescrew and vernier on the platen support (Figure 4c) allowed direct measurement of the platen movement normal to the surface (plane) so that stratigraphic thicknesses of inclined strata can be measured. The universal tracing table and the profile plotter were useful for geologic interpretation on projection-type plotters in their time; however, during the 1970s, these types of plotters were replaced by more modern Kern PG-2 plotters and the universal tracing table and the mechanical profile plotter were no longer used.

The PG-2 Plotter

The Kern PG-2 plotter is an optical-mechanical plotter (Figure 5) that was first introduced into the USGS Photogrammetric Plotter Laboratory in 1972. It offers the following features and advantages over the projection-type plotters: the capability of using black-and-white or color paper prints and film or glass transparencies with equal ease (with the paper print illumination option

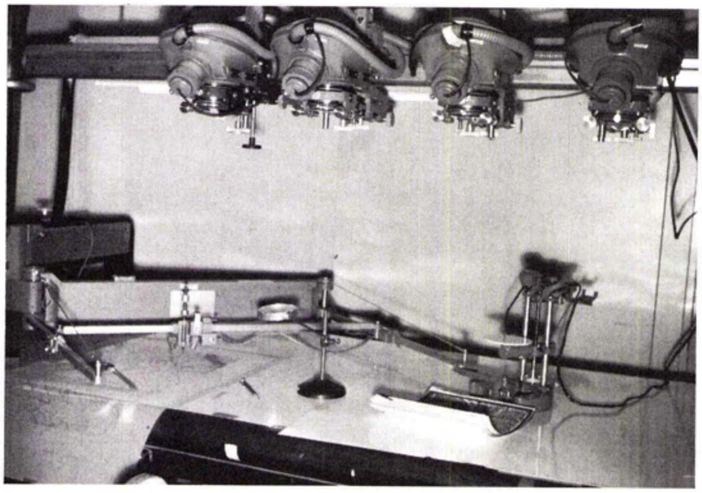


FIG. 2. Photograph of an ER-55 plotter with four projectors that allows three stereomodels to be set up at one time.

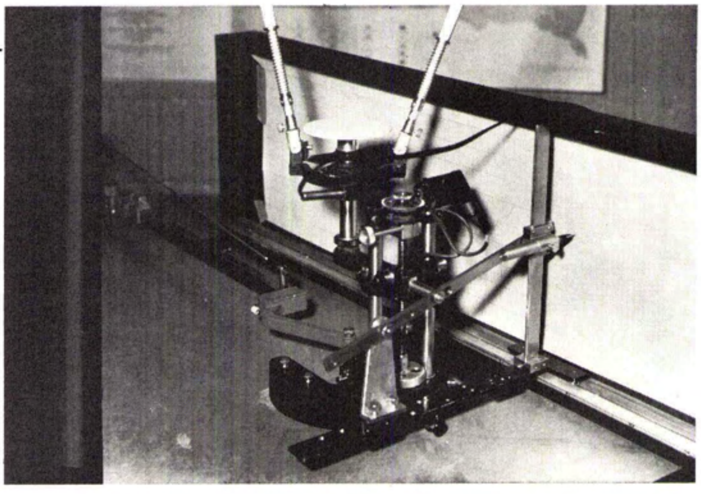
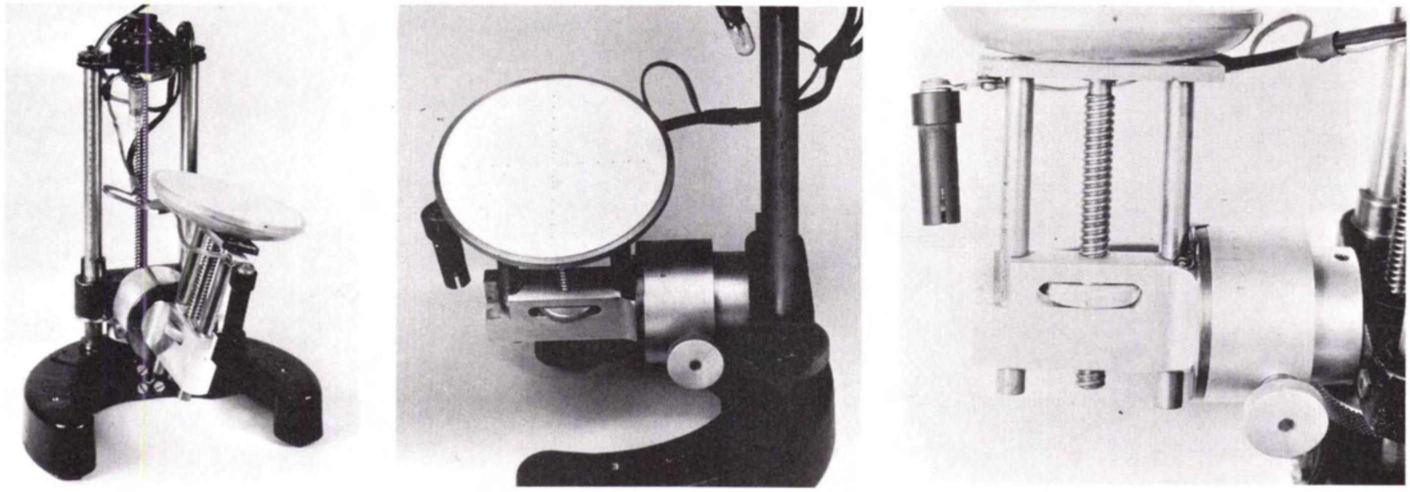


