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COMPUTER SUPPORTED GEOLOGICAL PHOTOINTERPRETATION

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Abstract

A desk-top computer is connected to a photogrammetric plotting instrument, and programs have been developed to calculate geological structural parameters. The plotting instrument is equipped with a stepping motor on the z-column which is guided by the computer. Hereby the measuring mark can be kept in a precalculated geological horizon during interpretation and plotting.

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## INTRODUCTION

The geological mapping of Greenland is carried out under rather extreme working conditions. Climate makes field work possible for only a few summer months every year. Due to restricted transport capacity during expeditions, combined with difficult terrain accessibility, only a limited part of the mapping area can be explored in the field. These conditions have been the reason for a systematic research on the use of high-order photogrammetric methods in the geological mapping procedure. The current mapping of North Greenland (a 130,000 km<sup>2</sup> ice-free area north of the inland ice) involves special problems because, when the geological work commenced in the mid-seventies, no topographic map was available.

In 1975, a research project was started to investigate alternative methods for a combined geological and topographic mapping of North Greenland using photogeology, photogrammetry, and computerized mapping procedures. The project has been supported by the Danish Science Research Councils, The Geological Survey of Greenland, and The Department of Surveying and Photogrammetry at The Technical University of Denmark. Results from the work are described by Dueholm (1979). These include computer-assisted photogrammetric procedures for geological photointerpretation and mapping, application of analytical aerotriangulation as a routine procedure in the geological mapping, combined geological and geodetic field expeditions, and the use of digital terrain models in topographic mapping. The present paper is an extract of one of the central items from this publication, namely the use of a digitized stereo plotter (the Kern PG2, DC2-B system) connected to a desk-top computer (the Hewlett Packard, HP 9825A) in geological mapping. Special emphasis is given to the mathematical background for interpretation programs developed in cooperation with Geologist Hans F. Jepsen, The Geological Survey of Greenland. Pilote investigations using less sophisticated instrumentation are described by Jepsen and Dueholm (1978).

## Use of Photogrammetry in Geology

Stereo plotters have been used for geological mapping outside Denmark for more than 25 years. Especially the United States Geological Survey in Denver, Colorado, have systematized the use of stereo plotters for regional geological mapping purposes (Pillmore, 1979). Research on the use of computerized methods has also been initiated at the U. S. Geological Survey and is now coordinated with the continuing work in Denmark. General aspects of this cooperation is described in a paper by Pillmore et al. (1980) presented at this congress.

The early experiments in the United States as well as in Denmark showed convincing results on the use of stereo plotters for one-step geological interpretation and mapping. The additional capability of the instrumentation to take precise spatial point measurements from the stereo model was recognized as a potential aid in structural geological analysis. However, the feasibility has been influenced by the lack of efficient methods for the transformation of point observations to descriptive geological measurements and thorough methods for evaluation and control of the measurements. Such possibilities are now at hand with the computerized photogrammetric systems.

### Z-GUIDING SYSTEM FOR STRUCTURAL INTERPRETATION

In geological mapping only a limited part of the mapping objects is visible in the stereoscopic model (and in nature). Based on rock outcrops and supported by general geological experience, the geologist needs to measure, extrapolate, and illustrate on a map the most likely geological composition of the area. Theories about the geological settling are tested by measurements on outcrops and consequently changed or modified during the mapping procedure. Observations, structural interpretation, and simulated geological models are related in a dynamic process until congruence between available measurements and theory is accomplished. This means that the geologist, although mapping all visible outcrops, also has to verify a geological structural model. In the computerized photogrammetric interpretation system this has been solved by introducing a feed-back from the computer to the plotting instrument, designated the z-guiding principle.

A stepping motor is mounted on the z-column of the tracing assembly of the PG2 and is operated by the HP 9825A desk-top computer. Point

measurements on geological horizons, taken by the geologist in the stereo model, are transformed to ground coordinates by the Kern DC2-B registration device and sent to the computer. The geologist uses interactive programs to build up mathematical/digital models of the geological structure. Via the stepping motor the z-settling of the floating mark is guided by the computer model as the tracing device is moved around in the stereo model. With the guided floating mark, the geologist can inspect the terrain for additional rock outcrops belonging to the structure in question. If the computer model does not fit into the geological structure, the model can be rectified, possibly by means of supplementary measurements on newly discovered outcrops. Accepted geological boundaries can be extrapolated into covered areas where they are traced in a way similar to the way in which contours are traced in topographic mapping, except that the floating mark is guided to follow an inclined geological surface.

