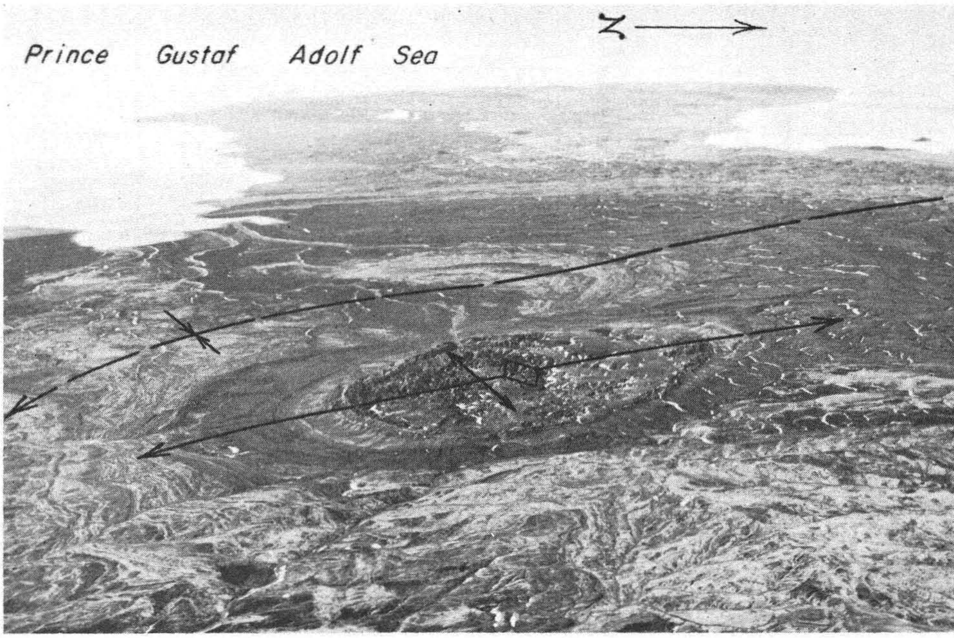

FIG. 1. Trimetrogon oblique photograph of the Isachsen Dome, Ellef Ringnes Island, District of Franklin, N.W.T., Canada.

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Digital Structural Analysis

A computerized delineation of surface geologic structure in areas of low relief and discontinuous bedding.

PURPOSE

THE MULTIPOINT SYSTEM of digital structural analysis was developed by Geophoto Services as an outgrowth of experience gained in photogrammetric structural contouring of low-dip areas such as the Edwards Plateau in Texas.

The system was designed to fill the petroleum industry's need for a method of mapping surface geologic structure in regions of extremely gentle folds expressed in poorly exposed beds which are difficult or impossible to map by conventional field or photogrammetric procedures.

During Geophoto's twenty years of experience in structural contouring, structural formlining, and other means of depicting the structural configuration of stratified rocks, the problem of successfully mapping areas of low structural relief and discontinuous bedding has been a recurring challenge. The arrival of the digital computer makes possible a solution to this problem and has led to a new concept

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of structural form-lining and to a recognition of its place in a modern program of petroleum exploration.

The computerized photogrammetric system of digital structural analysis developed by Geophoto may be called the multipoint system because it minimizes the effect of minor observational errors by averaging numerous readings made on a single stratigraphic horizon within a limited area. Essentially, the method consists of substituting a series of computer-calculated composite dip-strike determinations for the conventional three-point measurements made in areas of moderately dipping beds to control the trend and spacing of structural form lines.

Instrumentation

The initial phase of a digital structural mapping program is like that of a conventional photogrammetric structural contouring operation. After the appropriate scale of air photography is determined, a set of paper contact prints and a corresponding set of glass diapositive prints of stereoscopic photographs are ordered. The paper prints are used in a preliminary study to select suitable key beds for the photogrammetric procedures. Annotation of alternate contact prints is an aid to the operator in identifying the horizons to be mapped and will reduce the time required to perform the stereoplotting operation.

