Computer-Assisted Geologic Photogrammetry

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ABSTRACT: Methods have been developed that aid geologic interpretation, structural analysis, and geologic mapping on a computer-assisted photogrammetric plotting instrument. Software, called the GEOPROGRAM, is used to digitize geologic data from the stereoscopic model and to make various direct geologic measurements. The GEOPROGRAM also allows the integration of mathematical structural models generated in the computer with the visual stereoscopic image of the terrain so that surfaces can be calculated, projected, and used for interpretation. The intersection of a computer-calculated plane that represents a geologic surface and the perceived stereoscopic image of the terrain can be traced with a computer-guided floating mark and plotted. Used with the basic elements of interpretation – tone, texture, shape, and topographic expression – these projected surfaces provide a powerful capability for geologic interpretation of aerial photographs. Some aspects of the method treated herein are strata and fault-throw measurement, fault interpretation, profiling, gridding and structure contouring, and isopach mapping.

INTRODUCTION

GEOLOGIC MAPPING can be characterized as the art of understanding, modeling, and portraying the three-dimensional (3-D) relationship between rock units at and beneath the surface of the Earth. During fieldwork, the geologist gradually develops a "conceptual geologic model" that he/she intellectually compares and adjusts to continuing field observations. The geologist's ground-level perspective necessitates considerable imagination and talent to envision and model the 3-D relationships of the rocks. Observations and measurements are commonly difficult to correlate from this limited surface view and lack of overview.

The synoptic view of the "stereoscopic model" of overlapping aerial photographs provides supplemental information valuable to the understanding of the 3-D geologic relations. By use of photogrammetry (Pillmore, 1989), very precise measurements can be performed in the stereoscopic model. To the degree that geologic structures can be interpreted from the photographs, photogrammetric point measurements further aid the geologist in developing a conceptual model and ultimately in controlling the final map product.

The interfacing of a computer to a photogrammetric instrument allows the 3-D point measurements to be recorded digitally and, by means of computer programs, to be transformed into geological parameters such as strike and dip of bedding. Based on the measured points and the calculated parameters, mathematical models of the geological setting are developed.

Three models are available to aid the geologist in understanding and illustrating the geology: the hypothetical model in the mind of the geologist, the stereoscopic model perceived by viewing photographs under a stereoscope or in a photogrammetric instrument, and the mathematical computer model. These models are equally important to the mapping process but also have completely different functionality: (1) The hypothetical model is flexible, but without consistent scale or quantitative aspects; (2) the stereoscopic model created by photogrammetric instrumentation is a precise, scaled model of the terrain; three-dimensional point measurements and projection of traced lines to map manuscripts are possible but limited to what can be seen and interpreted by the geologic operator; and (3) the mathematical model interpolates and extrapolates the measurements; through mathematical formulas the model objectively conforms to the underlying observations. Today, mathematical models are confined to relatively simple structural surfaces as compared to the commonly complex, real-world geology; therefore, the models have to be compared to nature and adjusted, preferably in an interactive process.

The computer-assisted photogrammetric mapping system (CPMS) – described by Dueholm (1979) and Pillmore *et al.* (1981), and further discussed in this paper – provides an interactive tool for the geologist to build mathematical structural models based on measurements from the field, the photogrammetric plotting instrument, and a topographic base map registered on a digitizing tablet. A unique feature of the CPMS is the ability to project the mathematical model, which is based on calculated planes and surface grids, back into the stereoscopic photographic model. The geologist can then visually measure and compare geologic features with the stereoscopic image of the terrain, and interpolate or extrapolate visible outcrops according to the projected mathematical model. This has proved to be a very powerful tool for forming and testing hypothetical models and for subsequent mapping of geologic horizons.