FIG. 3. Photograph of the exaggeration profile plotter. Using a standard profile plotter, movement of a pencil mounted on the platen of a tracing carriage plotted a 1:1 profile on the vertical plotting board. Using the profile plotter shown above, the vertical pantograph allowed vertical exaggerations of 2×, 3×, and 5× of the profile, which enhanced breaks in slope and aided geologic interpretation.



(a) (b) (c)

FIG. 4. Photograph of the Universal Tracing Table (a). By rotating the tracing table and tilting the platen, a cross of lighted dots (b) is made to lie on a geologic surface. The inclination of the surface is then read directly on a graduated dial. A vernier on the vertical drive screw (c) allows direct measurement of thickness of inclined strata.

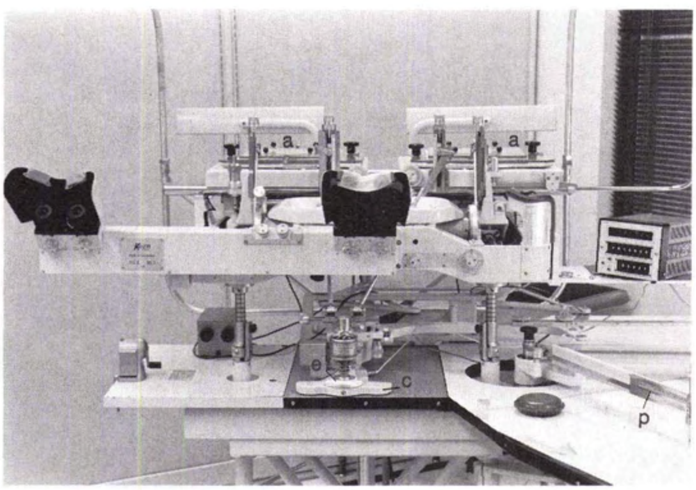


FIG. 5. Photograph of a Kern PG-2 photogrammetric plotting instrument used for geologic mapping in the U.S. Geological Survey: (a) stage plates that hold either transparencies or paper prints of aerial photographs; (b) binocular stereographic viewer; (c) tracing carriage showing (e) elevation control wheel; (t) plotting table showing (p) pantograph positioned above a base map.

installed); a high-quality viewing system incorporating variable, easily changed magnification; and a machine configuration that allows the operator to sit comfortably at the instrument in a lighted room (the projection-type plotters required low-intensity lighting conditions and were unconfortable to work on). Like the projection-type plotters, the PG-2 has an illuminated floating mark that is readily visible in the model, especially in dark portions of the image (as compared to black dots used on some other mechanical plotters). The PG-2 features an ease of operation that enables geologists with normal stereoscopic vision and no prior training in photogrammetry to begin to map shortly after parallax has been cleared and their models have been oriented to a base by a technician. Geologic details visible in the stereomodel can readily be followed and mapped, but importantly, in PG-2's with paper print illumination, annotations representing obscure geologic contacts mapped on air photos in the field can be viewed and traced in the model and drawn accurately on the base map. A large number of geologists of the USGS have used PG-2 plotters to do geologic photointerpretation and to improve the accuracy and quality of their geologic map compilations. The plotters are used primarily at the Plotter Laboratory in Denver (Frontispiece), but also at the field center in Menlo Park, California, the Hawaii Volcano Observatory in Hawaii, and the National Center in Reston, Virginia.

Though the PG-2 offers many advantages, its design allows neither the use of more than one model at a time nor the convenient use of geologic accessory devices, such as those described above for directly plotting profiles and for making the geologic measurements that were possible on the Universal Tracing Table. However, horizontal distances and altitudes can be accurately measured with the PG-2 for computing attitudes and determining thicknesses of units and displacements on faults. In addition, distances paced or taped in the field or measured vertically with a hand level can be readily recaptured and used for positioning and mapping contacts. Another disadvantage of PG-2-type mechanical plotters is that vision is restricted to the small area observed through the viewing binocular, in contrast to the ER-55 and Multiplex plotters in which entire models could be viewed stereoscopically on the table surface. But even with some of their disadvantages, during the 1970s the PG-2 plotters continued to gain in popularity, and ways of improving their capabilities and overcoming their limitations were pursued.