ABSTRACT: *A computerized multipoint system for delineating surface geologic structure in areas of low relief and discontinuous bedding was designed to fill a need of the petroleum industry. A Balplex Triangulator, Auto-Trol converter, and IBM 1620 are used to produce a comprehensive printout of needed quantities and their reliabilities, in addition to the map. An important application is in areas where conventional structural contour mapping cannot be accomplished, or is more expensive and less accurate. The system provides a fast and economical exploration technique in conjunction with geophysical methods, either as a guide or as confirmatory evidence.*

The attitude of a tilted plane is expressed in terms of its dip and strike. Strike is the direction of a line formed by the intersection of a bedding plane with the horizontal; dip is the angle between the bedding plane and the horizontal. On a map, the dip and strike are shown graphically by a symbol consisting of the strike line with a line perpendicular to it which points in the direction of dip and is accompanied by a numerical value. This is demonstrated by Figures 1 and 2.

Parameters

Application of this method to several test areas in the western United States and some foreign countries over a period of three years, using photography of different scales, and vertical control of varying density and limits of accuracy, has provided data for establishing approximate parameters to govern the use of digital structural analysis. Assuming adequate definition of bedding and knowing the anticipated rate of dip, the most suitable scale of photography can be determined, as well as accuracy requirements for vertical control to level the models and the minimum area and number of points for each digital dip computation.

Figure 3 is a photograph of part of the Edwards Plateau in Sutton County, Texas where nearly horizontal Cretaceous limestones exhibit well-defined bedding.

Projection of the glass diapositives to form a three-dimensional model may be accomplished by means of several types of stereoplotting instruments, of which the Kelsh plotter and the Balplex Triangulator can be well adapted. Figure 4 illustrates a standard Bausch and Lomb Balplex Triangulator to which an analog recorder has been added.

The addition of the analog recorder marks the start of the multipoint phase of the program, which may be described in terms of Data Collection, Data Processing, and Data Analysis.

Data Collection

The analog recorder was designed specifically for Geophoto by the Auto-Trol Corporation. Its essential constituent is a coordinatograph, attached to the moveable tracing table in such a manner that the north-south, east-west, and up-down position of the "floating dot" is continuously under surveillance as it is moved along the trace of a stratigraphic marker within the three-dimensional stereo-