THE COMPUTER-ASSISTED PHOTOGRAMMETRIC MAPPING SYSTEM

The basic component of the CPMS is a Kern PG-2† analog photogrammetric plotting instrument with digital output. The floating mark in the stereoscopic model is guided in all three coordinates by means of a tracing assembly operated by the geologist. The current coordinates of the floating mark are digitized incrementally and transmitted to the host computer. From the computer the coordinates transformed to a map projection may be plotted on an attached pen plotter. A stepping motor is mounted on the Z-wheel of the tracing assembly, which allows the computer to control and position the floating mark on precalculated elevations. A digitizing tablet is used to integrate coordinate data digitized from a map. A technician orients the stereoscopic model in the photogrammetric instrument, registers a base map on the digitizing table, and prepares a manuscript sheet on the pen plotter. Typically, ground control for the orientation of the stereoscopic model is digitized from the map with sufficient accuracy for geologic mapping.

The CPMS is designed so that a geologist can operate the system. By means of the GEOPROGRAM, geologists can digitize geologic data from the stereoscopic model, the base map, or from field sheets as desired. Elevations interpreted from well logs and from observations noted at field stations marked on pho-

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PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 55, No. 8, August 1989, pp. 1191–1196.

0099-1112/89/5508–1191$02.25/0

tographs or topographic maps are entered into the system by means of the keyboard. The digitized data can be used in the calculation of mathematical structural models, plotted on the pen plotter, or stored in data files, simultaneously or individually. The data can be gridded and contoured to show the shape of geologic surfaces (structure contour maps) and used to compute attitudes (dips and strikes) of geologic surfaces, boundaries, or strata.

The projection of mathematical structural models into the stereoscopic model is achieved by the so-called Z-drive function of the GEOPROGRAM, which automatically drives the Z motion of the tracing assembly on mathematical planes and surfaces that represent geologic contacts.

Review of the Z-Drive Facility

In the conventional topographic use of photogrammetric plotting instruments, the movements of the floating mark may be fixed at selected elevations to trace contours along horizontal planes. Therefore, photogrammetric plotting instruments are designed to facilitate the guiding of the floating mark in such a manner. Although some geologic boundaries are planar surfaces, they are rarely horizontal; they dip gently or steeply, or are overturned completely. Thus, tracing the intersection of horizontal planes with the terrain is of limited value to geologists; instead, geologists need to be able to trace or follow inclined planes or irregular surfaces that represent contacts or geologic horizons. Following such contacts or horizons with the floating mark presents no problem in areas where exposed rocks are visible in the stereoscopic model, but photogeologic mapping is of limited value where rocks are obscured by soil and vegetation. The Z-drive facility guides the floating mark on precalculated mathematical surfaces through these obscured areas.

In order to guide the floating mark on inclined planes or irregular surfaces, the GEOPROGRAM continually compares the current elevation measured in the stereoscopic model with the elevation calculated from the mathematical surface. The stepping motor mounted on the Z-wheel continually adjusts the floating mark to the elevation of the surface as the tracing assembly is moved around the stereoscopic model by the geologist.

Using the Z-drive, isolated exposures may be compared with the precalculated structural projection of a bed, thus permitting recognition and correlation of unidentified or misidentified outcrops. Geologic boundaries can be projected across valleys or from one side of a ridge to another and mapped where they cannot be traced readily through covered areas by visual inspection alone. The pen plotter tracks the movement of the tracing assembly at any scale while the Z-drive is operating, so that the apparent intersection of the projected mathematical surface with the terrain observed in the stereoscopic model can be mapped. In this manner, contacts obscured by talus, soil, or vegetation can be mapped in the stereomodel nearly as routinely as contours are mapped in conventional topographic mapping.

Subsurface elevation data on particular geologic horizons can be entered from the digitizer to compute mathematical surfaces and to control the Z-drive. Thus, buried horizons can be projected from the subsurface and their intersection with the ground surface can be mapped. Also, the elevation of the horizons of interest can be displayed at any selected position in the model; this feature allows the geologist to predict the position or depth of a particular horizon in adjacent proposed drill holes for the purpose of correlating rock units or lithologic beds.

Projection of Geoplanes

The Z-drive was first developed to aid in geologic mapping of sub-horizontal sedimentary formations in North Greenland (Jepsen and Dueholm, 1978). Therefore, elaborate plane manipulations are included in the CPMS system. The derivation of this capability is described in detail by Dueholm (1981), so only an overview of the geologic capabilities is presented here.