#### PROGRAM FOR STRUCTURAL INTERPRETATION

The program is designed according to the measuring procedure applied in the field by geologists. A compass with clinometer is used in the field to measure local dip and strike of rock outcrops, i. e. the orientation of a tangent plane to the geological surface is measured. Such local observations are later combined, by means of statistical methods, to give parameters describing the complete structure, for instance plunge and direction (orientation) of fold-axis systems. Actually, geological structures are rarely planar surfaces. However, most frequently they can be approximated to a plane within limited areas (sometimes hundreds of square kilometers). When at least three points are measured in the stereo model within such an area, the computer can calculate the orientation of a plane through the points. In order to be able to control and evaluate the measurements, the plane is calculated by a least-squares adjustment. The plane equation is

$$ax + by + cz + d = 0, \quad a^2 + b^2 + c^2 = 1$$

where  $(a, b, c)$  is a normal unit vector to the plane. A least-squares adjustment gives the following coefficients in the normal equations:

$$\begin{aligned}
N(0) &= n, & N(1) &= \Sigma x, & N(2) &= \Sigma y, & N(3) &= \Sigma z \\
N(4) &= \Sigma xx, & N(5) &= \Sigma yy, & N(6) &= \Sigma zz \\
N(7) &= \Sigma yz, & N(8) &= \Sigma xz, & N(9) &= \Sigma xy
\end{aligned}$$

where  $n$  is the number of points. These coefficients can be summed up point by point so that only ten registers are used independently of the number of points. Therefore the points can be obtained incrementally without capacity problems as a geological horizon is traced by the floating mark. This has proved to facilitate the measurements. As calculations are performed in ground coordinates (UTM coordinates), rounding off errors on the square coefficients disturb the calculations. Therefore the origin of the coordinate system is currently shifted to the central point of the measured point group. This provides other advantages which are described later. In this case  $N(1)$ ,  $N(2)$ , and  $N(3)$  become 0. Instead the coordinates of the central point are stored in these registers so that no information is lost by the transformation. If point  $n+1$  has the coordinates  $(x, y, z)$ , the shifted coefficients are calculated from

$$\begin{aligned}
(1) \quad N(1)_{n+1} &= (nN(1)_n + x)/n + 1 \\
N(2)_{n+1} &= (nN(2)_n + y)/n + 1 \\
N(3)_{n+1} &= (nN(3)_n + z)/n + 1 \\
N(4)_{n+1} &= N(4)_n + \frac{n}{n+1} (N(1)_n - x)^2 \\
N(5)_{n+1} &= N(5)_n + \frac{n}{n+1} (N(2)_n - y)^2 \\
N(6)_{n+1} &= N(6)_n + \frac{n}{n+1} (N(3)_n - z)^2 \\
N(7)_{n+1} &= N(7)_n + \frac{n}{n+1} (N(2)_n - y)(N(3)_n - z) \\
N(8)_{n+1} &= N(8)_n + \frac{n}{n+1} (N(1)_n - x)(N(3)_n - z) \\
N(9)_{n+1} &= N(9)_n + \frac{n}{n+1} (N(1)_n - x)(N(2)_n - y)
\end{aligned}$$

These coefficients are easily shifted back to an arbitrary origin of the coordinate system:

$$\begin{aligned}
(2) \quad N(1)_a &= (N(1) - x_a) n \\
N(2)_a &= (N(2) - y_a) n \\
N(3)_a &= (N(3) - z_a) n \\
N(4)_a &= N(4) + N(1)_a^2/n \\
N(5)_a &= N(5) + N(2)_a^2/n \\
N(6)_a &= N(6) + N(3)_a^2/n \\
N(7)_a &= N(7) + N(2)_a N(3)_a/n \\
N(8)_a &= N(8) + N(1)_a N(3)_a/n \\
N(9)_a &= N(9) + N(1)_a N(2)_a/n
\end{aligned}$$

where  $(x_a, y_a, z_a)$  is the new origin.