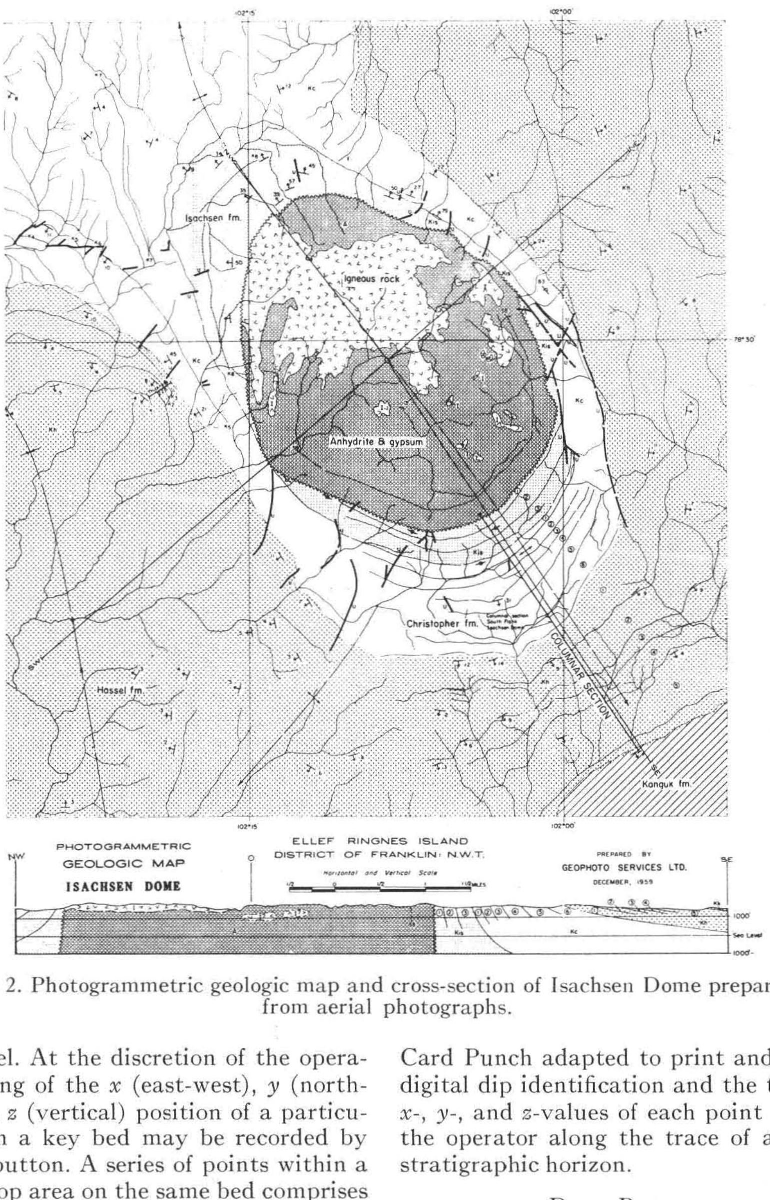

FIG. 2. Photogrammetric geologic map and cross-section of Isachsen Dome prepared from aerial photographs.

scopic model. At the discretion of the operator, a reading of the x (east-west), y (north-south), and z (vertical) position of a particular point on a key bed may be recorded by pressing a button. A series of points within a given outcrop area on the same bed comprises a net. A digital dip-strike calculation is made by the computer for each net. This information is plotted manually in graphic form. Several steps, however, intervene between pressing the button and plotting the digital dip.

Figure 5 (right) is a photograph of the Analog-to-Digital Converter designed by Auto-Trol Corporation to receive the electrical impulses transmitted by the analog recorder, convert them to digital form and transmit them to a standard IBM printing card punch.

Figure 5 (left) shows the IBM Printing Card Punch adapted to print and punch the digital dip identification and the transmitted x-, y-, and z-values of each point selected by the operator along the trace of a particular stratigraphic horizon.

Data Processing

The data-processing program was written specifically for Geophoto by Auto-Tronix, Inc., and utilizes a statistical least-squares technique to determine the plane that fits the data best. The rate and direction of dip as well as a statistically determined rate and direction of dip confidence factor are computed. Symbolic Programming System (SPS), fixed-point arithmetic, and 15-decimal precision were selected to give the best combination of speed, maximum accuracy, and minimum memory storage.