By means of a least-squares adjustment, planes called "geoplanes" are fitted to coordinate data measured point by point or incrementally along a visible contact in the stereoscopic model, elevations from drill holes, or attitude data from field observations (Figure 1). Strike and dip and standard deviations are computed and displayed or printed. The geoplanes are stored in the system and may be later combined in different ways to aid geologists in the measurement of structural parameters. The perpendicular distance between geoplanes representing separate geologic horizons or from the floating mark to any geoplane can be calculated and displayed. Such measurements represent stratigraphic thickness (Figure 1). Two geoplanes derived from the same geologic horizon on opposite sides of a fault can be used to determine the amount of fault displacement. The orientation and plunge of fold axes also can be calculated by combining two or more geoplanes. The parallel shift function raises or lowers the geoplane to the position of the floating mark. This function enables a geoplane calculated from readings taken on a visible dipping bed or contact in the stereomodel to

FIG. 1. Photograph showing a geologic surface (contact) represented by a shaded plane (geoplane). Geoplanes are calculated from points measured on geologic horizons (beds) in the stereomodel of a photogrammetric plotter. The Z-guiding mode of the GEOPROGRAM maintains the floating mark of the plotter on that calculated surface throughout the model, enabling the geologist to correlate outcrops within the model and to map the trace of the geoplane across covered areas.
The reconstructed profile beneath the photograph shows the geoplane. The vertical distance (v) from the floating mark (F) to the geoplane and the stratigraphic thickness (s) can be automatically calculated by the system.

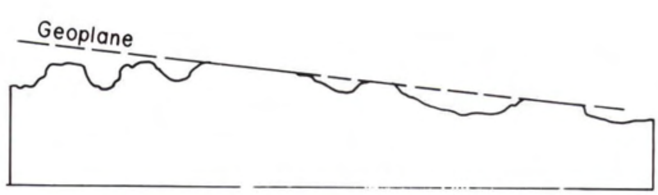

FIG. 2. Distances from geoplanes projected from geomorphic surfaces to modern stream levels can be accurately measured and surfaces correlated by projecting the geoplane.

be shifted to another contact or to a field station and projected at that level parallel to the original geoplane. An example of use of geoplanes for evaluation of geomorphic surfaces such as alluvial terraces is shown in Figure 2.

The plane-projection function integrates statistical error-surfaces on each side of the geoplane, which allows the geologist to evaluate new outcrops recognized during Z-driving that do not fall exactly at the level of the calculated plane.

In sub-horizontal planar bedding, the geoplane functions allow marker horizons to be measured with accuracies around 0.1 degree on dip, and projected throughout the mapping area as a valuable aid in the structural interpretation. Fluctuations in stratigraphic thickness can be monitored over large distances, and even small and varying displacements along minor faults can be readily computed. In intensely folded, thrusted, and overturned strata, the geoplane functions can aid the computation of local attitudes, which later may be combined to describe the major axes involved.

IRREGULAR SURFACES

Functions for gridding irregular surfaces from random data points and projection of curved surfaces using a Z-grid drive were added to the USGS system in response to requirements for coal-bed mapping in continental sedimentary deposits.

STRUCTURE-CONTOUR STUDIES

The configuration of geologic horizons can be shown by means of structure contours — lines that join points of equal elevation on any geologic surface, such as a formation boundary. The CPMS can be used to produce structure-contour maps from both subsurface data and outcrop data. Point elevations are entered manually through the keyboard, or automatically from the photogrammetric instrument. A GEOPROGRAM function for storing drill-hole information allows the operator to enter the collar elevation, followed by the depths of the rock units or beds identified in the drill records. Depth data are converted automatically to elevations of rock units. The elevations of points measured along outcrops, as observed in the stereoscopic model, also can be entered and coded for later retrieval.