### Calculation of Dip and Strike

The normal equation translated to the central point is solved for  $(a, b, c)$ ,  $d$  is zero. The standard deviation unit weight gives the mean distance from the observed points to the calculated plane, which is used by the geologist as a first check on the measurements. Dip and strike are calculated from

$$\begin{aligned}
\text{dip} &= \text{atan}((a^2 + b^2)/c) \\
\text{str} &= \text{atan}(-a/b); \quad 0 \leq \text{str} < \pi
\end{aligned}$$

Standard error on dip and strike is calculated from the weight matrix, and the following print-out is given by the program:

92	N = 29
STRIKE/DIP	
81(171)/05.4	S
err. 1	0.5
st.est.	4 m

plane 92, number of points 29, dip 05.4° south, strike 081°, standard error on dip 0.5°, on strike 01°. st. est. is standard error on the distance from the observed points to the plane.

Whenever a point group is measured, two things happen immediately. 1) Dip and strike are calculated and the above print-out given. 2) The coefficients  $N(0)$  to  $N(9)$  are stored on tape under an identification number; this file is in the following referred to as a "point group".

## Combination of Measurements

The geologist can at any time and in any model recall the point groups from the tape and combine them in several ways:

1) Two or more point groups can be added for calculation of a common plane through all points. This is accomplished in the following way. A common central point is calculated as a weighted mean of the local central points. The coefficients for the involved point groups are shifted to the common central point by means of formula (2) and added. By solving these new normal equations, dip, strike, and error estimates are calculated for the common plane.

2) Point groups on a set of plane-parallel horizons can be combined to give a composite orientation of the entire unit. This is accomplished simply by adding the coefficients translated to the central point for the point groups involved and solving the normal equations thus obtained (see Figure 1). Geologically this gives the composite orientation of different bedding planes within the same stratigraphic unit.

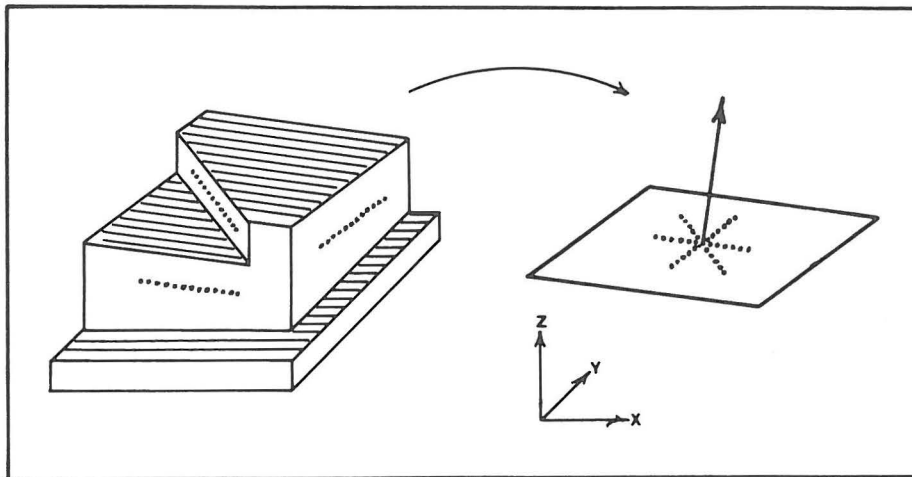


Figure 1 Terrain diagram illustrating the principles in calculation of common orientation of parallel bedding.

3) Point groups can be parallelly shifted so that the calculated plane goes through an arbitrary point occupied by the floating mark in the stereo model. This is accomplished by substituting the calculated central point by the new measured point.

4) If the measured point groups were originally taken on different outcrops belonging to a fold structure, they can be recalled for calculation of plunge and direction of the fold-axis system (Figure 2). A vector oriented as the fold axis ( $f_1, f_2, f_3$ ) is calculated by least-squares adjustment from the expression  $a_1 f_1 + b_1 f_2 + c_1 f_3 = 0$ , where  $(a, b, c)_i$  are the normal vectors involved, calculated as described earlier. The calculated standard error on the length of each normal vector is used as weight in this adjustment.