The input data are supplied to the com-

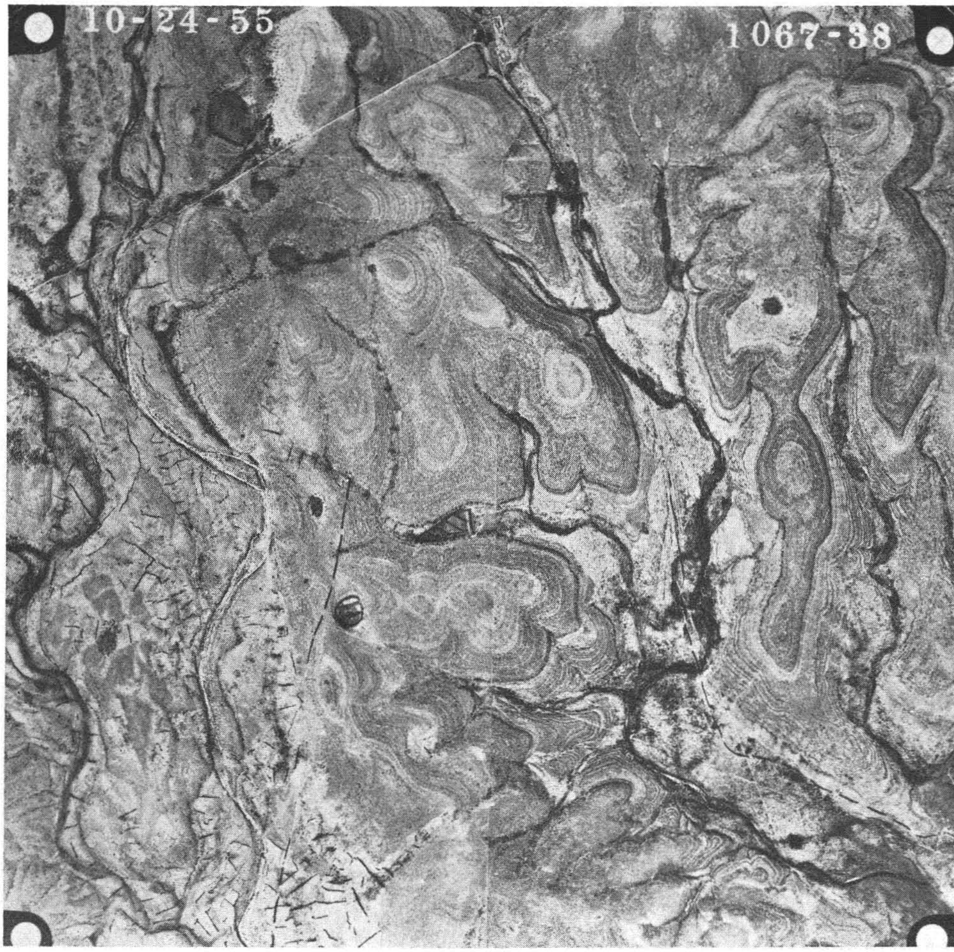

FIG. 3. Part of Edwards Plateau in Sutton County, Texas where nearly horizontal Cretaceous limestones exhibit well-defined bedding.

puter on punch cards. Computer output is on punch cards but is also printed in tabular form to facilitate graphic representation on the map and for use in analysis of the data.

Data processing utilizes the IBM 1620 Model II digital computer with 20,000 addressable positions of magnetic core storage, the IBM 1622 Card Read-Punch or equivalent, and the IBM 1403 Printer or equivalent to print the tabulated digital dip listing.

DATA ANALYSIS

The end product of the multipoint system of digital structural analysis is a form-line map showing the structural configuration of beds exposed within the project area. As in structural contouring, the drawing of structural form lines is an interpretive procedure which in critical areas may require comparison and evaluation of diverse data or which may require that certain values be interpreted in proportion to their apparent reliability. The term "confidence" is used in connection with multipoint dip-strike determinations to indicate their order of reliability and forms the heading of two of the columns in the sample of Tabulated Computer Output (Figure 6). Also involved in the evaluation of the quality of a given digital dip are the values in the columns headed "rating" and "Sigma." An explanation of these and other headings is as follows, where the numbers refer to the columns in Figure 6.

1. *PROJ* is the project number, assigned for the purpose of identifying the punch cards and all other project materials.
2. *QUAD* is the number of the quadrangle or map sheet which contains the stereo model being processed.
3. *FLT* refers to the flight line of air photography within the quadrangle, numbered in sequence for identification.