Once the coded rock data are entered into the computer, separate files are made for each rock or bed code, so that all the elevation data, both outcrop and subsurface, for each geologic horizon can be handled as a single data set. Points can be deleted or inserted, and the *XYZ* data of each point can be edited. After editing, the data are transferred to the Surface Display Library (SDL) of Dynamic Graphics, Inc., where they are interpolated, gridded, and contoured by a main-frame computer holding the SDL procedures and transmitted back to the CPMS's onboard microcomputer. (The communication procedures were written by David Lake, a contact software specialist.)

After gridding and contouring, the grids and contours are retrieved and stored in the CPMS. The structure contour maps and data points can be plotted by the pen plotter in correct position on the base map (Figure 3a). If the shape of the gridded, contoured surface is not realistic and does not fit the geologist's hypothetical model, points can be checked and edited or additional points can be added to the file on an interactive basis. The interpolated grids can then be retrieved separately for use in the Z-grid drive function as described below.

Z-GRID DRIVE

In the Z-grid function, the computer maintains the Z-motion of the tracing table on the gridded surface by bilinear interpolation. The function allows continual readout of elevations from the gridded surface; it also can display the distance from the floating mark placed on the ground surface to the gridded surface (depth), which can be used to evaluate overburden. Numbers may be added to or subtracted from the grid to effectively raise or lower the gridded surface so that geologic "parallel" surfaces above or below the gridded datum can be investigated and mapped (Figure 4). In effect, contacts can be mapped throughout the stereomodel or the outcrop area by raising the gridded surface to the altitude of a known point on a contact in the model. Integration of the computer model with the visual model is accomplished by observing ledges, cliffs, breaks in slope, and other topographic or geologic features in the visual model and using them as guides to mapping. Known changes in thickness of a stratigraphic unit within the stereomodel may be accounted for by adding or subtracting wedges from grids. Finally, at any specified point on the gridded surface, a function of the GEOPROGRAM permits plotting of the strike and dip of the surface.

The implementation of gridded surfaces is very useful in gently undulating, non-faulted to moderately faulted terrain, especially where subsurface information is available. Use of the Z-grid

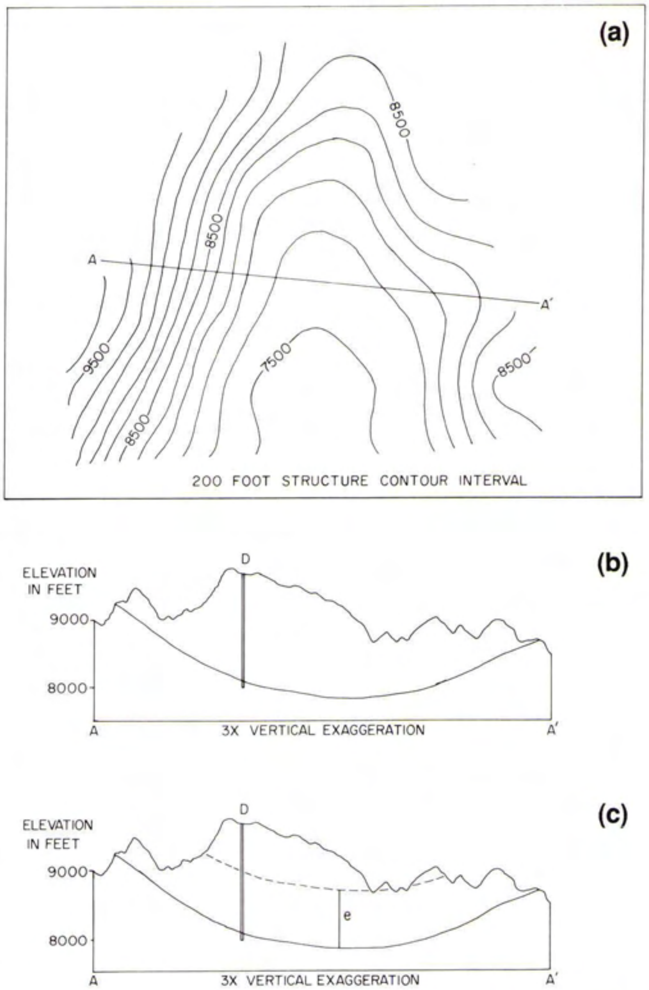

FIG. 3. (a) A structure contour map computed by the Surface Display Library of Dynamic Graphics, Inc. from drill-hole locations and outcrops. (b) Terrain profile showing the trace of the gridded surface drawn by GEOPROGRAM along line A-A′. (D is drill hole.) (c) The same terrain profile as in (b), showing the trace of a surface identical in form to the gridded surface of (b) but raised a vertical distance e (i.e., a stratigraphic height e).