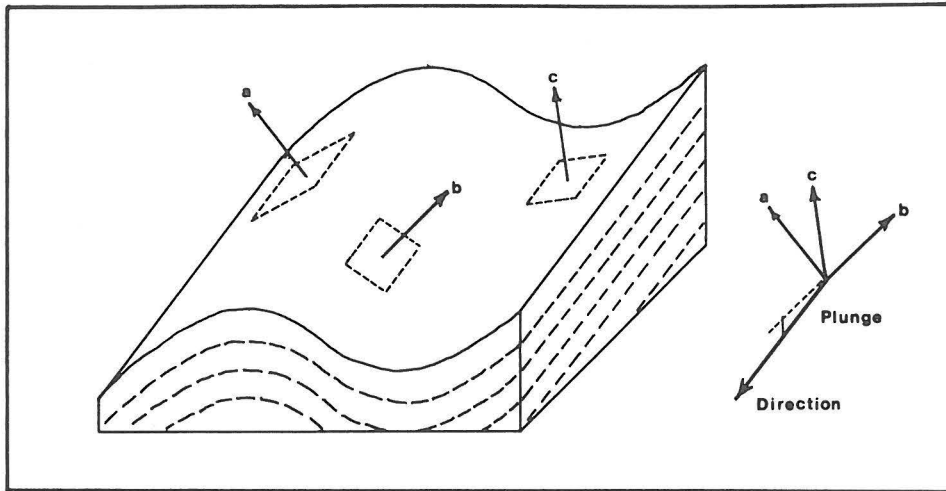


Figure 2 Calculation of fold axis from local normal vectors to the fold.

Combined point groups are stored on tape under an identification number, as were the measured point groups. Point groups accepted by the geologist can be recalled and restored under an alphanumeric name for later use and conservation. The system is dimensioned to store five hundred named point groups, and this appears to be sufficient for several photogrammetric models.

### z-Guiding

Point groups can be recalled from tape and used for z-guiding. z is calculated from

$$z_c = (aN(1) + bN(2) + cN(3) - ax - by)/c$$

During z-guiding the standard error on  $z_c$  (as a function of  $x, y$ ) is continuously calculated and displayed. This results in a parabolic surface that depends, among other things, on the distribution of the measured points (Figure 3). This is a useful feature when the geologist extrapolates horizons from the measured outcrop.



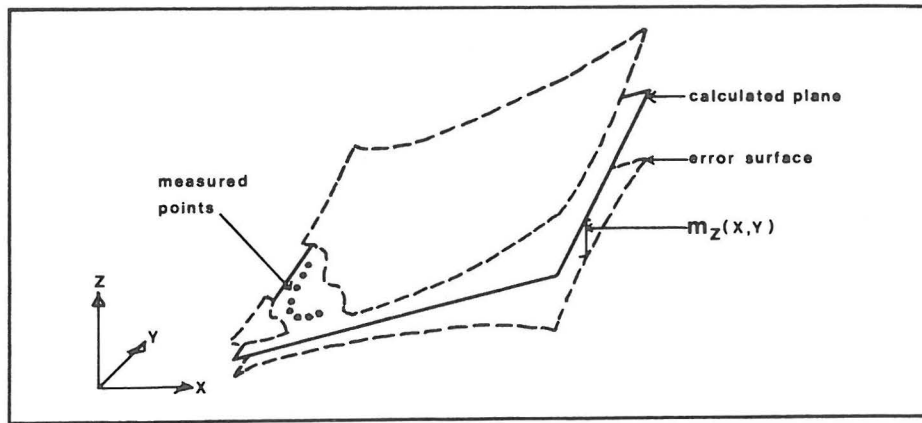


Figure 3

### Other Facilities

When a plane is established in the computer, the perpendicular distance from a point occupied by the floating mark in the stereo model to the plane can be continuously calculated and displayed. This is useful for calculation of stratigraphic thickness of geological beds and for a fast check on thickness variations. Similarly, the distance between two planes established in the computer can be calculated and displayed, which is used for search of faults and calculation of displacements along a fault.

### Discussion

The calculations are so fast that the geologist never has to wait for results, and all functions are accessed by pressing only a single special key on the computer. These are important features because geologists need to use a trial-and-error approach when evaluating geological structures.

The system has been in operation for a couple of years at The Geological Survey of Greenland and has been occupied full time. It has proved useful in projects which contain both simple and complicated geological structure. In sub-horizontal geological terrain, structural measurements have been performed, which would have been almost impossible to measure in the field. Accuracies on dip angles of about  $0.1^{\circ}$  are frequently obtained. In complexly folded terrain, the method has provided valuable knowledge of general structure trends to help subsequent field work. In several projects the methods have led to the discovery of geological features which would otherwise have been very difficult to observe.

## CONCLUSIONS

A digitized photogrammetric plotting instrument connected to a desk-top computer for interactive calculation of geological structures is a profitable aid to geological mapping. The z-guiding principle and the software developed for structural interpretation have been very useful, and work continues to develop, among other things, programs for representation of folded strata. It seems reasonable to conclude that the previous use of photogrammetric methods in geological mapping has to be re-evaluated considering the possibilities of direct computer support in the interpretation procedure.

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