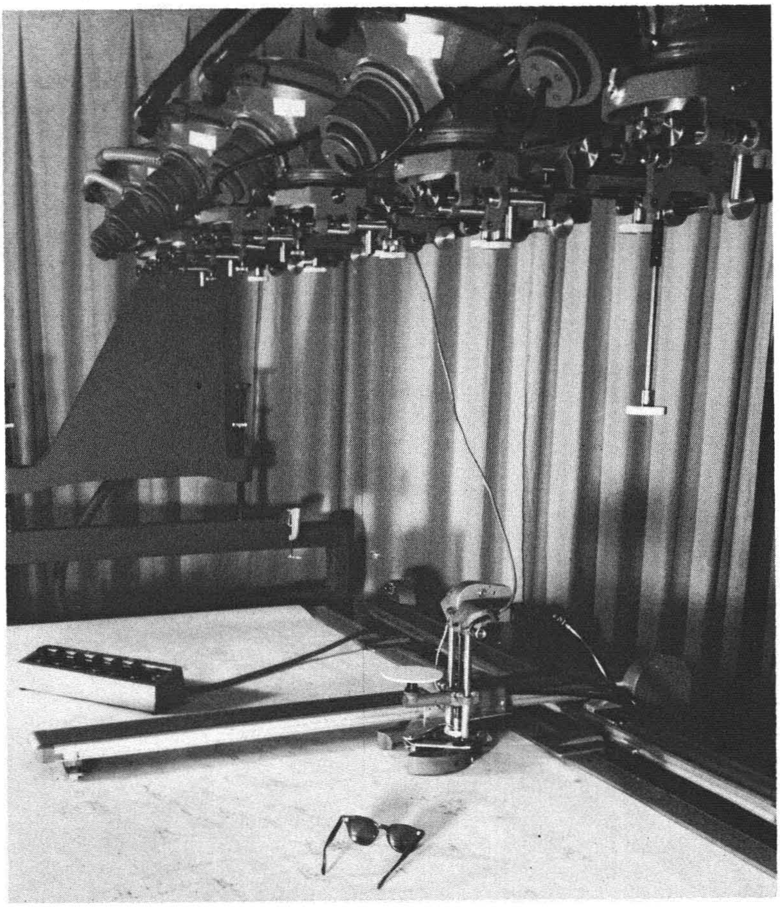

FIG. 4. Standard Bausch and Lomb Balplex Triangulator to which an analog recorder has been added.

4. *AB* identifies the stereoscopic model, numbered in sequence along the flight line.
5. *SET* identifies the group of points for which a digital dip computation is made. The groups or sets are numbered consecutively and each forms a net within a selected outcrop area. All points in a given set are read on the same stratigraphic horizon.
6. *Rating* is a provision to allow the operator to evaluate the geologic quality of each digital

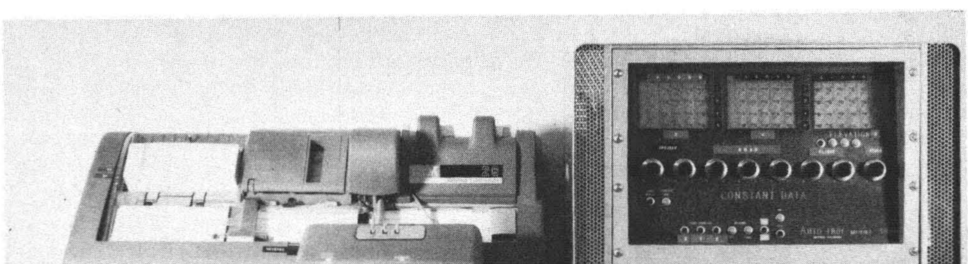

FIG. 5. On the left is an IBM Printing Card Punch adapted for dip identification and x-, y-, z-coordinates. On the right is the Analog-to-Digital converter designed by Auto-Trol Corporation.