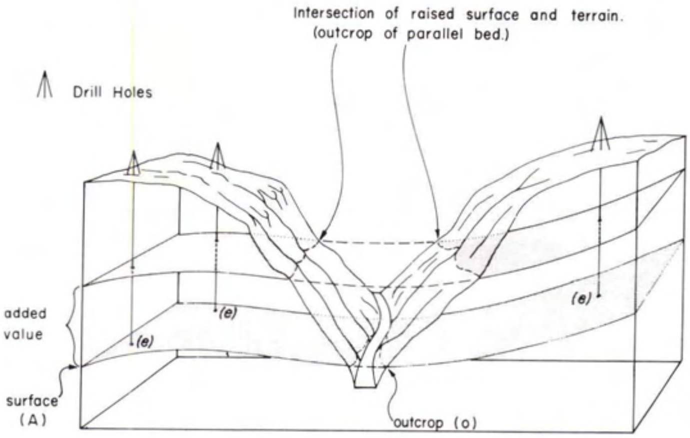

FIG. 4. Computation of a curved gridded surface (A) from drill-hole elevations (e) and points measured on outcrops (o). The sketch illustrates how the surface can be raised to describe another level and how it traces outcrops on the terrain. The *Z*-grid function keeps the floating mark of the photogrammetric instrument on the surface while the operator traces the intersection with the terrain.

drive can indicate areas of stratigraphic thinning, channeling, and possible faulting.

ISOPACH MAPS AND OVERBURDEN MAPS

Elevations on tops of geologic units such as formations, coal beds, and coal interbeds may be entered from drill-hole data. Grids that represent the top and bottom of a bed are calculated from these data. The grids are then subtracted and the difference contoured, thus making an isopach map, which shows changes in thickness of the geologic bed or unit. Interburden maps showing thickness of strata between coal beds can be computed in a similar manner.

Overburden maps can be constructed by subtracting the gridded geological horizon from a digital elevation model (DEM) of the surface. The DEM may be calculated from points digitized in an arbitrary pattern from the stereoscopic model, or it could be one generated by the USGS National Mapping Division.

An overburden map to be used as a guide to surface mining can be easily prepared using the Z-grid drive function of the GEOPROGRAM. Open-pit mines are usually planned on the basis of ratios between thickness of the bed to be mined (a coal bed, for instance) and the rocks and soil above it (overburden) that can be economically removed. By gridding the surface of the coal bed to be mined from drill data, required overburden-limit maps can readily be constructed by adding designated overburden increments to the coal-bed grid and tracing the floating mark along the terrain surface as the Z-grid drive function maintains the proper vertical increment.

PROFILES AND CROSS SECTIONS

Terrain profiles are used to construct geologic cross sections that show the relationship of rock units and geologic structures intersected along the line of profile. Cross sections represent the geologist's concept of the geometry beneath the surface of the profile. The system allows profiles to be drawn in any direction and displayed at any scale within the limits of the plotter. They can be plotted as true length profiles along any curved path of data gathering (e.g., stream profiles) or projected to a profile line defined by the starting and stopping points of data. The vertical (*Z*) element of the profile can be exaggerated as desired to enhance topographic relief that might aid in geologic interpretation.

Profiles can be drawn from either the stereoscopic model or the base map. Profiles are digitally constructed from the model using points that are entered incrementally as the tracing assembly is moved along the line of section, keeping the floating mark on the ground surface. The profile points are stored in the system, and the profile can be drawn on the pen plotter at desired scales and vertical exaggeration ratios. To draw profiles from the contours on the base map using the digitizing table, only the elevations of the start and end points, and the contour interval of the map need be entered into the system. By pressing keys on the digitizer cursor that are coded for uphill, level, or downhill movement, points are digitized where contours cross the line of profile. Terrain extremes (ridge crests and valley bottoms) may be digitized and elevations entered manually as they are encountered along the profile.