THE COMPUTER-ASSISTED PHOTOGRAMMETRIC MAPPING SYSTEM

During the late 1970s, a computer-assisted photogrammetric mapping system (CPMS) for geologic mapping was developed in Denmark (Dueholm, 1979). This system consisted of a PG-2 plotter with a Kern DC-2B digitizing system that was connected to a Hewlett Packard desk-top computer and a flat-bed pen plotter. The system included a stepping motor on the tracing carriage of the plotter that drove the floating dot to a computer-specified position (the so-called "Z-drive facility"). Software, called the GEOPROGRAM, performed all the various geologic measurements and capabilities that had been possible with the Universal Tracing Table and the profile plotter on the projection-type plotters plus many, many more functions.

The success of the PG-2 plotters for conventional geologic mapping and compilation in the USGS, together with a predicted need to produce digital geologic data from aerial photographs and a requirement to produce special derivative geologic map products, led to a cooperation between the USGS, the Technical University of Denmark, and the Geological Survey of Greenland, and the subsequent development of a similar system for the USGS (Pillmore *et al.*, 1981). A configuration of equipment similar to the Danish system was installed on a PG-2 in the USGS Plotter Laboratory in 1978 by HASP Inc., a photogrammetric engineering firm in Loveland, Colorado. Since that time, the system has been further developed and improved and additional capabilities have been devised for the software that are especially adapted for geologic studies and geologic mapping requirements (Dueholm and Pillmore, 1989).

CPMS Design Concepts

The spatial position of the floating dot of the PG-2 tracing carriage is represented mathematically through a tri-axial recording system. Horizontal movements (X and Y) of the carriage and vertical motion (Z) are recorded by electronic signals generated by encoders placed on X and Y coordinate guide rails on the plotter and on the Z-column of the tracing carriage. The basic components of any CPMS include XYZ encoders; a computer programmed to assign values to signals generated by the encoders, perform required mathematical calculations, store data, and drive a two-axis XY flat-bed or drum-type pen plotter, and record graphically the XY movement of the tracing carriage; a stepping motor mounted on the Z column of the tracing carriage that drives the Z-motion of the floating dot; and XY digitizer to aid in map orientation; and a line printer.

Geologic Applications of the CPMS

The CPMS is designed for geologists to operate the system. The geologic applications of the CPMS are limited only by the mechanical design of the PG-2 and the imagination of the geologist. The geologic measurement and profile capabilities provided by the universal tracing table and the profile plotters on the projection-type plotters are greatly expanded by the versatile GEOPROGRAM of the CPMS. The ability to guide the Z-motion of the floating dot on calculated planes and grids in the stereomodel enhances geologic mapping, and the ease of profiling with the system allows the geologist to more readily use shapes of valleys and canyon walls as tools to correlate resistant units and interpret rock types. A further description of some of the many applications of the CPMS is given in Dueholm and Pillmore (1989). The capabilities of the CPMS continue to increase both in Denmark and at the USGS, but further development is limited by the analog design of the PG-2. Computer-controlled analytical plotters permit further automation of the CPMS functions and allow additional geologic mapping tasks to be performed that are not possible on the present system.

Analytical Plotters

Analytical plotters are fully computer controlled and are not limited by mechanical linkage. These advanced plotters offer several design features that are useful to geologists: zoom magnification and high-quality viewing optics; the capability to accept oblique or terrestrial photographs and small-format photographs taken with non-metric cameras; and, in some plotters, 9 in. by 18 in. stage plates that duplicate the ER-55 plotter's ability to simultaneously set multiple 9 in. by 9 in. stereomodels and to set models using 9 in. by 18 in. panoramic photographs. See Dueholm and Pillmore (1989) for further discussions of analytical plotters.

Summary

Photogrammetric techniques and instruments, developed primarily for topographic mapping, have been used successfully for many years for geologic mapping in the USGS. Projection-type plotting instruments constituted the basic equipment used successfully for more than a decade by many geologic projects, but these plotters were replaced during the 1970s by Kern PG-2 plotters fitted with paper print illumination. These versatile plotters have proved especially useful for geologic mapping studies, though limited by their mechanical design. The addition of computer support to the PG-2 has greatly expanded the measuring and mapping potential of the instrument. Fully computer-operated analytical plotters provide for further enhancement of geologic mapping capabilities.

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