PROJ.	QUAD	FLT.	AB	SET	Rating	SCALE	No. of POINTS	SIGMA	AZIMUTH	Confidence	DIP RATE	Confidence	X Co-ordinate	Y Co-ordinate	Elevation	
3383	113	03	03	001	0	1000	N=0048	SIG= 3.7	AZ=285D 23M	1D 47M	DIP= 1D 27M	0D 01M	26170.2	17380.0	6851.7	
3383	113	03	03	002	0	1000	N=0043	SIG= 2.6	AZ=276D 35M	0D 00M	DIP= 1D 11M	0D 01M	28110.9	19677.7	6896.5	
3383	113	03	03	003	0	1000	N=0022	SIG= 2.0	AZ=267D 46M	2D 27M	DIP= 1D 14M	0D 02M	24088.2	20535.5	6779.3	
3383	113	03	03	004	0	1000	N=0029	SIG= 3.5	AZ=234D 41M		DIP= 0D 50M	0D 03M	22232.0	16640.3	6569.6	COMPN
3383	113	03	03	004	3	1000	N=0029	SIG= 2.4	AZ=223D 01M	10D 29M	DIP= 0D 51M	0D 14M	22232.1	16640.3	6569.7	
3383	113	03	03	005	0	1000	N=0045	SIG= 3.6	AZ=291D 56M	1D 47M	DIP= 1D 27M	0D 01M	21349.6	17066.2	6546.4	
3383	113	03	03	006	0	1000	N=0055	SIG= 2.6	AZ=268D 27M	0D 56M	DIP= 1D 26M	0D 05M	20478.5	18536.9	6518.8	
3383	113	03	03	007	0	1000	N=0030	SIG= 3.8	AZ=268D 50M	2D 39M	DIP= 1D 07M	0D 11M	19896.3	20662.3	6510.6	
3383	113	03	03	008	0	1000	N=0049	SIG= 4.2	AZ=263D 21M	1D 59M	DIP= 1D 26M	0D 10M	19923.3	20659.4	6514.4	
3383	113	03	03	009	0	1000	N=0023	SIG= 3.5	AZ=358D 20M		DIP= 0D 31M	0D 03M	17267.8	19540.8	6564.3	COMPN
3383	113	03	03	009	3	1000	N=0023	SIG= 3.5	AZ=292D 44M	10D 06M	DIP= 1D 15M	0D 51M	17267.8	19540.9	6564.5	
3383	113	03	03	010	3	1000	N=0018	SIG= 1.8	AZ=355D 55M		DIP= 0D 16M	0D 03M	17122.7	21505.0	6550.5	COMPN
3383	113	03	03	010	3	1000	N=0018	SIG= 1.9	AZ= 59D 26M	19D 03M	DIP= 0D 37M	0D 26M	17122.8	21505.0	6551.1	
3383	113	03	03	011	3	1000	N=0027	SIG= 11.9	AZ=286D 46M		DIP= 1D 15M	0D 16M	14436.6	17904.4	6641.4	COMPN
3383	113	03	03	011	3	1000	N=0027	SIG= 2.3	AZ=268D 36M	10D 20M	DIP= 1D 19M	0D 04M	14436.7	17904.4	6641.3	
3383	113	03	03	012	0	1000	N=0047	SIG= 3.7	AZ=274D 16M	0D 03M	DIP= 0D 38M	0D 02M	14898.1	14765.5	6606.4	
3383	113	03	03	013	0	1000	N=0031	SIG= 6.2	AZ=299D 30M	3D 30M	DIP= 1D 47M	0D 03M	13573.5	15669.4	6577.1	
3383	113	03	03	014	0	1000	N=0048	SIG= 6.1	AZ=287D 47M	4D 47M	DIP= 1D 04M	0D 04M	11755.0	17029.0	6531.3	
3383	113	03	03	015	0	1000	N=0051	SIG= 5.3	AZ=265D 31M	2D 13M	DIP= 1D 18M	0D 04M	8513.1	17918.8	6453.0	

FIG. 6. Tabulated computer output.

dip from 0 (best) through 9 (poorest). Generally, the clarity of expression of bedding is the most important factor involved and this is affected by the amount and type of vegetation, soil cover, tonal characteristics and other variables.

7. *SCALE* indicates the number of feet on the ground represented by one inch on the manuscript map and supplies the computer with the proper vertical-to-horizontal factor for the scale of photography used.
8. *No. of POINTS* is the total number of observations recorded on a stratigraphic horizon to comprise the set of points used in computing a digital dip. The number can vary at the operator's discretion from 2 to 999 depending upon the definition, length, and attitude of a particular stratigraphic unit and upon the accuracy that can be attained from the scale of the photography used.
9. *SIGMA*, or standard deviation (see also Figure 7), is a statistical coefficient which can be interpreted as the number of feet above or below the plane of a computed dip that 67.4 per cent of an infinite number of points will fall based on dispersion of the observed readings about the computed plane. For example, if the sigma value is given as 3.7, it indicates that 67.4 per cent of an infinite number of observations will fall within 3.7 feet above or below the plane of the computed dip. Low sigma values result from: good quality, large-scale photography; well-defined bedding; lateral integrity of selected horizon (no facies change); planar structure of selected horizon within net-area. High sigma values result from: poor quality, small-scale photography; poorly defined bedding; lateral facies changes which invalidate mapping horizon; deviation of selected horizon from planar structure (warped surface).
10. *AZIMUTH* is the direction of dip measured clock-wise from true north in degrees and minutes. The use of dip direction instead of strike to describe the attitude of the dipping plane avoids possible ambiguity and is simpler to program and tabulate.
11. *Confidence*, as printed in the column to the right of AZIMUTH, is the statistically determined probable maximum variation, plus or minus, from the computed azimuth that the data will permit. For example, in Figure 6, top line, the azimuth confidence is given as 1 degree 47 minutes or from 284 degrees 36 minutes to 287 degrees 10 minutes.
12. *DIP RATE* is the angle of dip measured from the horizontal in degrees and minutes.
13. *Confidence*, as printed in the column to the right of DIP RATE, is the statistically determined probable maximum variation, plus or minus, from the computed dip rate that the data will permit. For example, in Figure 6, top line, the dip rate is given as 1 degree 27 minutes and the probable maximum variation is 0 degrees 1 minute, or from 1 degree 26 minutes to 1 degree 28 minutes.
14. *x-coordinate* is the east-west horizontal distance in feet from the computed center-of-area (net) of all observations used for a given digital dip to a reference point in each stereo model.
15. *y-coordinate* is the north-south horizontal distance in feet from the computed center-of-area of a digital dip to the reference point.