Once the profile is stored and drawn (using either technique), geoplanes that represent geologic surfaces stored in the system can be retrieved and projected into the profile to aid in construction of geologic cross sections (Figure 5). The program is designed so that geoplanes can also be generated from field observations by entering the strike and dip from the keyboard. These geoplanes can also be plotted on the profile. The trace of gridded surfaces, generated by the computer from subsurface and outcrop information, can be shown on the plotted profile, as well (Figure 3b and 3c); thus, automated construction of geologic cross sections is possible.

Stream profiles that accurately portray changes in gradient and knick points along streams can be drawn and plotted as true length profiles or projected profiles. Stream cross sections show changes in the shape of the channel along the stream that may reflect the rock type.

Another function allows the construction of thickness sections. A profile is constructed along a line where a photogrammetrically measured section is desired. After the profile is drawn, either a photogrammetric or a field-measured geoplane is entered and projected on the profile (Figure 6). The floating mark is then positioned on field stations or model image points along the line of section; these stations are then automatically noted and labeled on the line of section at their proper position (Figure 6).

COMPUTER-CONTROLLED PHOTOGRAMMETRIC SYSTEMS

The CPMS, however versatile, is limited by the analog/mechanical design of the photogrammetric plotting instrument used (i.e., the Kern PG-2), and many GEOPROGRAM functions are restricted because of the limited capacity of the computer used for the original program development (the HP-9825 desk-top computer) and the programming language applied (HPL).

ANALYTICAL PLOTTERS

Analytical plotters reconstruct ground-coordinate positions mathematically instead of by mechanical analogs. They are not limited by mechanical linkage, and the photograph stage movements are computer-controlled. System software may control the movement of the measuring mark in all three coordinate directions. In the PG-2-based system, only the *Z*-motion can be driven by the computer, which presents problems when the geoplanes used to drive the *Z* become too steep. In general, the PG-2 based system works well if dips are less than 60 degrees. The PG-2 can drive the pen plotter, but neither the digitizer nor the flat-bed plotter can drive the *X* and *Y* motions of the PG-2. This restricts the flexibility in comparing the stereoscopic model with lines drawn on a map, or already digitized data in a file. Such restrictions are not present in analytical plotters. Some new features of potential importance to geological mapping are described below.

Points and linework that were measured along an outcrop or

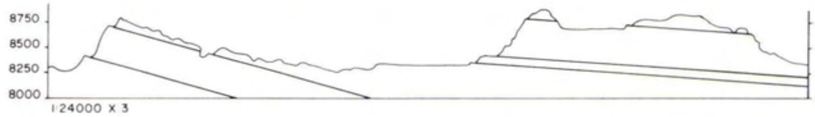

FIG. 5. Cross section containing planes automatically projected into, and plotted on, the 3x exaggerated terrain profile. The planes represent true or apparent dip, depending on the strike, the azimuth of the line of section, and vertical exaggeration. If the azimuth of the profile is not perpendicular to the azimuth of the strike of the geoplane, apparent dip is displayed.

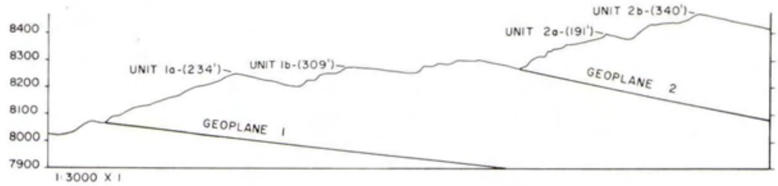

FIG. 6. Cross section showing actual or inferred outcrop points drawn and labeled by the GEOPROGRAM. Stratigraphic distances to subunit tops (shown after each unit label) are automatically calculated for each point using a projected geoplane as basis (geoplane 1). If attitudes change along the section, another geoplane may be entered (geoplane 2) and used for stratigraphic distance calculations.

contact in the analytical plotter and stored in the system can be re-occupied automatically and checked. By following contacts on a geologic map with the cursor, the floating mark can also be driven in X and Y, once the map has been oriented to the aerial photographs. By keeping the dot on the ground as contacts are followed on the map, the operator(s) can visualize what was mapped originally. This feature could promote data verification and enable error estimates to be assigned and tracked throughout the map compilation process. Likewise, the computer can record a photogrammetric traverse during mapping and drive the photograph stages to reverse the traverse or repeat the exact movements of the cursor, to show how particular features were mapped and indicate any necessary corrections.

Analytical plotters may be controlled by modern microcomputers (PCs) that have much more capacity than was available in the CPMS computer system, or by multitasking minicomputers that have virtual memory. Powerful commercial software programs for database manipulations and geographic information systems are available for these computers. The integration of modern database systems with the GEOPROGRAM functions for the storage and retrieval of points, planes, profiles, and drill-hole information will improve the flexibility of the data manipulations. Geologic structures commonly are more complicated than those that can be represented by simple flat planes and gridded surfaces used for Z-guiding in the CPMS. Software for more complex modeling of geological structures, including mathematically described curved surfaces instead of the gridded surfaces and allowing for incorporation of faults and complicated folds is being researched and developed at many universities and companies. Such software, in an easy-to-use version, would be an important supplement to the more primitive modeling software now used. On the other hand, modeling software for geologic structures would, in fact, benefit from the comparison with the stereoscopic model.

A stereo superimposition system is available for some analytical plotters (Cogan *et al.*, 1988). By means of this system, the geologist can observe a 3-D model of digitized lines superimposed on the stereoscopic photographic model. Because any stored linework can be superimposed, complicated mathematical structural surfaces can be depicted graphically and projected into the model as an improvement of the present Z-guiding facility.

GEOGRAPHICAL INFORMATION SYSTEMS

Incorporation of a modern Geographical Information System (GIS) for storing, editing, and drawing of digitized geologic map data will enhance mapping capabilities of the systems and improve the quality of the final map products. Though prototype 3-D raster systems exist, commercially available GIS programs are based on two-dimensional topology. Some even consider the elevation data as an attribute rather than a spatial coordinate. Because the CPMS is a three-dimensional system, such two-dimensional GIS systems would impose limitations that would cause problems with many applications of the GEOPROGRAM. A database and GIS system with true three-dimensional topology, where the spatial relationship between points, lines, surfaces, and volumes are solved, would, on the other hand, be the ultimate tool when combined with an analytical plotter and the stereoscopic model. Combined with the above described superimposition system, a stereoscopic framework of topologically arranged data could be compared to the stereoscopic image of the terrain, thereby allowing a superior check of digitized and stored data in the GIS system. The ability to access, utilize, and project other data sets resident in the GIS could benefit the photogrammetric mapping process.

SUMMARY

Though a prototype system, the CPMS has been very useful in many different geological mapping projects at the Geological Survey of Greenland and the U.S. Geological Survey in Denver, Colorado.

The CPMS is designed so that geologists can operate the system after a technician has oriented the stereoscopic model to the base map. The CPMS is interactive and aids the geologist in the verification of hypothetical structural models by allowing the formation of three-dimensional mathematical models fitted to measurements, and the projection of these models into the stereoscopic photographic image. Intersection between these mathematical models and the terrain can be interpreted, verified, traced, and mapped.

The CPMS offers a true three-dimensional mapping capability. Geologic data digitized into a two-dimensional GIS system may someday become obsolete because the nature of geology is three dimensional. Topographic mapping can utilize contours to describe the terrain because all topographic features reside on the ground surface – geology extends beneath that surface.

Software for geologic photogrammetry is being developed continuously. Analytical plotters greatly expand the horizons for development of automated mapping systems for geology, especially when ultimately combined with software to handle a true three-dimensional topological description of the geology.

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