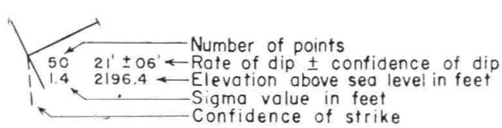

FIG. 7. Graphic dips and statistical data for structural form-line map.

16. *Elevation*, or *z*-coordinate, is the vertical distance in feet of the computed center-of-area of a digital dip above a datum plane, usually sea level.
17. *COMPN* is an abbreviation for "Component." When printed in the last column it indicates the dip data found on that line applies to a component computation rather than a conventional dip computation. Each group of observations assigned to a single dip computation is mathematically circumscribed by an ellipse. If the ratio of the major to minor axis of the circumscribed ellipse is greater than 8, both dip and component determinations are made. If the ratio is less than 8, only a dip determination is made.

In order to proceed with analysis of the tabulated computer output data in its true spatial relationship, each digital dip is plotted directly on the manuscript map (Figure 7) using the *x*- and *y*-coordinates for location and the azimuth value for direction of dip. Length of the dip line is proportional to the rate of dip; for convenience, it is plotted so as to represent the spacing of one form-line interval at map scale.

To facilitate the evaluation of each digital dip, the following supplementary data are also posted to the manuscript map: No. of points, Dip rate, Confidence of dip rate, Standard deviation, Elevation of computed center-of-area.

Strike confidence, or confidence of azimuth, if it is a value large enough to be plotted, is also shown graphically. The manuscript map is then photographically reduced to the scale of the final map and form lines are drawn perpendicular to the dip directions of the digital dip symbols. Modifications or departures from the indicated trend or spacing are made where permitted by the supplementary data.

Applications

As petroleum exploration has shifted from regions with well-defined surface structure of relatively large amplitude to gently folded regions with restricted outcrops and short, discontinuous bedding traces, the need for a fast, accurate and economical method for determining the attitude of bedding to provide control in structural form lining has become acute.

The multipoint method is designed to map photogrammetrically surface structure in areas of isolated, restricted outcrops which result in short, discontinuous bedding. It provides high density dip data to control the trend and spacing of form lines. Each digital dip is rated as to geologic quality, validity as indicated by its standard deviation, and by confidence of the rate and direction of dip. These ratings are taken into consideration during preparation of the form-line map.

Although most applications have been in low-dip areas, the multipoint method is also adapted to areas of moderate dip where short bedding traces and lack of persistent horizons prevent conventional structural contouring.

An effective combination of digital structural form-lining with structural contouring may often be achieved in certain sedimentary basins where structural contours can be locally drawn but cannot be related to a common datum throughout the area. If exposures are adequate for use of the multipoint system in the areas of discontinuous bedding which separate the contoured portions, structural form lines can be drawn to establish continuity of structural delineation and, under suitable conditions, to provide a basis for projecting the structural contours on strike across the intervening areas of restricted outcrops.

Probably the most important application of the multipoint method is in areas where conventional structural contour mapping cannot be accomplished or is more expensive and less accurate.

In regions of low structural relief the multipoint method is particularly successful in delineating the pattern and trend of minor structures and in defining the shape and extent of areas of surface closure which may reflect closure at depth. In some areas, structural terraces too subtle to be recognized by other means have been revealed by the multipoint method. Their delineation may indicate subsurface conditions significant to petroleum accumulation. In conjunction with geophysical methods, either as a guide to geophysical surveys or as a means of obtaining confirmatory evidence of structure following eophysical investigation, digital structural analysis provides a fast and economical method of petroleum exploration.